WG III contribution to the Sixth Assessment Report

List of corrigenda to be implemented

The corrigenda listed below will be implemented in the Chapter during copy-editing.

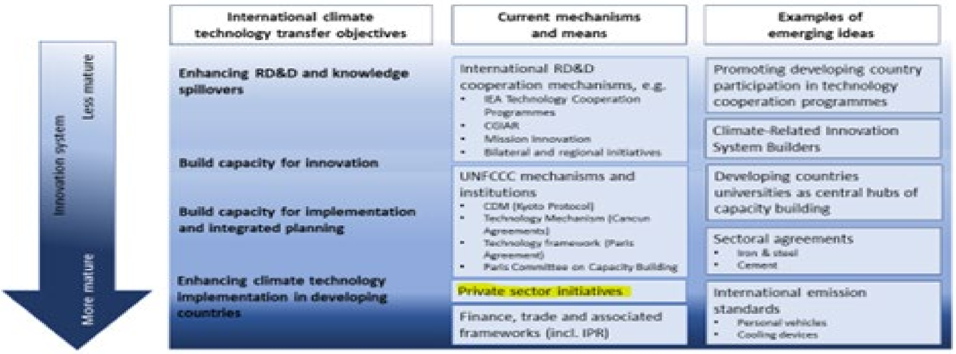
CHAPTER 16

Document (Chapter, Annex, Supp. Material)	Page (Based on the final pdf FGD version)	Line	Detailed information on correction to make
Chapter 16	4	35	in-text citation 'Box 16.5' should be Box 16.10 (the box on agriculture)
Chapter 16	5	29	add line of sight: {16.6}.
Chapter 16	5	38	in-text citation 'Box 16.10' should be Box 16.9 (the box on IPR)
Chapter 16	17	10 & 17	replace Aghion et al 2013 with Aghion et al 2016
Chapter 16	22	30	replace Aghion et al 2013 with Aghion et al 2016

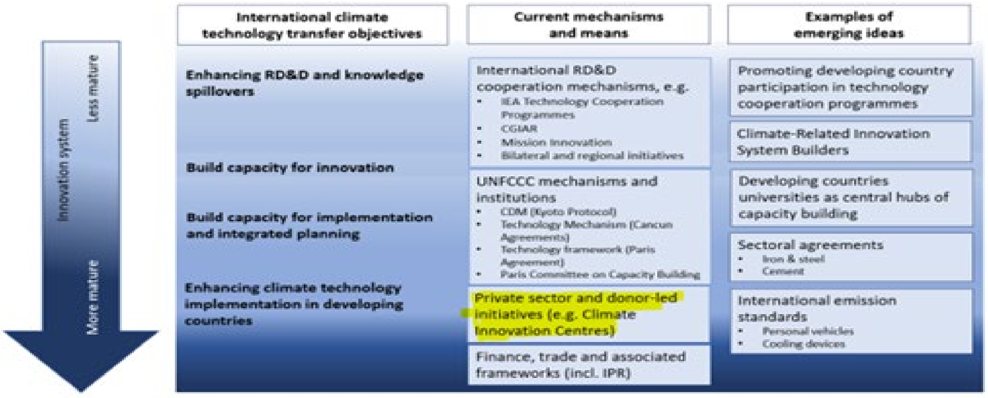
Chapter 16	74	Figure 16.3	replace the figure 16.3 see end of doc for revised version
Chapter 16	77	18	CCB12 Authors list: Maria Figueroa should read María Josefina Figueroa Meza
Chapter 16	1	13	Joni Juspesta (Indonesia) should read Joni Jupesta (Indonesia/Japan)
Chapter 16	18	25	Joni Juspesta (Indonesia) should read Joni Jupesta (Indonesia/Japan)
Chapter 16	Front	6	Ambuj D. Sagar

Corrected Figure 16.3

FGD Figure 16.3



NEW Figure 16.3



Chapter 16: Innovation, technology development and transfer

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Executive summary

Innovation in climate mitigation technologies has seen enormous activity and significant progress in recent years. Innovation has also led to, and exacerbated, trade-offs in relation to sustainable development. (*high confidence*). Innovation, can leverage action to mitigate climate change by reinforcing other interventions. In conjunction with other enabling conditions innovation can support system transitions to limit warming and help shift development pathways. The currently widespread implementation of solar photovoltaic (solar PV) and LEDs, for instance, could not have happened without technological innovation *(high confidence).* Technological innovation can also bring about new and improved ways of delivering services that are essential to human well-being. At the same time as delivering benefits, innovation can result in trade-offs that undermine both progress on mitigation and progress towards other sustainable development goals. Trade-offs include negative externalities – for instance greater environmental pollution and social inequalities – rebound effects leading to lower net emission reductions or even increases in emissions, and increased dependency on foreign knowledge and providers *(high confidence)*. Effective governance and policy has the potential to avoid and minimise such misalignments (*medium evidence, high agreement*). {16.1, 16.2, 16.3, 16.4, 16.5.1, 16.6}

A systemic view of innovation to direct and organize the processes has grown over the last decade. This systemic view of innovation takes into account the role of actors, institutions, and their interactions and can inform how innovation systems that vary across technologies, sectors and countries, can be strengthened (*high confidence).* Where a systemic view of innovation has been taken, it has enabled the development and implementation of indicators that are better able to provide insights in innovation processes. This, in turn, has enabled the analysis and strengthening of innovation systems. Traditional quantitative innovation indicators mainly include R&D investments and patents. Systemic indicators of innovation, however, go well beyond these approaches. They include structural innovation system elements including actors and networks, as well as indicators for how innovation systems function, such as access to finance, employment in relevant sectors, and lobbying activities. For example, in Latin America, monitoring systemic innovation indicators for the effectiveness of agroecological mitigation approaches has provided insights on the appropriateness and social alignment of new technologies and practices. Climate-energy-economy models, including integrated assessment models, generally employ a stylised and necessarily incomplete view of innovation, and have yet to incorporate a systemic representation of innovation systems {16.2, 16.2.4, 16.3, 16.3.4, 16.5, Table 16.7, Box 16.1, Box 16.5}.

A systemic perspective on technological change can provide insights to policymakers supporting their selection of effective innovation policy instruments *(high confidence).* A combination of scaled-up innovation investments with demand-pull interventions can achieve faster technology unit cost reductions and more rapid scale-up than either approach in isolation *(high confidence).* These innovation policy instruments would nonetheless have to be tailored to local development priorities, to the specific context of different countries, and to the technology being supported. The timing of interventions and any trade-offs with sustainable development also need to be addressed. Public R&D funding and support as well as innovation procurement have shown to be valuable for fostering innovation in small to medium cleantech firms. Innovation outcomes of policy instruments not necessarily aimed at innovation, such as feed-in tariffs, auctions, emissions trading schemes, taxes and renewable portfolio standards, vary from negligible to positive for climate change mitigation. Some specific designs of environmental taxation can also result in negative distributional outcomes. Most of the available literature and evidence on innovation systems come from industrialised countries and larger developing countries. However, there is a growing body of evidence from developing countries and small island developing states (SIDS) {16.4, 16.4.4.3, 16.4.4.4, 16.5, 16.7}.

Experience and analyses show that technological change is inhibited if technological innovation system functions are not adequately fulfilled, this inhibition occurs more often in developing countries. *(high confidence).* Examples of such functions are knowledge development, resource mobilisation, and activities that shape the needs, requirements and expectations of actors within the innovation system (guidance of the search). Capabilities play a key role in these functions, the build-up of which can be enhanced by domestic measures, but also by international cooperation *(high confidence)*. For instance, innovation cooperation on wind energy has contributed to the accelerated global spread of this technology. As another example, the policy guidance by the Indian government, which also promoted development of data, testing capabilities and knowledge within the private sector, has been a key determinant of the success of an energy-efficiency programme for air conditioners and refrigerators in India. {16.3, 16.5, 16.6, Cross-Chapter Box 12 in this chapter, Box 16.3}

Consistent with innovation system approaches, the sharing of knowledge and experiences between developed and developing countries can contribute to addressing global climate and sustainable development goals. The effectiveness of such international cooperation arrangements, however, depends on the way they are developed and implemented (*high confidence*). The effectiveness and sustainable development benefits of technology sharing under market conditions appears to be determined primarily by the complexity of technologies, local capabilities and the policy regime. This suggests that the development of planning and innovation capabilities remains necessary, especially in least-developed countries and SIDSs. International diffusion of low-emission technologies is also facilitated by knowledge spillovers from regions engaged in clean R&D (*medium confidence*).

The evidence on the role of intellectual property rights (IPR) in innovation is mixed. Some literature suggests that it is a barrier while and other sources suggests that it is an enabler to the diffusion of climate-related technologies *(medium confidence).* There is agreement that countries with well-developed institutional capacity may benefit from a strengthened IPR regime, but that countries with limited capabilities might face greater barriers to innovation as a consequence. This enhances the continued need for capacity building. Ideas to improve the alignment of the global IPR regime and addressing climate change include specific arrangements for least-developed countries, case-by-case decision-making and patent-pooling institutions. {16.2.3.3, 16.5, Box 16.10}

Although some initiatives have mobilised investments in developing countries, gaps in innovation cooperation remain, including in the Paris Agreement instruments. These gaps could be filled by enhancing financial support for international technology cooperation, by strengthening cooperative approaches, and by helping build suitable capacity in developing countries across all technological innovation system functions (*high confidence*). The implementation of current arrangements of international cooperation for technology development and transfer, as well as capacity building, are insufficient to meet climate objectives and contribute to sustainable development. For example, despite building a large market for mitigation technologies in developing countries, the lack of a systemic perspective in the implementation of the Clean Development Mechanism, operational since the mid-2000s, has only led to some technology transfer, especially to larger developing countries, but limited capacity building and minimal technology development (*medium confidence)*. In the current climate regime, a more systemic approach to innovation cooperation could be introduced by linking technology institutions, such as the Technology Mechanism, and financial actors, such as the financial mechanism. {16.5.3}

Countries are exposed to sustainable development challenges in parallel with the challenges that relate to climate change. Addressing both sets of challenges simultaneously presents multiple and recurrent obstacles that systemic approaches to technological change could help resolve, provided they are well managed *(high confidence)*. Obstacles include both entrenched power relations dominated by vested interests that control and benefit from existing technologies, and governance structures that continue to reproduce unsustainable patterns of production and consumption (*medium confidence*). Studies also highlight the potential of cultural factors to strongly influence the pace and direction of technological change. Sustainable solutions require adoption and mainstreaming of locally novel technologies that can meet local needs, and simultaneously address the Sustainable Development Goals (SDGs). Acknowledging the systemic nature of technological innovation, which involve many levels of actors, stages of innovation and scales, can lead to new opportunities to shift development pathways towards sustainability. {16.4, 16.5, 16.6}

An area where sustainable development, climate change mitigation and technological change interact is digitalisation. Digital technologies can promote large increases in energy efficiency through coordination and an economic shift to services, but they can also greatly increase energy demand because of the energy used in digital devices. System-level rebound effects may also occur. (*high confidence*) Digital devices, including servers, increase pressure on the environment due to the demand for rare metals and end-of-life disposal. The absence of adequate governance in many countries can lead to harsh working conditions and unregulated disposal of electronic waste. Digitalization also affects firms' competitiveness, the demand for skills, and the distribution of, and access to, resources. The existing digital divide, especially in developing countries, and the lack of appropriate governance of the digital revolution can hamper the role that digitalization could play in supporting the achievement of stringent mitigation targets. At present, the understanding of both the direct and indirect impacts of digitalization on energy use, carbon emissions and potential mitigation, is limited (*medium confidence*). {Cross-Chapter Box 11 in this chapter, 16.2}

Strategies for climate change mitigation can be most effective in accelerating transformative change when actions taken to strengthen one set of enabling conditions also reinforce and strengthen the effectiveness of other enabling conditions *(medium confidence)*. Applying transition or system dynamics to decisions can help policymakers take advantage of such high-leverage intervention points, address the specific characteristics of technological stages, and respond to societal dynamics. Inspiration can be drawn from the global unit cost reductions of solar PV, which were accelerated by a combination of factors interacting in a mutually reinforcing way across a limited group of countries (*high confidence*). {Box 16.2, Cross-Chapter Box 10 in chapter 14}

Better and more comprehensive data on innovation indicators can provide timely insights for policymakers and policy design locally, nationally and internationally, especially for developing countries, where such insights are missing more often. Data needed include on those that can show the strength of technological, sectoral and national innovation systems. It is also necessary to validate current results and generate insights from theoretical frameworks and empirical studies for developing countries contexts. Innovation studies on adaptation and mitigation other than energy and ex-post assessments of the effectiveness of various innovation-related policies and interventions, including R&D, would also provide benefits. Furthermore, methodological developments to improve the ability of Integrated Assessment Models (IAMs) to capture energy innovation system dynamics, and the relevant institutions and policies (including design and implementation), would allow for more realistic assessment. {16.2, 16.3, 16.7}

16.1 Introduction

Technological change and innovation are considered key drivers of economic growth and social progress (Brandão Santana et al. 2015; Heeks and Stanforth 2015). The economic benefit derived from increased production and consumption of goods as well as services create higher demands for improved technologies (Gossart 2015). Since the Industrial Revolution, however, and notwithstanding the benefits, this production and consumption trend and the technological changes associated to it have also come at the cost of long-term damage to the life support systems of our planet (Alarcón and Vos 2015; Steffen et al. 2015). The significance of the such impacts depends on the technology, but also on the intrinsic characteristics of the country or region analysed (Brandão Santana et al. 2015).

Other chapters in this volume have discussed technological change in various ways, including as a framing issue (chapter 1), in the context of specific sectors (chapters 6-11), for specific purposes (chapter 12) and as a matter of policy, international cooperation and finance (chapters 13-15). Chapter 2 discusses past trends in technological change and chapters 3 and 4 discuss it in the context of future modelling. In general, implicitly or explicitly, technological change is assigned an important role in climate change mitigation and achieving sustainable development (Thacker et al. 2019), also in past IPCC reports (IPCC 2014, 2018a). Chapter 16 describes how a well-established innovation system at a national level, guided by well-designed policies, can contribute to achieve mitigation and adaptation targets along with broader sustainable development goals avoiding, in the process, undesired consequences of technological changes.

The environmental impacts of social and economic activities, including emissions of GHG, are greatly influenced by the rate and direction of technological changes (Jaffe et al. 2000). Technological changes usually designed and used to increase productivity and reduce the use of natural resources can lead to increasing production and consumption of goods and services through different rebound effects that diminish the potential benefits of reducing the pressure on the environment (Grübler 1998; Kemp and Soete 1990; Gossart 2015; Sorrell 2007; Barker et al. 2009).

Those environmental impacts depend not only on which technologies are used, but also on how they are used (Grübler et al. 1999a). Technological change is not exogenous to social and economic systems; technologies are not conceived, selected, and applied autonomously (Grubler et al. 2018). Underlying driving forces of the problem, such as more resource intensive lifestyles and larger populations (Hertwich and Peters 2009; UNEP 2014), remain largely unchallenged. Comprehensive knowledge of the direct and indirect effects of technological changes on physical and social systems could improve decision-making, also in those cases where technological change mitigates environmental impacts.

A sustainable global future for people and nature requires rapid and transformative societal change by integrating technical, governance (including participation), financial and societal aspects of the solutions to be implemented (Pörtner et al. 2021; Sachs et al. 2019). A growing body of interdisciplinary research from around the world can inform implementation of adaptive solutions that address the benefits and drawbacks of linkages in social-ecological complexity, including externalities and rebound effects from innovation and technological transformation (Pörtner et al. 2021; Balvanera et al. 2017).

Technological change and transitional knowledge can reinforce each other. The value of traditional wisdom and its technological practices provide examples of sustainable and adaptive systems that could potentially adapt to and mitigate climate change (Singh et al. 2020; Kuoljok 2019). Peasants and traditional farmers have been able to respond well to climate changes through their wisdom and traditional practices (Nicholls and Alteri 2013). The integration of the traditional wisdom with new technologies can offer new and effective solutions (Galloway McLean 2010).

Achieving climate change mitigation and other sustainable development goals thus also requires rapid diffusion of knowledge and technological innovations. However, these are hampered by various barriers, some of which are illustrated in Table 16.1 (Markard et al. 2020).

Table 16.1 Overview of Challenges to Accelerated Diffusion of Technological Innovations. Based on (Markard et al. 2020)

Challenges	Description	Examples
Innovations in whole systems	Since entire systems are changing, also changes in system architecture are needed, which may not keep pace.	Decentralization of electricity supply and integration of variable sources.
Interaction between multiple systems and subsystems	Simultaneous, accelerating changes multiple systems or sectors, vying for the same resources and showing other interactions.	Electrification of transport, heating and industry all using the same renewable electricity source.
Industry decline and incumbent resistance	Decline of existing industries and businesses can lead to incumbents slowing down change, and resistance from e.g. unions or workers.	Traditional car industry leading to facture closures, demise of coal mining and coal-fired power generation leading to local job loss.
Consumers and social practices	Consumers need to change practices and demand patterns.	Less car ownership in a sharing economy, trip planning for public and non-motorised transport, fuelling practices in electric driving.
Coordination in governance and policy	Increasing complexity of governance requires coordination between multiple levels of government and a multitude of actors relevant to the transition, e.g. communities, financial institutions, private sector.	Multi-level governance between European Commission and member states in Energy Union package.

The literature on how, in a systemic way, the barriers to sustainability transition can be overcome in various circumstances has been growing rapidly over the past decades. A central element is that national systems of innovation can help achieving both climate change and sustainable development goals, by integrating new ideas, devices, resources, new and traditional knowledge and technological changes for more effective and adaptive solutions (Lundvall 1992). At the organizational level, innovation is seen as a process that can bring value by means of creating more effective products, services, processes, technologies, policies and business models that are applicable to commercial, business, financial and even societal or political organizations (Brooks 1980; Arthur 2009).

The literature refers to the terms “technology push,” “market pull,” “regulatory push-pull,” and “firm specific factors” as drivers for innovation, mostly to inform policymakers (Zubeltzu-Jaka et al. 2018). There has also been growing interest in social drivers, motivated by the recognition of social issues, such as unemployment and public health, linked to the deployment of innovative low-carbon technologies (Altantsetseg et al. 2020). Policy and social factors and the diverse trajectories of innovation are influenced by regional and national conditions (Tariq et al. 2017), and such local needs and purposes need to be considered in crafting international policies aimed at fostering the global transition towards increased sustainability (Caravella and Crespi 2020). From this standpoint, a multidimensional, multi-actor systemic innovation approach would be needed to enhance global innovation diffusion (de Jesus and Mendonça 2018), especially if this is to lead to overall sustainability improvements rather than resulting in new sustainability challenges.

Policies to mitigate climate change do not always take into account the effects of mitigation technologies on other environmental and social challenges (Arvesen et al. 2011). Policies also often disregard the strong linkages between technological innovation and social innovation; the latter understood as the use of soft technologies that brings about transformation through establishing new institutions, new practices, and new models to create a positive societal impact characterized by collaboration that crosses traditional roles and boundaries, between citizens, civil society, the state, and the private sector (Reynolds et al. 2017). Market forces do not provide sufficient incentives for investment in development or diffusion of technologies, leaving a role for public policy to create the conditions to assure a systemic innovation approach (Popp 2010; Popp and Newell 2012). Moreover, public action is more than just addressing market failure, it is an unalienable element of an innovation system (Mazzucato 2013).

Coupling technological innovation with sustainable development and the SDGs would need to address overall social, environmental, and economic consequences, given that public policy is intertwined with innovation, technological changes and other factors in a complex manner. Chapter 16 is organized in the following manner to provide an overview of innovation and technology development and transfer for climate change and sustainable development.

Section 16.2 discusses drivers of innovation process, including macro factors that can redirect technological change towards low-carbon options. Representations of these drivers in mathematical and statistical models allow for explaining the past and constructing projections of future technological change. They also integrate the analysis of drivers and consequences of technological change within economic-energy-economy (or integrated assessment) models (see Chapter 3). The section also describes the different phases of innovation and metrics, such as the widely used but also criticized technology readiness levels (TRLs).

Section 16.3 discusses innovation as a systemic process based on recent literature. While the innovation process is often stylized as a linear process, innovation is now predominantly seen as a systemic process in that it is a result of actions by, and interactions among, a large set of actors, whose activities are shaped by, and shape, the context in which they operate and the user group with which they are engaging.

Section 16.4 presents innovation and technology policy, including technology push (e.g., publicly funded R&D) and demand-pull (e.g., governmental procurement programmes) instruments that addresses potential market failures related to innovation and technology diffusion. The section also assesses the cost-effectiveness and other policy assessment criteria introduced in Chapter 13 of innovation policies.

In section 16.5, the chapter assesses the role of international cooperation in technology development and transfer, in particular the mechanisms established under the UNFCCC, but also other international initiatives for technology cooperation. The discussion on international cooperation includes information exchange, research, development and demonstration cooperation, access to financial instruments, intellectual property rights, as well as promotion of domestic capacities and capacity building.

Section 16.6 describes the role of technology in sustainable development, including unintended effects of technological changes, and synthesizes the chapter. Finally, section 16.7 discusses gaps in knowledge emerging from this chapter.

16.2 Elements, drivers and modelling of technology innovation

Models of the innovation process, its drivers and incentives provide a tool for technology assessment, constructing projections of technological change and identifying which macro conditions facilitate development of low-carbon technologies. The distinction between stages of innovation process allows to assess technology readiness (Section 16.2.1). Qualitative and quantitative analysis of main elements underpinning innovation - R&D, learning-by-doing, spillovers allow for explanation of past and project future technological change (Section 16.2.2). In addition, general purpose technologies can play a role in climate change mitigation.

In the context of mitigation pathways, the feasibility of any emission reduction targets depends on the ability to promote innovation in low- and zero-carbon technologies, as opposed to any other technology. For this reason, the section reviews the literature of the levers influencing the *direction* of technological change in favour of low- and zero-carbon technologies (Section 16.2.3). Moreover, representation of drivers in mathematical and statistical models from section 16.2.2 allows integrating its analysis with economic and climate effects within IAMs, hence permitting more precise modelling of decarbonisation pathways (Section 16.2.4).

In addition to technological innovation, other innovation approaches are relevant in the context of climate mitigation and more broadly sustainable development (Section 16.6). Frugal innovations, i.e. “good enough” innovations that fulfil the needs of non-affluent consumers mostly in developing countries (Hossain 2018), are characterized by low costs, concentration on core functionalities, and optimised performance level (Weyrauch and Herstatt 2016) and are hence often associated with (ecological and social) sustainability (Albert 2019). Grassroots innovations are products, services and processes developed to address specific local challenges and opportunities, and which can generate novel, bottom-up solutions responding to local situations, interests and values. (Dana et al. 2021; Pellicer-Sifres et al. 2018).

16.2.1 Stages of the innovation process

The innovation cycle is commonly thought of as having three distinct innovation phases on the path between basic research and commercial application: Research and Development (R&D), demonstration, and deployment and diffusion (IPCC 2007). Each of these phases differs with respect to the kind of activity carried out, the type of actors involved and their role, financing needs and the associated risks and uncertainties. All phases involve a process of trial and error, and failure is common; the share of innovation that successfully reaches the deployment phase is small. The path occurring between basic research to commercialization is not linear (see also Section 16.3); it often requires a long time and is characterized by significant bottlenecks and roadblocks. Furthermore, technologies may regress backwards in the innovation cycle, rather than move forward (Skea et al. 2019). Successfully passing from each stage to the next one in the innovation cycle requires overcoming “valleys of deaths” (Auerswald and Branscomb 2003; UNFCCC 2017), most notably the demonstration phase (Frank et al. 1996; Weyant 2011; Nemet et al. 2018). Over time, new and improved technologies are discovered; this often makes the dominant technology obsolete, but this is not discussed here further.

Table 16.2 summarizes the different innovation stages and main funding actors, and maps phases into the technology readiness levels (TRLs) discussed in Section 16.2.1.4.

Table 16.2 Stages of the innovation process (16.2.1) mapped onto Technology Readiness Levels (16.2.1.4)

Stage	Main funding actors	Phases	Related TRL
Research and development	Governments Firms	Basic research	1 – Initial idea (basic principles defined)
		Applied research and technology development	2 – Application formulated (technology concept and application of solution formulated)
			3 – Concept needs validation (solutions need to be prototyped and applied
			4 – Early prototype (prototype proven in test conditions)
			5 – Full prototype at scale (components proven in conditions to be deployed)
Demonstration	Governments Firms Venture Capital Angel investors	Experimental pilot project or full scale testing	6 – Full prototype at scale (prototype proven at scale in conditions to be deployed)
			7 – Pre-commercial demonstration (solutions working in expected conditions)
			8 – First-of-a-kind commercial (commercial demonstration, full scale deployment in final form)
Deployment and diffusion	Firms Private equity Commercial banks Mutual funds	Commercialization and scale up *(business)*	9 – Commercial operation in early environment (solution is commercial available, needs evolutionary improvement to stay competitive) 10 – Integration needed at scale (solution is commercial and competitive but needs further integration efforts) 11 – Proof of stability reached (Predictable growth)
	International organizations and financial institutions NGOs	Transfer	

Adapted from: Auerswald and Branscomb (2003), Technology Executive Committee (2017), IEA (IEA 2020a)

16.2.1.1 Research and Development

This phase of the innovation process focuses on generating knowledge or solving particular problems by creating a combination of artefacts that is intended to perform a particular function, or to achieve a specific goal. R&D activities comprise basic research, applied research and technology development. Basic research is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view. Applied research is original investigation undertaken in order to acquire new knowledge, primarily directed towards a specific, practical aim or objective (OECD 2015a). Importantly, R&D activities can be incremental, i.e. focused on addressing a specific need by marginally improving an already existing technology, or radical, representing a paradigm shift, promoted by new opportunities arising with the accumulation of new knowledge (Mendonça et al. 2018). Technology development, often leading to prototyping, consists of generating a working model of the technology that is usable in the real world, proving the usability and customer desirability of the technology and giving an idea of its design, features and functioning (OECD 2015a). These early stages of technological innovation are referred to as “formative phase”, during which the conditions are shaped for a technology to emerge and become established in the market (Wilson and Grubler 2013) and the constitutive elements of the innovation system emerging around a particular technology are set up (see Section 16.3)(Bento et al. 2018; Bento and Wilson 2016).

The outcomes of R&D are uncertain: the amount of knowledge that will result from any given research project or investment is unknown ex ante (Rosenberg 1998). This risk to funders (Goldstein and Kearney 2020) translates into underinvestment in R&D due to low appropriability (Sagar and Majumdar 2014; Weyant 2011). In the case of climate mitigation technologies, low innovation incentives for the private sector also result from a negative environmental externality (Jaffe et al. 2005). Furthermore, in absence of stringent climate policies and targets, incumbent fossil-based energy technologies are characterized by lower financing risk, are heavily subsidized (Kotchen 2021; Davis 2014) and depreciate slowly (see Section 16.2.3) (Nanda et al. 2016; Semieniuk et al. 2021; Arrow 1962a). In this context public research funding therefore plays a key role in supporting high-risk R&D both in developed and developing economies: it can provide patient and steady funding not tied to short-term investment returns (see Section 16.4) (Anadon et al. 2014; Mazzucato 2015a; Howell 2017; Zhang et al. 2019; Anadón et al. 2017; Chan and Diaz Anadon 2016; Kammen and Nemet 2007). Public policies also play a role increasing private incentives in energy research and development funding (Nemet 2013). R&D statistics are an important indicator of innovation and are collected following the rules of the Frascati Manual (OECD 2015b) (Section 16.3.3, Box 16.3, Table 16.7).

16.2.1.2 Demonstration

Demonstration is carried out through pilot projects or large-scale testing in the real world. Successfully demonstrating a technology shows its utility and that it is able to achieve its intended purpose and, consequently, that the risk of failure is reduced (i.e. that it has market potential) (Hellsmark et al. 2016). Demonstration project are an important step to promote the deployment of low-carbon energy and industrial technologies in the context of the transition. government funding often plays a large role in energy technology demonstration projects because scaling up hardware energy technologies is expensive and risky (Brown and Hendry 2009; Hellsmark et al. 2016). Governments’ engagement in low-carbon technology demonstration also signals support for business willing to take the investment risk (Mazzucato 2016). Venture capital, traditionally not tailored for energy investment, can play an increasingly important role also thanks to the incentives (e.g. through de-risking) provided by public funding and policies (Gaddy et al. 2017; IEA 2017a).

16.2.1.3 Deployment and diffusion

Deployment entails producing a technology at large scale and scaling up its adoption use across individual firms or households in a given market, and across different markets (Jaffe 2015). In the context of climate change mitigation and adaptation technologies, the purposeful diffusion to developing countries, is referred to as “technology transfer”. Most recently, the term " innovation cooperation" has been proposed to indicate that technologies needs to be co-developed and adapted to local contexts (Pandey et al. 2021). Innovation cooperation is an important component of stringent mitigation strategies as well as international agreements (see Section 16.5).

Diffusion is often sluggish due to lock-in of dominant technologies (Liebowitz and Margolis 1995; Unruh 2000; Ivanova et al. 2018), as well as the time needed to diffuse information about the technologies, heterogeneity among adopters, the incentive to wait until costs fall even further, the presence of behavioural and institutional barriers and the uncertainty surrounding mitigation policies and long-term commitments to climate targets (Corey 2014; Haelg et al. 2018; Gillingham and Sweeney 2012; Jaffe 2015). In addition, novel technology has been hindered by the actions of powerful incumbents who accrue economic and political advantages over time, as in the case of renewable energy generation (Unruh 2002; Supran and Oreskes 2017; Hoppmann et al. 2019).

Technologies have been shown to penetrate the market with a gradual non-linear process in a characteristic logistic (S-shaped) curve (Rogers 2003; Grübler 1996). The time needed to reach widespread adoption varies greatly across technologies relevant for adaptation and mitigation (Gross et al. 2018); in the case of energy technologies, the time needed for technologies to get from a 10 to 90% market share of saturation ranges between 5 to over 70 (Wilson 2012). Investment in commercialization of low-emission technology is largely provided by private financiers; however, governments play a key role in ensuring incentives through supportive policies, including R&D expenditures providing signals to private investors (Haelg et al. 2018), pricing carbon dioxide emissions, public procurement, technology standards, information diffusion and the regulation for end-life cycle treatment of products (Cross and Murray 2018) (see Section 16.4).

16.2.1.4 Technology Readiness Levels

Technology Readiness Levels (TRLs) are a categorization that enables consistent, uniform discussions of technical maturity across different types of technology. They were developed by NASA in the 1970s (Mankins 2009, 1995) and originally used to describe the readiness of components forming part of a technological system. Over time, more classifications of TRLs have been introduced, notably the one used by the EU. Most recently, the IEA extended previous classifications to include the later stages of the innovation process (IEA 2020b) and applied it to compare the market readiness of clean energy technologies and their components (OECD 2015a; IEA 2020b). TRLs are currently widely used by engineers, business people, research funders and investors, often to assess the readiness of whole technologies rather than single components. To determine a TRL for a given technology, a Technology Readiness Assessment (TRA) is carried out to examine programme concepts, technology requirements, and demonstrated technology capabilities. In the most recent version of the IEA (IEA 2020b), TRLs range from 1 to 11, with 11 indicating the most mature (see Table 16.2).

The purpose of TRLs is to support decision making. They are applied to avoid the premature application of technologies, which would lead to increased costs and project schedule extension (US Department of Energy 2011). They are used for risk management, and can also be used to make decisions regarding technology funding and to support the management of the R&D process within a given organization or country (De Rose et al. 2017).

In practice, the usefulness of TRLs is limited by several factors. These include limited applicability in complex technologies or systems, the fact that they do not define obsolescence, nor account for manufacturability, commercialization or the readiness of organizations to implement innovations (European Association of Research Technology Organisations 2014) and do not consider any type of technology-system mismatch or the relevance of the products' operation environment to the system under consideration (Mankins 2009). Many of these limitations can be eased by using TRLs in combination with other indicators such as System Readiness Levels and other economic indicators on, for example, investments and returns (IEA 2020b).

16.2.2 Sources of technological change

The speed of technological change could be explained with the key drivers of innovations process: R&D effort, learning-by-doing and spillover effects. In addition, new innovations are sometimes enabled by the development of general purpose technologies, such as digitalization.

16.2.2.1 Learning-by-doing and research and development

Learning by doing and R&D effort are two factors commonly used by the literature to explain past and project future speed of technological change (Klaassen et al. 2005; Mayer et al. 2012; Bettencourt et al. 2013). Learning-by-doing is the interaction of workers with new machines or processes that allows them to use them more efficiently (Arrow 1962b). R&D effort is dedicated to looking for new solutions (e.g. blueprints) that could increase the efficiency of existing production methods or result in entirely new methods, products or services (see section 16.2.1.1).

Learning-by-doing and research and development are interdependent. Young (1993) postulates that learning-by-doing cannot continue forever without R&D because it is bounded by an upper physical productivity limit of an existing technology. Research and development can shift this limit because it allows replacing the existing technology with a new one. On other hand, incentives to invest in R&D depend on future cost of manufacturing, which in turn depend on the scale of learning-by-doing. The empirical evidence for virtuous circle between costs reduction, market growth and R&D were found in the case of PV market ((Watanabe et al. 2000); see also Box 16.4), but could also lead to path dependency and lock-in (Erickson et al. 2015). Section 16.4.4 and Chapter 13 Section 13.7.3.1. discuss how simultaneous use of technology push and pull policies could amplify effects of research and learning.

The benefits of R&D and learning-by-doing are larger at the economy level than at the firms level (Romer 1990; Arrow 1962b). As a result, the market, left to its own, tends to generate less investment than socially optimal. For instance, if the cost of a technology is too high before a large amount of learning-by-doing has occurred, there is a risk that it will not be adopted by the market even if it is economically advantageous for the society. Indeed, initially new technologies are often expensive and cannot compete with the incumbent technologies (Cowan 1990). Large numbers of adopters could lower this cost via learning-by-doing to a level sufficient to beat the incumbent technology (Gruebler et al. 2012). However, firms could hesitate to be the first adopter and bear the high cost (Isoard and Soria 2001). If this disadvantage overwhelms the advantages of being a first mover[1] and if adopters are not able to coordinate, it will lead to situation of a lock-in (Gruebler et al. 2012).

The failure of markets to deliver the size of R&D investment and learning-by-doing that would be socially optimal is one of the justifications of government intervention. Policies to address these market failures can be categorized as technology push and demand pull policies. The role of these policies is explained in Table 16.3. Section 16.4 discusses individual policy instruments in greater detail.

Table 16.3 Categories of policies and interventions accelerating technological changes, the factors promoting them and slowing them down, illustrated with examples

	What it refers to:	What promotes technological change	What slows down technological change	Examples
Technology Push	Support the creation of new knowledge to make it easier to invest in innovation	R&D, funding and performance of early demonstrations (Brown and Hendry 2009; Hellsmark et al. 2016)	Inadequate supply of trained scientists and engineers (Popp and Newell 2012); gap with demand pull (Grübler et al. 1999b).	Japan's Project Sunshine, the US Project Independence in the 1970s. Breakthrough Energy Coalition and Mission Innovation, respectively private- and public-sector international collaborations to respectively focus energy innovation and double energy R&D, both initiated concurrently with the Paris Agreement in 2015 (Sanchez and Sivaram 2017).

FOOTNOTE[1] see e.g. (Spence 1981) and (Bhattacharya 1984) for discussion of first-mover advantages

Demand Pull	Instruments creating market opportunities.	Enlarging potential markets, increasing adoption of new fuels and mitigation technology. Digital innovations Social innovation and awareness	Willingness of consumers to accept new technology. Policy and political volatility can deter investment.	Subsidies for wind power California, the German feed-in tariff for PV, quotas for electric vehicles in China (Wang et al. 2017a) and Norway (Pereirinha et al. 2018) Biofuels (Brazil); Social innovation with Wind Energy (Denmark, Germany)

The size of learning-by-doing effect is quantified in literature using learning rates i.e. estimates of negative correlation between costs and size of deployment of technologies. The results from this literature include estimates for energy technologies (McDonald and Schrattenholzer 2001), electricity generation technologies (Rubin et al. 2015; Samadi 2018), for storage (Schmidt 2017), for end-of-pipe control (Kang et al. 2020) and for energy demand and energy supply technologies (Weiss et al. 2010). Meta-analyses find learning rates vary across technologies, within technologies and over time (Wei et al. 2017; Nemet 2009a; Rubin et al. 2015). Moreover, different components of one technology have different learning rates (Elshurafa et al. 2018). Central tendencies are around 20% cost reduction for each doubling of deployment (McDonald and Schrattenholzer 2001).

Studies of correlation between cumulative deployment of technologies and costs are not sufficiently precise to disentangle the causal effect of increase in deployment from the causal effects of research and development and other factors (Nemet 2006). Numerous subsequent studies attempted to, amongst others, separate the effect of learning-by-doing and research and development (Klaassen et al. 2005; Mayer et al. 2012; Bettencourt et al. 2013), economies of scale (Arce 2014), and knowledge spillovers (Nemet 2012). Once those other factors are accounted for, some empirical studies find that the role of learning-by-doing in driving down the costs becomes minor (Kavlak et al. 2018; Nemet 2006). In addition the relation could reflect reverse causality: increase in deployment could be an effect (and not a cause) of a drop in price (Witajewski-Baltvilks et al. 2015; Nordhaus 2014). Nevertheless, in some applications, learning curves can be a useful proxy and heuristic (Nagy et al. 2013).

The negative relation between costs and experience is a reason to invest in a narrow set of technologies; the uncertainty regarding the parameters of this relation is the reason to invest in wider ranges of technologies (Way et al. 2019; Fleming and Sorenson 2001). Concentrating investment in narrow sets of technologies (specialization) enables fast accumulation of experience for these technologies and large cost reductions. However, when the potency of technology is uncertain, one does not know which technology is truly optimal in the long-run. The narrower the set the higher the risk that the optimal technology will not be supported, and hence will not benefit from learning-by-doing. Widening the set of supported technologies would reduce this risk (Way et al. 2019). Uncertainty is present because noise in historical data hides the true value of learning rates as well as because of unanticipated future shocks to technology costs (Lafond et al. 2018). Ignoring uncertainty in integrated assessment models implies that these model results are biased towards supporting narrow set of technologies neglecting the benefits of decreasing risk trough diversification (Sawulski and Witajewski-Baltvilks 2020).

16.2.2.2 Knowledge spillovers

Knowledge spillovers drive continuous technological change (Rivera-Batiz and Romer 1991; Romer 1990) and are for that reason relevant to climate technologies as well as incumbent, carbon-intensive technologies. Knowledge embedded in innovations by one innovator give an opportunity for others to create new innovations and increase the knowledge stock even further. The constant growth of knowledge stock through spillovers translates into constant growth of productivity and cost reduction.

By allowing for experimenting with existing knowledge and combining different technologies, knowledge spillovers can result in the emergence of novel technological solutions, which has been referred to as recombinant innovation (Weitzman 1998; Olsson and Frey 2002; Tsur and Zemel 2007; Arthur 2009; Fleming and Sorenson 2001). Recombinant innovations speed up technological change by combining different technological solutions, and make things happen that would be impossible with only incremental innovations (Safarzyńska and van den Bergh 2010; van den Bergh 2008; Frenken et al. 2012). It has been shown that 77% 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). Spillovers related to energy and low-carbon technologies has been documented by a number of empirical studies (*high confidence*) (Popp 2002; Aghion et al. 2013; Witajewski-Baltvilks et al. 2017; Verdolini and Galeotti 2011; Conti et al. 2018). The presence of spillovers can have both positive and negative impacts on climate change mitigation *(high confidence)*.

The spillover effect associated with innovation in carbon-intensive technologies may lead to lock-in of fossil-fuel technologies. Continuous technological change of carbon-intensive industry raises the bar for clean technologies: a larger drop in clean technologies' cost is necessary to become competitive (Acemoglu et al. 2012; Aghion et al. 2013). The implication is that delaying climate policy increases the cost of that policy (Aghion 2019).

On the other hand, the spillover effect associated with innovation in low-emission technologies increase the potency of climate policy (Aghion 2019). For instance, a policy that encourages clean innovation leads to accumulation of knowledge in clean industry which, through spillover effect encourages further innovation in clean industries. Once the stock of knowledge is sufficiently large, the value of clean industries will be so high, that technology firms will invest there even without policy incentives. Once this point is reached, the policy intervention can be discontinued (Acemoglu et al. 2012).

In addition, the presence of spillovers implies that a unilateral effort to reduce emissions in one region could reduce emissions in other regions (*medium confidence*) (Gerlagh and Kuik 2014; Golombek and Hoel 2004). For instance, in the presence of spillovers, a carbon tax that incentivises clean technological change increases the competitiveness of clean technologies not only locally, but also abroad. The size of this effect depends on the size of spillovers. If they are sufficiently strong, the reduction of emissions abroad due to clean technological change could be larger than the increase of emissions due to carbon leakage (Gerlagh and Kuik 2014). Different types of carbon leakage are discussed in Chapter 13, Section 13.7.1 and other consequences of spillovers for the design of policy are discussed in Chapter 13, Section 13.7.3.

16.2.2.3 General purpose technologies and digitalization

General purpose technologies (GPTs) provide solutions that could be applied across sectors and industries (Goldfarb 2011) by creating technological platforms for a growing number of interrelated innovations. Examples of GPTs relevant to climate change mitigation are hydrogen and fuel cell technology, which may find applications in transport, industry and distributed generation (Hanley et al. 2018), and nanotechnology which played a significant role in advancement of all the different types of renewable energy options (Hussein 2015). Assessing the environmental, social and economic implications of such technologies, including increased emissions through energy use, is challenging (see Chapter 5, Section 5.3.4.1 and Cross-Chapter Box 11 below).

Several GPTs relevant for climate mitigation and adaptation emerged as a result digitalization, namely the adoption or increase in use of information and communication technologies (ICTs) by citizens, organizations, industries or countries and the associated restructuring of several domains of social life and of the economy around digital technologies and infrastructures (IEA 2017b; Brennen and Kreiss 2016). The digital revolution is underpinned by innovation in key technologies, e.g. ubiquitous connected consumer devices such as mobile phones (Grubler et al. 2018), rapid expansions of global internet infrastructure and access (World Bank 2014), and steep cost reductions and performance improvements in computing devices, sensors, and digital communication technologies (Verma et al. 2020). The increasing the pace at which the physical and digital worlds are converging increase the relevance of disruptive digitalization in the context of climate mitigation and sustainability challenges (European Commission 2020) (see Cross-chapter Box 11 in this chapter and Chapter 4, Section 4.4.1).

Digital technologies require energy, but increase efficiency, potentially offering technology-specific GHG emission savings; they also have larger system wide impacts (Kaack et al. 2021). In industrial sectors, robotization, smart manufacturing (SM), internet of things (IoT), artificial intelligence (AI), and additive manufacturing (AM or 3D printing), have the potential to reduce material demand and promote energy management (Chapter 11, Section 11.3.4.2). Smart mobility is changing transport demand and efficiency (Chapter 10, Section 10.2.3). Smart devices in buildings, the deployment of smart grids and the provision of renewable energy increase the role of demand-side management (Serrenho and Bertoldi 2019) (Chapter 9, Sections 9.4 and 9.5), and support the shift away from asset redundancy (Chapter 6, Section 6.4.3). Digital solutions are equally important on the supply side, for example by accelerating innovation with simulations and deep learning (Rolnick et al. 2021) or realizing flexible and decentralized opportunities through energy-as-a-service concepts and particularly with Pay-As-You-Go (Chapter 15, Box 15.8, Table 1).

Yet, increased digitalization could give increase energy demand, thus wiping away potential efficiency benefits, unless appropriately governed (IPCC 2018a). Moreover, digital technologies could negatively impact labour demand and increase inequality (Cross-Chapter Box 11 in this chapter).

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Cross-Chapter Box 11: Digitalization: efficiency potentials and governance considerations

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Digital technologies impact positively and negatively GHG emissions through their own carbon footprint, via technology application for mitigation, and via induced larger social change. Digital technologies also raise broader sustainability concerns due to their use of rare materials and associated waste, and their potential negative impact on inequalities and labour demand.

Direct impacts emerge because digital technologies consume large amounts of energy, but also have the potential to steeply increase energy efficiency in all end-use sectors through material input savings and increased coordination (*medium evidence, medium agreement*) (Horner et al. 2016; Jones 2018) (Huang et al. 2016; IEA 2017b)**.** Global energy demand from digital appliances reached 7.14 EJ in 2018 (Chapter 9, Box 9.5), implying higher related carbon emissions. However, a small smart phone offers services previously requiring many different devices (Grubler et al. 2018). Demand for data services is increasing rapidly; quantitative estimates of the growth of associated energy demand range from slow and marginal to rapid and sizeable, depending the efficiency trends of digital technologies (see Chapter 5.3.4.1)(Avgerinou et al. 2017; Stoll et al. 2019; Vranken 2017; Masanet et al. 2020). Renewable energy serves as low-carbon energy provider for the operation of data centre, which in turn can provide waste heat for other purposes. Digital technologies can markedly increase the energy efficiency of mobility and residential and public buildings, especially in the context of systems integration (IEA 2020a). Reduction in energy demand and associated GHG emissions from buildings and industry while maintaining service levels equal is estimated at 5 to 10%, with larger savings possible. Approaches include building energy management systems (BEMS), home energy management system (HEMS), demand response and smart charging (Cross-Chapter Box 11, Table 1. Data centres can also play a role in energy system management, e.g., by increasing renewable energy generation through predictive control (Dabbagh et al. 2019), and by helping drive the market for battery storage and fuel cells (Riekstin et al. 2014). Temporal and spatial scheduling of electricity demand can provide about 10 GW in demand response in the European electricity system in 2030 (Koronen et al. 2020; Wahlroos et al. 2017, 2018; Laine et al. 2020).

However, system-wide effects may endanger energy and GHG emission savings (*high evidence, high agreement*). Economic growth resulting from higher energy and labour productivities can increase energy demand (Lange et al. 2020) and associated GHG emissions. Importantly, digitalization can also benefit carbon-intensive technologies (Victor 2018). Impacts on GHG emissions are varied in smart and shared mobility systems, as ride hailing increases GHG emissions due to deadheading, whereas shared pooled mobility and shared cycling reduce GHG emissions, as occupancy levels and/or weight per person km transported improve (Chapter 5, Section 5.3). Energy and GHG emissions impacts from the ubiquitous deployment of smart sensors and service optimization applications in smart cities through are insufficiently assessed in the literature (Milojevic-Dupont and Creutzig 2021). Systemic effects have wider boundaries of analysis, including broader environmental impacts (e.g. demand for rare materials, disposal of digital devices). These need to be integrated holistically within policy design (Kunkel and Matthess 2020), but they are difficult to quantify and investigate (Bieser and Hilty 2018). Policies and adequate infrastructures and choice architectures can help manage and contain the negative repercussions of systemic effects (Section 5.4, 5.6, 9.9).

Cross-chapter Box 11, Table 1. Selected sector approaches for reducing GHG emissions that are supported by new digital technologies. Contributions of digitalization include a) supporting role (+), b) necessary role in mix of tools (++), c) necessary unique contribution (+++), but digitalization may also increase emissions (−). See also chapters 5, 8, 9, and 11.

Sector	Approach	Quantitative evidence	Contribution of digitalization	Systems perspective and broader societal impacts	References
Residential energy use	Nudges (feedback, information, etc.)	2-4% reduction in global household energy use possible	+ in combination with monetary incentives, non-digital information	New appliances increase consumption	(Buckley 2020; Zangheri et al. 2019; Khanna et al. 2021; Nawaz et al. 2020)
Smart mobility	Shared mobility and digital feedback (ecodriving)	Reduction for shared cycling and shared pooled mobility; increase for ride hailing/ ride sourcing; reduction for ecodriving	− or ++ Apps together with big data and machine learning algorithm key precondition for new shared mobility	Ride hailing increases GHG emissions, especially due to deadheading	(OECD and ITF 2020; Zeng et al. 2017)
Smart cities	Using digital devices and big data to make urban transport and building	Precise data about roadway use can reduce material intensity and associated GHG	++ Big data analysis necessary for optimization	Efficiency gains are often compensated by more driving and other rebound effects; privacy	(Milojevic-Dupont and Creutzig 2021) (Chapter 10, Box 10.1)

	use more efficient	emissions by 90%,		concerns linked with digital devices in homes	
Agriculture	Precision agriculture through sensors and satellites providing information on soil moisture, temperature, crop growth and livestock feed levels,	Very high potential for variable-rate nitrogen application, moderate potential for variable-rate irrigation	+ ICTs provide information and technologies which enables farmers to increase yields, optimize crop management, reduce fertilizers and pesticides, feed and water; increases efficiency of labour-intensive tasks	The digital divide is growing fast, especially between modern and subsistence farming; Privacy and data may erode trust in technologies	(Townsend et al. 2019; Deichmann et al. 2016; Soto Embodas et al. 2019; Chlingaryan et al. 2018)
Industry	Industrial Internet of Things (IIoT)	Process, activity & functional optimization increases energy and carbon efficiency	++ increased efficiency ++ 1.3 Gt CO_2-eq estimated abatement potential in manufacturing + promote sustainable business models	Optimization in value chains can reduce wasted resources	(GeSI 2012; Parida et al. 2019; Rolnick et al. 2021; Wang et al. 2016)
Load management and battery storage optimization	Big data analysis for optimizing demand management and using flexible load of appliances with batteries	Reduces capacity intended for peak demand, shifts demand to align with intermittent renewable energy availability	+ Accelerated experimentation in material science with artificial intelligence ++ / +++ Forecast and control algorithms for storage and dispatch management	Facilitate integration of renewable energy sources Improve utilization of generation assets System-wide rebound effects possible	(Akorede et al. 2010; Hirsch et al. 2018; de Sisternes et al. 2016; Sivaram 2018a; Gür 2018; Aghaei and Alizadeh 2013; Vázquez-Canteli and Nagy 2019; Voyant et al. 2017) (Chapter 6, Section 6.4)

Broader societal impacts of digitalization can also influence climate mitigation because of induced demand for consumption goods, impacts on firms' competitiveness, changes the demand for skills and labour, worsening of inequality – including reduced access to services due to the digital divide – and governance aspects (*low evidence, medium agreement*) (Chapter 4, Section 4.4, Chapter 5, Sections 5.3, 5.6). Digital technologies expand production possibilities in sectors other than ICTs through robotics, smart manufacturing, and 3D printing, and have major implications on consumption patterns (Matthess and Kunkel 2020). Initial evidence suggests that robots displace routine jobs and certain skills, change the demand for high-skilled and low-skilled workers, and suppress wages (Acemoglu and Restrepo 2019). Digitalization can thus reduce consumers' liquidity and consumption (Mian et al. 2020) and contribute to global inequality, including across the gender dimension, raising fairness concerns (Kerras et al. 2020; Vassilakopoulou and Hustad 2021). Digital technologies can lead to additional concentration in economic power (e.g. Rikap 2020) and lower competition; open source digital technologies can however counter this tendency (e.g. Rotz et al. 2019). Digital technologies play a role in mobilizing citizens for climate and sustainability actions (Westerhoff et al. 2018; Segerberg 2017).

Whether the digital revolution will be an enabler or a barrier for decarbonization will ultimately depend on the governance of both digital decarbonization pathways and digitalization more in general (*medium evidence, high agreement*). The understanding of the disruptive potential of the wide range of digital technologies is limited due to their ground-breaking nature, which makes it hard to extrapolate from previous history/experience. Municipal and national entities can make use of digital technologies to manage and govern energy use and GHG emissions in their jurisdiction (Bibri 2019a,b) and break down solution strategies to specific infrastructures, building, and places, relying on remote sensing and mapping data, and contextual (machine-) learning about their use (Milojevic-Dupont and Creutzig 2021). Mobility apps can provide mobility-as-a-service access to cities ensuring due preference to active and healthy modes (see 9.9 for the example of the Finnish city of Lahti). Trusted data governance can promote the implementation of local climate solutions, supported by available big data on infrastructures and environmental quality (Hansen and Porter 2017; Hughes et al. 2020). Governance decisions, such as taxing data, prohibiting surveillance technologies, or releasing data that enable accountability can change digitalization pathways, and thus underlying GHG emission (Hughes et al. 2020).

Closing the digital gap in developing countries and rural communities enables an opportunity for leapfrogging (*medium evidence, medium agreement*). Communication technologies (such as mobile phones) enable participation of rural communities, especially in developing countries, and promote technological leapfrogging, e.g. decentralized renewable energies and smart farming (Ugur and Mitra 2017; Foster and Azmeh 2020; Arfanuzzaman 2021). Digital technologies have sector-specific potentials and barriers, and may benefit certain regions/areas/socioeconomic groups more than others. For example, integrated mobility services benefit cities more than rural and peripheral areas (OECD 2017).

Appropriate mechanisms also need to be designed to govern digitalization as megatrend (*medium evidence, high agreement*). Digitalization is expected to be a fast process, but this transformation takes place against entrenched individual behaviours, existing infrastructure, the legacy of time frames, vested interest and slow institutional processes and requires trust from consumers, producers and institutions. A core question relates to who controls and manages data created by everyday operations (calls, shopping, weather data, service use, etc.). Regulations that limit or ban the expropriation and exploitation of behavioural data, sourced via smart phones, represent crucial aspects in digitalization pathways, alongside the possibility to create climate movements and political pressure from the civil society. Governance mechanisms need to be developed to ensure that digital technologies such as artificial intelligence take over ethical choices (Craglia et al. 2018; Rahwan et al. 2019). Appropriate governance is necessary for digitalization effectively work in tandem with established mitigation technologies and choice architectures. Consideration of system-wide effects and overall management is essential to avoid run-away effects. Overall governance of digitalization remains a challenge, and will have large-scale repercussions on energy demand and GHG emissions.

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16.2.2.4 Explaining past and projecting future technology cost changes

Researchers and policymakers alike are interested in using observed empirical patterns of learning to project future reductions in costs of technologies. Studies cutting across a wide range of industrial sectors (not just energy) have tried to relate cost reductions to different functional forms, including cost reductions as a function of time (Moore's law) and cost reductions as a function of production or deployment (Wright's law, also known as Henderson'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 et al. 2013). A comparison of expert elicitation and model-based forecasts of the future cost of technologies for the energy transition indicates that model-based forecast medians were closer to the average realized values in 2019 (Meng et al. 2021).

Recent studies attempt to separate the influence of learning-by-doing (which is a basis of Wright's law) versus other factors in explaining cost reductions specifically in energy technologies. Some studies explain cost reductions with two factors: cumulative deployment (as proxy for experience) and R&D investment (see the "two factor" learning curve (Klaassen et al. 2005). However, reliable information on public energy R&D investments for developing countries is not systematically collected. Available data for OECD countries cannot be precisely assigned to specific industrial sectors or sub-technologies (Verdolini et al. 2018). Some learning-curve studies take into account that historical variation in technology costs could be explained by variation in key materials and fuel costs (for example steel costs for wind turbines (Qiu and Anadon 2012) silicon costs (Kavlak et al. 2018; Nemet 2006) coal and coal plant construction costs (McNerney et al. 2011). Economies of scale played a significant role in the PV cost reductions since the early 2000s (Yu et al. 2011) (See also Box 16.4), which can also be the case in organic PV technologies (Gambhir et al. 2016; Kavlak et al. 2018).

16.2.3 Directing technological change

Technological change is characterized not only by its speed, but also its direction. The early works that considered the role of technology in economic and productivity growth (Solow 1957; Nelson and Phelps 1966) assumed that technology can move forward along only one dimension - every improvement led to an increase in efficiency and increased demand for all factors of production. This view however ignores the potency of technological change to alter the otherwise fixed relation between economic growth and the use of resources.

Technological change that saves fossil fuels could decouple economic growth and CO_2 emissions (Acemoglu et al. 2014; Hémous 2016; Greaker et al. 2018; Acemoglu et al. 2012). Saving of fossils could be obtained with increasing efficiency of producing alternatives to fossils (Acemoglu et al. 2012, 2014). This is the case of oil consumption by combustion engine cars which could be substituted with electric cars (Aghion et al. 2013). If there is no close substitute to dirty resource, then its intensity in production could still be reduced by increasing efficiency of the dirty resource relative to efficiency of other inputs (Hassler et al. 2012; André and Smulders 2014; Witajewski-Baltvilks et al. 2017). For instance, energy efficiency improvement leads to drop in relative demand for energy (Hassler et al. 2012; Witajewski-Baltvilks et al. 2017).

16.2.3.1 Determinants of technological change direction: prices, market size and government

Firms change their choice of technology upon change in prices: when one input (e.g. energy) becomes relatively expensive, firms pick technologies which allow them to economize on that input, according to price-induced technological change theory (Reder and Hicks 1965; Samuelson 1965; Sue Wing 2006). For example, an increase in oil price will lead to a choice of fuel-saving technologies. Such response of technological change was evident during the oil-price shocks in the 1970s (Hassler et al. 2012). Technological change that is induced by an increase in price of a resource can never lead to an increase in use of that resource. In other words, rebound effects associated induced technological change can never offset the saving effect of that technological change (Antosiewicz and Witajewski-Baltvilks 2021).

The impact of energy prices on the size of low-carbon technological change is supported by large number of empirical studies (Popp 2019; Grubb and Wieners 2020). Studies document that higher energy prices are associated with higher number of low-carbon energy or energy efficiency patents (Noailly and Smeets 2015; Ley et al. 2016; Lin and Chen 2019; Newell et al. 1999; Popp 2002; Witajewski-Baltvilks et al. 2017; Verdolini and Galeotti 2011). Sue Wing (2008) finds that innovation induced by energy prices had a minor impact on the decline in U.S. energy intensity in the last decades of 20th century and that autonomous technological change played a more important role. Several studies explore the impact of a carbon tax on green innovation (see Section 16.4). However, disentangling the effect of policy tools is complex because presence of some policies could distort the functioning of other policies (Böhringer and Rosendahl 2010; Fischer et al. 2017) and because the impact of policies could be lagged in time (Antosiewicz and Witajewski-Baltvilks 2021).

The direction of technological change depends also on the market size for dirty technologies relative to the size of other markets (Acemoglu et al. 2014). Due to this dependence, climate and trade policy choices in a single region can alter the direction of technological change at the global level (see Section 16.2.3.3).

The value of the market for clean technologies is determined not only by a current but also by firm's expectations of future stream of profits (Alkemade and Suurs 2012; Greaker et al. 2018; Aghion 2019). One implication is that bolstering the credibility and durability of policies related to low-carbon technology is crucial to accelerating technological change and inducing the private sector investment required (Helm et al. 2003), especially in rapidly growing economies of Asia and Africa who are on the brink of making major decisions about the type of infrastructure they build as they grow, develop, and industrialize (Nemet et al. 2017).

If governments commit to climate policies, firms expect that the future size of markets for clean technologies will be large and they are eager to redirect research effort towards development of these technologies today. Furthermore the commitment would also incentivise acquiring skills that could further reduce the costs of those technologies (Aghion 2019). However, historical evidence shows that policies related to energy and climate over the long term have tended to change (Nemet et al. 2013; Taylor 2012; Koch et al. 2016). Still, where enhancing policy durability has proven infeasible, multiple uncorrelated potentially overlapping policies can provide sufficient incentives (Nemet 2010).

16.2.3.2 Determinants of direction of technological change: financial markets

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 venture capital 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 et al. 2017), which led to a retreat from investors from hardware technologies required for renewable energy generation and storage to software based technologies and demand-side solutions (Bumpus and 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 invest 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. The role of finance in directing investment is further discussed in Chapter 15, Section 15.6.2.

16.2.3.3 Internationalization of green technological change

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 induce emission reduction in the countries outside the coalition (Di Maria and Smulders 2005; Di Maria and van der Werf 2008; van den Bijgaart 2017; Golombek and Hoel 2004; Hémous 2016). The literature suggests various mechanisms leading to this result. Di 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 model in Hemous (2016) predict that the coalition could induce acceleration of clean technological change 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. 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 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 (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, which we list in table 16.4. For instance, countries might not benefit fully from international knowledge spillover due to insufficient domestic R&D investment, 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). From the policy perspective this implies that simple transfer of technologies could be insufficient to guarantee adoption of new technologies (Gruebler et al. 2012).

Table 16.4 Examples of institutional deficiencies preventing deployment of new technologies in countries behind technological frontier.

Institutions	Examples of deficiencies	Literature reference
Industrial	Inability to benefit fully from international knowledge spillover due to insufficient domestic R&D investment	(Mancusi 2008; Unel 2008; Gruebler et al. 2012)
Commercial	Insufficient experience with the organization and management of large-scale enterprise	(Abramovitz 1986; Aghion et al. 2005)
Political	Vested interests and customary relations among firms and between employers and employees	(Olson 1982; Abramovitz 1986).
Financial	Financial markets incapable of mobilizing capital for individual firms at large scale	(Abramovitz 1986; Aghion et al. 2005)

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 and labour saving will be efficient only in countries where costs of capital are low and costs of labour are high. 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).

16.2.3.4 Market failures in directing technological change

Market forces alone cannot deliver Pareto optimal (i.e. socially efficient) due to at least two types of externalities: GHG emissions that cause climate damage and knowledge spillovers that benefit firms other than the inventor. Nordhaus (2011) argues that these two problems would have to be tackled separately: once the favourable intellectual property right regimes (i.e. the laws or rules or regulation on protection and enforcement) 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 also necessary to break the lock-in of dirty technological change. Recommendations for technical changes often are based on climate considerations only and neglect secondary externalities and environmental costs of technology choices (such as loss of biodiversity due to inappropriate scale-up of bioenergy use). The scale of adverse side effects and co-benefits varies considerably between low-carbon technologies in the energy sector (Luderer et al. 2019).

16.2.4 Representation of the innovation process in modelled decarbonization pathways

A variety of models are used to generate climate mitigation pathways, compatible with 2°C and well below 2°C targets. These include Integrated Assessment Models (IAMs), energy system models, computable general equilibrium models and agent based models. They range from global (Chapter 3) to national models and include both top-down and bottom-up approaches (Chapter 4). Innovation in energy technologies, which comprises the development and diffusion of low-, zero- and negative-carbon energy options, but also investments to increase energy efficiency, is a key driver of emissions reductions in model-based scenarios.

16.2.4.1 Technology cost development

Assumptions on energy technology cost developments are one of the factors that determine the speed and magnitude of the deployment in climate-energy-economy models. The modelling is informed by the empirical literature estimating rates of cost reductions for energy technologies. A first strand of literature relies on the extrapolation of historical data, assuming that costs decrease either as a power law of cumulative production, exponentially with time (Nagy et al. 2013) or as a function of technical performance metrics (Koh and Magee 2008). Another approach relies on expert estimates of how future costs will evolve, including expert elicitations (Verdolini et al. 2018).

In these models, technology costs may evolve exogenously or endogenously (Krey et al. 2019; Mercure et al. 2016). In the first case, technology costs are assumed to vary over time at some predefined rate, generally extrapolated from past observed patterns or based on expert estimates. This formulation of cost dynamics generally underestimates future costs (Meng et al. 2021) as, among other things, it does not capture any policy-induced carbon-saving technological change or any spillover arising from the accumulation of national and international knowledge (Section 16.2.2 and 16.2.3) or positive macroeconomics effects of a transition (Karkatsoulis et al. 2016). The influence of cost and diffusion assumptions may be evaluated through sensitivity analysis. In the second case, costs are a function of a choice variable within the model. For instance, technology costs decrease as a function of either cumulative installed capacity (learning-by-doing) (Seebregts et al. 1998; Kypreos and Bahn 2003) or R&D investments or spillovers from other sectors and countries.

One factor in this 'learning-by-researching' is applied to a wide range of energy technologies but also to model improvements in the efficiency of energy use (Goulder and Schneider 1999; Popp 2004). More complex formulations include two-factor learning processes (see Section 16.2.2.1) (Criqui et al. 2015;

Emmerling et al. 2016; Paroussos et al. 2020), multi-factor learning curves (Kahouli 2011; Yu et al. 2011), or other drivers of cost reductions such as economies of scale and markets (Elia et al. 2021). The application of two-factor learning curves to model energy technology costs is often constrained by the lack of information on public and/or private energy R&D investments in many fast-developing and developing countries (Verdolini et al. 2018). The approach used to model energy technology costs reductions varies across technologies, even within the same model, depending on the availability of data and/or the level of maturity. Less mature technologies generally depend highly on learning-by-research, whereas learning-by-doing dominates in more mature technologies (Jamasb 2007).

In addition to learning, knowledge spillover effects are also integrated in climate-energy-economy models to reflect the fact that innovation in a given country depends also on knowledge generated elsewhere (Fragkiadakis et al. 2020; Emmerling et al. 2016). Models with a more detailed representation of sectors (Paroussos et al. 2020) can use spillover matrices to include bilateral spillovers and compute learning rates that depend on the human capital stock and the regional and/or sectoral absorption rates (Fragkiadakis et al. 2020). Accounting for knowledge spillovers in the EU for PV, wind turbines, EVs, biofuels, industry materials, batteries and advanced heating and cooking appliances can lead to the following results in a decarbonization scenario over the period 2020–2050 as compared to the reference scenario: an increase of 1.0–1.4% in GDP, 2.1–2.3% in investment, and 0.2–0.4% in employment by clean energy technologies (Paroussos et al. 2017). When comparing two possible EU transition strategies - being a first-mover with strong unilateral emission reduction strategy until 2030 versus postponing action for the period after 2030 - endogenous technical progress in the green technologies sector can alleviates most of the negative effects of pioneering low-carbon transformation associated with loss of competitiveness and carbon leakage (Karkatsoulis et al. 2016).

16.2.4.2 Technology deployment and diffusion

To simulate possible paths of energy technology diffusion for different decarbonisation targets, models rely on assumptions about the cost of a given technology cost relative to the costs of other technologies and its ability to supply the energy demand under the relevant energy system and physical constraints. These assumptions include, for example, considerations regarding renewable intermittency, inertia on technology lifetime (for instance, under less stringent temperature scenarios early retirement of fossil plants does not take place), distribution, capacity and market growth constraints, as well as the presence of policies. These factors change the relative price of technologies. Furthermore, technological diffusion in one country is also influenced by technology advancements in other regions (Kriegler et al. 2015).

Technology diffusion may also be strongly influenced, either positively or negatively, by a number of non-cost, non-technological barriers or enablers regarding behaviours, society and institutions (Knobloch and Mercure 2016)These include network or infrastructure externalities, the co-evolution of technology clusters over time ("path dependence"), the risk-aversion of users, personal preferences and perceptions and lack of adequate institutional framework which may negatively influence the speed of (low-carbon) technological innovation and diffusion, heterogeneous agents with different preferences or expectations, multi-objectives and/or competitiveness advantages and uncertainty around the presence and the level of environmental policies and institutional and administrative barriers (Iyer et al. 2015; Baker et al. 2015; Marangoni and Tavoni 2014; van Sluisveld et al. 2020; Napp et al. 2017; Biresselioglu et al. 2020). These types of barriers to technology diffusion are currently not explicitly detailed in most of the climate-energy-economy models. Rather, they are accounted for in models through scenario narratives, such as the ones in the Shared Socioeconomic Pathways (Riahi et al. 2017), in which assumptions about technology adoption are spanned over a plausible range of values. Complementary methods are increasingly used to explore their importance in future scenarios (Turnheim et al. 2015; Gambhir et al. 2019; Trutnevyte et al. 2019; Doukas et al. 2018; Geels et al. 2016). It takes a very complex modelling framework to include all aspects affecting technology cost reductions and technology diffusion, such as heterogeneous agents (Lamperti et al. 2020), regional labour costs (Skelton et al. 2020), materials cost and trade and perfect foresight multi-objective optimization (Aleluia Reis et al. 2021). So far, no model can account for all these interactions simultaneously.

Another key aspect of decarbonization 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 (Doukas and Nikas 2020; van Vliet et al. 2010; Nikas et al. 2017, 2018; van der Voorn et al. 2020).

16.2.4.3 Implications for the modelling of technical change in decarbonization pathways

Although the debate is still ongoing, preliminary conclusions indicate that integrated assessment models tend to underestimate innovation on energy supply but overestimate the contributions by energy efficiency (IPCC 2018b). Scenarios emerging from cost-optimal climate-energy-economy models are too pessimistic, especially in the case of rapidly changing technologies such as wind and batteries in the past decade Conversely, they tend be too optimistic regarding the timing of action, or the availability of a given technology and its speed of diffusion (Shiraki and Sugiyama 2020). Furthermore, some technological and economic transformations may emerge as technically feasible from IAMs, but are not realistic if taking into account political economy, international politics, human behaviours, and cultural factors (Bosetti 2021).

There is a range of projected energy technology supply costs included in the AR6 Scenario Database (Box 16.1). Variations of costs over time and across scenarios are within ranges comparable to those observed in recent years. Conversely, model results show that limiting warming to 2°C or 1.5°C will require faster diffusion of installed capacity of low-carbon energy options and a rapid phase out of fossil-based options. This points to the importance of focusing on overcoming real-life barriers to technology deployment.

START BOX 16.1 HERE

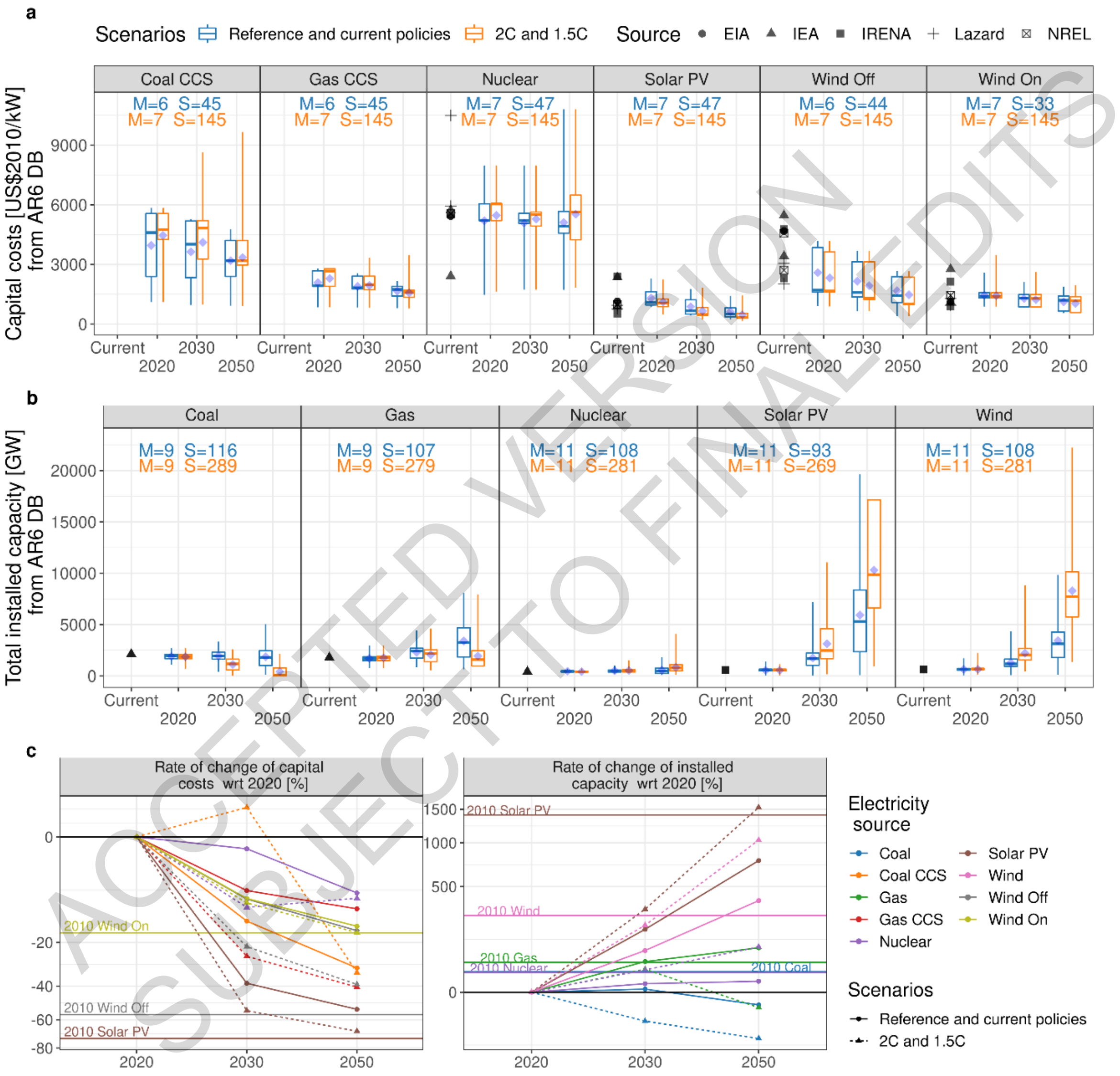
Box 16.1 Comparing observed energy technology costs and deployment rates with projections from AR6 low-carbon pathways

Currently observed costs and deployment for electricity supply technologies from a variety of sources are compared with projections from two different sets of scenarios contained in the AR6 Scenario database: 1) reference and current policies including NDCs and 2) 2°C and well-below 2°C (AR6 model database). Global aggregate costs are shown for the following technologies: Coal with CCS, Gas with CCS, Nuclear, Solar PV, Onshore and Offshore Wind.

The decrease in forecasted capital costs is not large compared to current capital costs for most technologies, and does not differ much between the two scenarios (Box 16.1, Figure 1a). For Wind offshore some of the models are more optimistic than the current reality (Timilsina 2020). Several sources of current solar PV costs report values that are at the low end of the AR6 model scenario database. By 2050, the median technology cost forecasts decrease by between 5% for nuclear and 45-52% for solar (Box 16.1, Figure 1c).

Median values of renewables installed capacity increase with respect to 2020 capacity in "*current policies"* scenarios (Box 16.1, Figure 1b), where energy and climate policies are implemented in line with the current NDCs. More ore stringent targets (2°C) are achieved through a higher deployment of renewable technologies: by 2050 solar (wind) capacity is estimated to increase by a factor of 15 (10) (Box 16.1, Figure 1c). This is accompanied by an almost complete phase out of coal (-87%). The percentage of median changes in installed capacity in the current policies scenarios is within comparable ranges of that observed in the last decade. In the case of the 2°C and well-below 2°C scenarios, capacity installed is higher for renewable technologies and nuclear, and lower for fossil-based technologies (Box 16.1, Figure 1c).

The higher deployment in 2°C scenarios cannot be explained solely as a result of technology cost dynamics. In IAMs, technology deployment is also governed by system constraints that characterize both scenarios, e.g. the flexibility of the energy system, the availability of storage technologies. From a modelling point of view, implementing more stringent climate policies to meet the 2°C targets forces models to find solutions, even if costly, to meet those intermittency and flexibility constraints and temperature target constraints.



Box 16.1, Figure 1: Global Technology cost and deployment in two groups of AR6 scenarios: (1) reference and current policies including NDCs and (2) 2°C and well-below 2°C.
Panel a) Current capital costs are sourced from Table 1, (Timilsina 2020); distribution of capital costs in 2030 and 2050 (AR6 database). Blue symbols represent the mean. 'Current' capital costs for coal and gas plants with CCS are not available; Panel b) Total installed capacity in 2019 (IRENA 2020a; IEA 2020c; IRENA 2020b); distribution of total installed capacity in 2030 and 2050 (AR6 database). Blue symbols represent the mean; Panel c) Percentage of change in capital costs and installed capacity between (2010-2020) and percentage of median change (2020-2030 and 2020-2050) (Median$_{year}$-

Median$_{2020}$)/Median$_{2020}$*100. "M" indicates the number of models, "S" the number of scenarios for which this data is available. Reference and current policies' are C6 and C7 scenario categories and '2C and 1.5C' are C1, C2 and C3 scenario categories. Each model may have submitted data for more than one model version.

END BOX 16.1 HERE

16.3 A systemic view of technological innovation processes

The innovation process, which consists of a set of sequential phases (Section 16.2.1), is often simplified to a linear process. Yet, it is now well understood that it is also characterised by numerous kinds of interactions and feedbacks between the domains of knowledge generation, knowledge translation and application, and knowledge use (Kline and Rosenberg 1986). Furthermore, it is not just invention that leads to technological change but the cumulative contribution of incremental innovations over time can be very significant (Kline and Rosenberg 1986). Innovations can come not just from formal R&D but also sources such as production engineers and the shop floor (Freeman 1995a; Kline and Rosenberg 1986).

This section reviews the literature focusing on innovation as a systemic process. This now predominant view enriches the understanding of innovation as presented in section 16.2; it conceptualizes innovation as the result of actions by, and interactions among, a large set of actors, whose activities are shaped by, and shape, the context in which they operate and the user group with which they are engaging. This section aligns with the discussion of socio-technical transitions (see Chapter 1 Section 1.7.3, the Supplementary Material in Chapter 5, and Cross-Chapter Box 12 in this chapter).

16.3.1 Frameworks for analysing technological innovation processes

The resulting overarching framework that is commonly used in the innovation scholarship and even policy analyses is termed as "innovation system", where the key constituents of the systems are actors, their interactions, and the institutional landscape, including formal rules, such as laws, and informal restraints, such as culture and codes of conduct, that govern the behaviour of the actors (North 1991).

One application of this framework is that of *national innovation systems (NIS)*, which highlights the importance of national and regional relationships for determining the technological and industrial capabilities and development of a country (Nelson 1993; Lundvall 1992; Freeman 1995a). Nelson (1993) and Freeman (Freeman 1995a) highlight the role of institutions that determine the innovative performance of national firms as way to understand differences across countries, while Lundvall (1992) focuses on the "elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge", i.e., notions of interactive learning, in which user-producer relationships are particularly important (Lundvall 1988). Building on this, various other applications of the "innovation systems" framework have emerged in the literature.

Technological Innovation systems (TIS), with technology or set of technologies (more narrowly or broadly defined in different cases) as the unit of analysis and focus on explaining what accelerates or hinders their development and diffusion. Carlsson and Stankiewicz (1991) define a technological system as "a dynamic network of agents interacting in a specific economic/ industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology." More recent work takes a "functional approach" to TIS (Bergek et al. 2008; Hekkert et al. 2007), which was later expanded with explanations of how some of the sectoral, geographical and political dimensions intersect with technology innovation systems (Bergek et al. 2015; Quitzow 2015).

Sectoral innovation systems (SIS): based on the understanding that the constellation of relevant actors and institutions will vary across industrial sectors, with each sector operating under a different technological regime and under different competitive or market conditions. A sectoral innovation, thus, can be defined as “that system (group) of firms active in developing and making a sector's products and in generating and utilising a sector's technologies” (Breschi and Malerba 1997).

Regional and Global innovation systems (RIS, GIS), recognising that the many innovation processes have a spatial dimension, where the development of system resources such as knowledge, market access, financial investment, and technology legitimacy may well draw on actors, networks, and institutions within a region (Cooke et al. 1997). In other cases, the distribution of many innovation processes are highly internationalised and therefore outside specific territorial boundaries (Binz and Truffer 2017). Importantly, Binz and Truffer (2017) note that the GIS framework “differentiates between an industry’s dominant innovation mode... and the economic system of valuation in which markets for the innovation are constructed.”

Mission-oriented innovation systems (MIS), whose relevance comes into focus with the move towards mission-oriented programs as part of the increasing innovation policy efforts to address societal challenges. Accordingly, an MIS is seen as consisting of “networks of agents and sets of institutions that contribute to the development and diffusion of innovative solutions with the aim to define, pursue and complete a societal mission” (Hekkert et al. 2020).

Notably the innovation systems approach has been used in a number of climate-relevant areas such as agriculture (Echeverría 1998; Klerkx et al. 2012; Horton and Mackay 2003; Brooks and Loevinsohn 2011), energy (Sagar and Holdren 2002; OECD 2006; Gallagher et al. 2012; Wieczorek et al. 2013; Mignon and Bergek 2016; Darmani et al. 2014), industry (Koasidis et al. 2020b) and transport (Koasidis et al. 2020a), and sustainable development (Clark et al. 2016; Bryden and Gezelius 2017; Anadon et al. 2016b; Nikas et al. 2020).

A number of functions can be used to understand and characterise the performance of technological innovation systems (Hekkert et al. 2007; Bergek et al. 2008). The most common functions are in Table 16.5.

Table 16.5 Functions that the literature identified as key for well-performing technological innovation systems (based on Hekkert et al (2007) and Bergek et al (2008))

Functions	**Description**
Entrepreneurial activities and experimentation	Entrepreneurial activities and experimentation for translating new knowledge and/or market opportunities into real-world application
Knowledge development	Knowledge development includes both “learning-by-searching” and “learning-by-doing”
Knowledge diffusion	Knowledge diffusion through networks, both among members of a community (e.g., scientific researchers) and across communities (e.g., universities, business, policy, and users).
Guidance of search	Guidance of search directs the investments in innovation in consonance with signals from the market, firms or government
Market formation	Market formation through customers or government policy is necessary to allow new technologies to compete with incumbent technologies
Resource mobilisation	Resource mobilisation pertains to the basic inputs – human and financial capital – to the innovation process

Creation of legitimacy/counteract resistance to change	Creation of legitimacy or counteracting resistance to change, through activities that allow a new technology to become accepted by users, often despite opposition by incumbent interests
Development of external economies	Development of external economies, or the degree to which other interests benefit from the new technology

Evidence from empirical case studies indicates that all the above functions are important and that they interact with one another (Hekkert and Negro 2009). The approach therefore serves as both a rationale for and a guide to innovation policy (Bergek et al. 2010).

A much-used, complementary systemic framework is the multilevel perspective (MLP) (Geels 2002), which focuses mainly on the diffusion of technologies in relation to incumbent technologies in their sector and the overall economy. A key point of MLP is that new technologies need to establish themselves in a stable 'socio-technical regime' and are therefore generally at a disadvantage, not just because their low technological maturity, but also because of an unwelcoming system. The MLP highlights that the uptake of technologies in society is an evolutionary process, which can be best understood as a combination of "variation, selection and retention" as well as "unfolding and reconfiguration" (Geels 2002). Thus new technologies in their early stages need to be selected and supported at the micro-level by niche markets, possibly through a directed process that has been termed "strategic niche management" (Kemp et al. 1998). As at the macro landscape level pressures on incumbent regimes mount, and those regimes destabilise, the niche technologies get a chance to get established in a new socio-technical regime, which allows these technologies to grow and stabilise, shaping a changed or sometimes radically renewed socio-technical regime. The MLP takes a systematic and comprehensive view about how to nurture and shape technological transitions by understanding them as evolutionary, multi-directional and cumulative socio-technical process playing out at multiple levels over time with a concomitant expansion in the scale and scope of the transition (Elzen et al. 2004; Geels 2005b). There have been numerous studies that draw on the MLP (van Bree et al. 2010; Geels et al. 2017; Geels 2012) to understand different aspects of climate technology innovation and diffusion.

Systemic analyses of innovation have predominantly focused on industrialised countries There have been some efforts to use the innovation systems lens for the developing country context (Jacobsson and Bergek 2006; Lundvall et al. 2009; Altenburg 2009; Choi and Zo 2019; Tigabu 2018; Tigabu et al. 2015) and specific suggestions on ways for developing countries to strengthening their innovation systems (e.g., by universities taking on a "developmental" role (Arocena et al. 2015) or industry associations acting as intermediaries to build institutional capacities (Watkins et al. 2015; Khan et al. 2020), including specifically for addressing climate challenges (Sagar et al. 2009; Ockwell and Byrne 2016). But the conditions in developing countries are quite different, leading to suggestions that different theoretical conceptualisations of the innovation systems approach may be needed for these countries (Arocena and Sutz 2020), although a system perspective would still be appropriate (Boodoo et al. 2018).

16.3.2 Identifying systemic failures to innovation in climate-related technologies

Traditional perspectives on innovation policy were mostly science-driven, and focused on strengthening invention and its translation into application in a narrow sense, and a second main traditional perspective on innovation policy was focused on correcting for 'market failures' (covered in Section 16.2) (Weber and Truffer 2017). The more recent understanding of, and shift of focus to, the systemic nature on the innovation and diffusion of technologies has implications for innovation policy since innovation outcomes depend not just on inputs such as R&D but much more on the functioning of the overall innovation system (see previous section and Section 16.4). Policies can therefore be directed at innovation systems components and processes that need the greatest attention or support. This may include, for example, strengthening the capabilities of weak actors and improving interactions between actors (Jacobsson et al. 2017; Weber and Truffer 2017). At the same time, a systemic perspective also brings into sharp relief the notion of 'system failures' (Weber and Truffer 2017).

Systemic failures include infrastructural failures; hard (e.g., laws, regulation) and soft (e.g., culture, social norms) institutional failures; interaction failures (strong and weak network failures); capability failures relating to firms and other actors; lock-in; and directional, reflexivity, and coordination failures (Klein Woolthuis et al. 2005; Chaminade and Esquist 2010; Weber and Rohracher 2012; Wieczorek and Hekkert 2012; Negro et al. 2012). By far most of the literature that unpacks such failures and explores ways to overcome them is on energy-related innovation policy. For example, Table 16.6 summarizes a meta-study (Negro et al. 2012) that examined cases of renewable energy technologies trying to disrupt incumbents across a range of countries to understand the roles, and relative importance, of the 'systemic problems' highlighted in Section 16.3.1.

Table 16.6 Examination of systemic problems preventing renewable energy technologies from reaching their potential, including number of case studies in which the particular 'systemic problem' was identified Source: (Negro et al. 2012).

Systemic problems	Empirical sub-categories	No. of cases
Hard institutions	- 'Stop and go policy': lack of continuity and long-term regulations; inconsistent policy and existing laws and regulations -'Attention shift': policy makers only support technologies if they contribute to the solving of a current problem -'Misalignment' between policies on sector level such as agriculture, waste, and on governmental levels, i.e. EU, national, regional level, etc. -"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	- Large-scale criteria - Incremental/near-to-market innovation - Incumbent's dominance	30
Soft institutions	- Lack of legitimacy - Different actors opposing change	28
Capabilities/capacities	- 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

Depending on the sector, specific technology characteristics, and national and regional context, the relevance of these systemic problems varies (Trianni et al. 2013; Bauer et al. 2017; Wesseling and Van der Vooren 2017; Koasidis et al. 2020b,a), suggesting that the innovation policy mix has to be tailor-made to respond to the diversity of systemic failures (Rogge et al. 2017). An illustration of how such systemic failures have been addressed is given in Box 16.2, which shows how the Indian government designed its standards and labelling programme for energy-efficient air conditioners and refrigerators. The success of this program resulted from the careful attention to bring on board and coordinate the relevant actors and resources, the design of the standards, and ensuring effective administration and enforcement of the standards (Malhotra et al. 2021).

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Box 16.2: Standards and Labelling (S&L) for energy efficient refrigerators and air conditioners in India[2]

Energy efficiency is often characterised as a "low-hanging fruit" for reducing energy use. However, systemic failures such as lack of access to capital, hidden costs of implementation, and imperfect information can result in low investments into adoption and innovation in energy efficiency measures (Sorrell et al. 2004). To address such barriers, India's governmental Bureau of Energy Efficiency (BEE) introduced the Standards and Labelling (S&L) programme for promotion of innovation in energy efficient appliances in 2006 (Sundaramoorthy and Walia 2017). While context-dependent, the programme design, policies and scale-up contain lessons for addressing systemic failures elsewhere too.

Program design and addressal of early systemic barriers

To design the S&L program, BEE drew on the international experiences and technical expertise of the Collaborative Labelling and Appliance Standards Program (CLASP) – a non-profit organisation that provides technical and policy support to governments in implementing S&L programs. For example, since there was no data on the efficiency of appliances in the Indian market, CLASP assisted with early data collection efforts, resulting in a focus on refrigerators and air conditioners (ACs) (McNeil et al. 2008).

FOOTNOTE [2] This section draws on "The role of capacity-building in policies for climate change mitigation and sustainable development: The case of energy efficiency in India" (Malhotra et al. 2021)

Besides drawing from international knowledge, the involvement of manufacturers, testing laboratories, and customers was crucial for the functioning of the innovation system.

To involve manufacturers, BEE employed three strategies to set the standards at an ambitious yet acceptable level. First, BEE enlisted IIT Delhi (a public technical university) to engage with manufacturers and to demonstrate cost-effective designs of energy-efficient appliances. Second, BEE agreed to make the standards voluntary from 2006 to 2010. In return, the manufacturers agreed to mandatory and progressively more stringent standards starting in 2010. Third, BEE established a multi-stakeholder committee with representation from BEE, the Bureau of Indian Standards, appliance manufacturers, test laboratories, independent experts, and consumer groups (Jairaj et al. 2016) to ensure that adequately stringent standards are negotiated every two years.

At this time, India had virtually no capacity for independent testing of appliances. Here too, BEE used multiple approaches towards creating the actors and resources needed for the innovation system to function. First, BEE funded the Central Power Research Institute (CPRI) – a national laboratory for applied research, testing and certification of electrical equipment – to set up refrigerator and AC testing facilities. Second, they invited bids from private laboratories, thus creating a demand for testing facilities. Third, BEE developed testing protocols in partnership with universities. Australian standards for testing frost-free refrigerators were adopted until local standards were developed. Thus, once the testing laboratories, protocols and benchmark prices for testing were in place, the appliance manufacturers could employ their services.

Finally, a customer outreach program was conducted from 2006 to 2008 to inform customers regarding energy efficient appliances, to enable them to interpret the labels correctly, and to understand their purchase decisions and information sources (Joshi et al. 2019; Jain et al. 2018). BEE initiated a capacity building program for retailers to be an information source for costumers. A comprehensive document with details of different models and labels was provided to retailers, together with a condensed booklet to be shared with customers.

Adapting policies to technologies and local context

While many of India's standards and testing protocols were based on international standards, they needed to be adapted to the Indian context. For example, because of higher temperatures in India, the reference outside temperature of 32°C for refrigerators was changed to 36°C.

AC testing protocols also had to be adapted because of the emergence of inverter-based ACs. Existing testing done only at a single temperature did not value inverter-based ACs' better average performance as compared to fixed-speed ACs over a range of temperatures. Thus, the Indian Seasonal Energy Efficiency Ratio (ISEER) was developed for Indian temperature conditions in 2015 by studying ISO standards and through consultations with manufacturers (Mukherjee et al. 2020).

These measures had multiple effects on technological change. As a result of stringent standards, India has some of the most efficient refrigerators globally. In the case of ACs, the ISEER accelerated technological change by favouring inverter-based ACs over fixed-speed ACs, driving down their costs and increasing their market shares (BEE 2020).

Scaling up policies for market transformation

As the S&L program was expanded, BEE took measures to standardise, codify and automate it. For example, to process a high volume of applications for labels efficiently, an online application portal with objective and transparent certification criteria was created. This gave certainty to the manufacturers, enabling diversity and faster diffusion of energy-efficient appliances. Thus by 2019, the program expanded to cover thousands of products across 23 appliance types (BEE 2020).

Besides issuing labels, the enforcement of standards also needed to be scaled up efficiently. BEE developed protocols for randomly sampling appliances for testing. Manufacturers were given a fixed period to rectify products that did not meet the standards, failing which they would be penalised and the test results would be made public.

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16.3.3 Indicators for technological innovation

Assessing the state of technological innovation helps understanding how current efforts and policies are doing in relation to stated objectives and how we might design policies in order to do better.

Traditionally, input measures such as RD&D investments and output measures such as scientific publication and patents were used to characterise innovation activities (Freeman and Soete 2009), partly because of the successes of specialised R&D efforts (Freeman 1995a), the predominant linear model of innovation, and because such measures can (relatively) easily obtained and compared. In the realm of energy-related innovation, RD&D investments remains the single most-used indicator to measure inputs into the innovation process (Box 16.3). Patents counts are a widely used indicator of the outputs of the innovation process, especially because they are detailed enough to provide information on specific adaptation and mitigation technologies. Mitigation and adaptation technologies have their own classification (Y02) with the European Patent Office (EPO) (Veefkind et al. 2012; Angelucci et al. 2018), which can be complemented with keyword search and manual inspection (Persoon et al. 2020; Surana et al. 2020b). However, using energy-related patents as indicator of innovative activities is complicated by several issues (Haščič and Migotto 2015; Jaffe and de Rassenfosse 2017; de Rassenfosse et al. 2013), including the fact that the scope of what are to be considered climate mitigation inventions is not always clear or straightforward.

Conversely, private energy R&D investments and investments by financing firms cannot be precisely assessed for a number of reasons, including limited reporting and the difficulty of singling out energy-related investments. This inability to precisely quantify private investments in energy R&D leads to a patchy understanding of the energy innovation system, and how private energy R&D investments responds to public energy R&D investments. 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) are investing relatively small fractions of sales on R&D (*medium evidence, high agreement*) (European Commission 2015; National Science Board 2018; American Energy Innovation Council 2017; Jasmab and Pollitt 2005; Sanyal and Cohen 2009; Jamasb and Pollitt 2008; Gaddy et al. 2017).

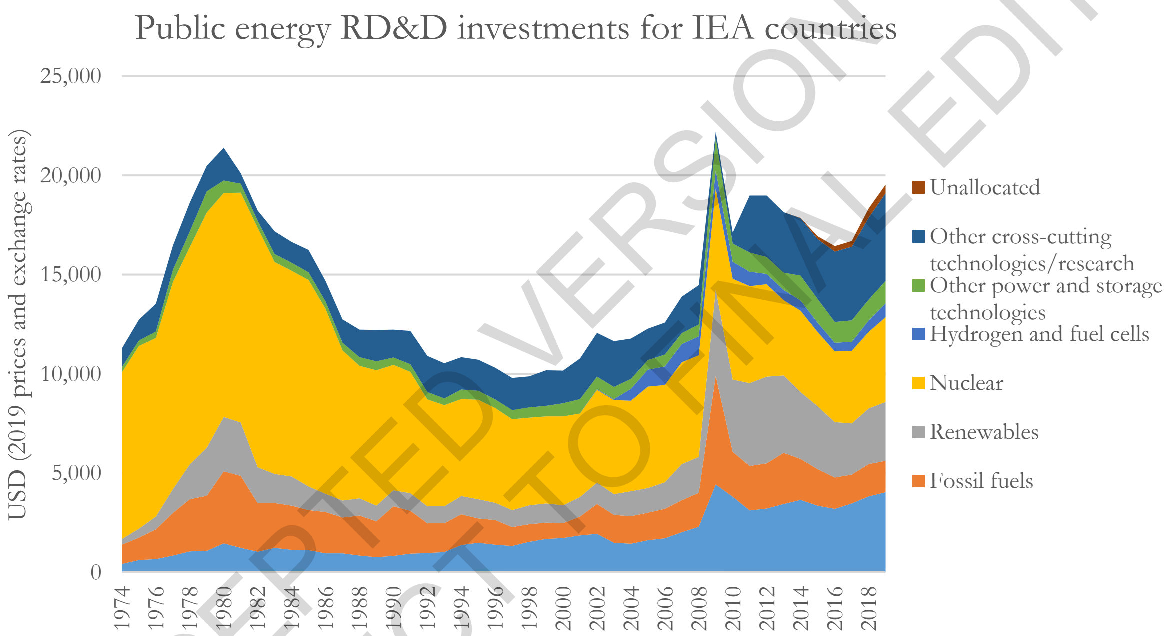
Financing firms also play an important role in the energy innovation process, but data availability is also limited. The venture capital (VC) financing model, used to overcome the “valley of death” in the biotech and IT space (Frank et al. 1996), has not been as suitable for hardware start-ups in the energy space: for example, the percentage of exit outcomes in clean-tech start-ups was almost half of that in medical start-ups and less than a third of software investments (Gaddy et al. 2017). The current VC model and other private finance do not sufficiently cover the need to demonstrate energy technologies at scale (Mazzucato 2013; Anadón 2012; Nemet et al. 2018). This greater difficulty in reaching 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 (Frankfurt School-UNEP Centre/BNEF 2019).

START BOX 16.3 HERE

Box 16.3 Investments in public energy R&D

Public energy R&D investments are a crucial driver of energy technology innovation (Sections 16.2.1.1, 16.4.1). Box 16.3, Figure 1 shows the time profile of energy-related RD&D budgets in OECD countries as well as some key events which coincided with developments of spending (IEA 2019). Such data on other countries, in particular developing countries, are not available, although recent evidence suggests that expenditures are increasing there (IEA 2020c). The IEA collected partial data from China and India in the context of Mission Innovation, but this is available only starting in 2014 and thus not included in the Figure.

The figure illustrates two points. First, energy-related RD&D has risen slowly in the last 20 years, and is now reaching levels comparable with the peak of energy RD&D investments following the two oil crises. Second, over time there has been a reorientation of the portfolio of funded energy technologies away from nuclear energy. In 2019, around 80% of all public energy RD&D spending was on low-emission technologies – energy efficiency, CCUS, renewables, nuclear, hydrogen, energy storage and cross-cutting issues such as smart grids. A more detailed discussion of the time profile of RD&D spending in IEA countries, including as a share of GDP, are available in (IEA 2020b).



Box 16.3, Figure 1 Fraction of public energy RD&D spending by technology over time for IEA (largely OECD) countries between 1974 and 2018.

Sources: IEA RD&D Database, 2019 (IEA 2019). (extracted on November 11, 2020).

END BOX 16.3 HERE

Quantitative indicators such as energy-related RD&D spending are insufficient for the assessment of innovation systems (David and Foray 1995): they only provide a partial view into innovation activities, and one that is potentially misleading (Freeman and Soete 2009). Qualitative indicators measuring the more intangible aspects of the innovation process and system are crucial to fully understand the innovation dynamics in a climate or energy technologies or sectors (Gallagher et al. 2006), including in relation to adopting an adaptive learning strategy and supporting learning through demonstration projects (Chan et al. 2017).

In Table 16.7, both quantitative and qualitative indicators for systemic innovation are outlined, using clean energy innovation as an illustrative example and drawing on a broad literature base, taking into account both the input-output-outcome classification and its variations (Hu et al. 2018; Freeman and Soete 1997; Sagar and Holdren 2002), combined with the functions of technological innovation systems

(Miremadi et al. 2018), while also being cognizant of the specific role of key actors and institutions (Gallagher et al. 2012). A specific assessment of innovation may focus on part of such a list of indicators, depending on what aspect of innovation is being studied, whether the analysis takes a more or less systemic perspective, and the specific technology and geography considered. Similarly, innovation policies may be designed to specifically boost only some of these aspects, depending whether a given country/region is committed to strengthen a given technology or phase.

The systemic approach to innovation and transition dynamics (see also Cross-Chapter Box 12 in this chapter) has advanced our understanding of the complexity of the innovation process, pointing to the importance of assessing the efficiency and effectiveness in producing, diffusing and exploiting knowledge (Lundvall 1992), including how the existing stock of knowledge may be recombined and used for new applications (David and Foray 1995). There remains a crucial need for more relevant and comprehensive approaches of assessing innovation (Freeman and Soete 2009; Dziallas and Blind 2019). In the context of climate mitigation, innovation is a means to an end; therefore, there is the need to consider the processes by which the output of innovation (e.g., patents) are translated into real-world outcomes (e.g., deployment of low-carbon technologies) (Freeman and Soete 1997; Sagar and Holdren 2002). Currently, a set of quantitative metrics that, collectively, can help get a picture of innovation in a particular energy technology or set of energy technologies is not available. Also the understanding of how to systematically use qualitative indicators to characterise the more intangible aspects of the energy innovation system and to improve front-end innovation decisions is still lacking (Dziallas and Blind 2019).

Table 16.7 Commonly used quantitative innovation metrics, organized by inputs, outputs and outcomes. Based on (Sagar and Holdren 2002; Gallagher et al. 2006; Hekkert et al. 2007; Gallagher et al. 2012; Miremadi et al. 2018; Hu et al. 2018; Gallagher et al. 2011; Avelino et al. 2019; Gruebler et al. 2012)

Function	Input indicators	Output indicators	Outcome indicators	Actors	Policies	Structural and systemic indicators
Knowledge development	Higher education investments R&D investments Number of researchers R&D projects over time	Scientific publications Highly-cited publications Patents New product configurations	Number of technologies developed (proof-of-concept/prototypes) Increase in number of researchers Learning rates	Governments Private corporations Universities	Research programs and strategies IPR policies International technical norms (e.g. standards) Higher education policies	Well-defined processes to define research priorities Stakeholder involvement in priority-setting
Knowledge diffusion	R&D networks Number of research agreement Number of research exchange programs Number of scientific conferences	Citations to literature or patents Public-private co-publications Co-patenting Number of co-developed products International scientific co-publications Number of workshops and conferences	Number of licensed patents Number of technologies transferred Knowledge-intensive services exports Number of patent applications by foreigners Number of researchers working internationally	Governments Private corporations Scientific societies Universities	Development of communication centres Facilitation of the development of networks Open-access publication policies IPR policies International policy: e.g. treaties, clean development mechanism	Accessibility to exchange programs Strength of linkage among key stakeholders Participation to framework agreements ICT access
Guidance of search	Policy action plans and long-term targets Shared strategies and roadmaps	Level of media coverage Scenarios and foresight projects	Budget allocations Mission-oriented innovation programs	Governments Interest groups	Targets set by government of industry Innovation policies	Media strength

	Articulation of interest from lead customers Expectations of markets/profits			Media	Credible political support	
Resource mobilization	Access to finance Graduate in STEMS Gross expenditures on R&D/total expenditures Domestic credit to private sector Number of researchers in R&D per capita Public energy R&D expenditures/total expenditures Expenditure on education Investment in complementary assets and/or infrastructure (e.g. Charging	Number of green projects/technologies funded Share of domestic credit granted to low-carbon technology projects Share of domestic credit granted to projects developing complementary assets/infrastructure	Employment in knowledge-intensive activities Employment in relevant industries Scale of innovative activities Rate of growth of dedicated investment Availability of complementary assets and infrastructure	Governments Private firms Private investors (angel, venture capital, private equity) Banks	Financial resources support Development of innovative financing International agreements (e.g. technology agreements) Infrastructure support Project/program evaluation Innovation policies Higher education policies	

	infrastructure for EVs, smart grids) Venture capital on deals					
Entrepreneurial activities	No. of new entrants % of clean energy start-ups/incumbents access to finance for clean-tech start up	SMEs introducing product or process innovation Market introduction of new technological products Number of new businesses Experimental application projects Creative goods exports		Private firms Government Risk-capital providers Philanthropies	Ease of starting a business Risk-capital policies Start-up support programs Incubator programs	Start-up support services
Market formation	Public market support High-tech imports	Market penetration of new technologies Increase in installed capacity No of niche markets Number of technologies commercialized	Environmental performance Level of environmental impact on society Renewable energy jobs Renewable energy production Trade of energy technology and equipment High-tech exports	Private firms Governments institutions regulating trade, finance, investment, environment, development, security, and health issues	Environmental and Energy Regulation Fiscal and financial incentives Cleantech-friendly policy processes Transparency Specific tax regimes	Resource endowments Attractiveness of renewable energy infrastructure Coordination across relevant actors (e.g., renewable energy producers, grid operators, and distribution companies)

Creation of legitimacy	Youth and public demonstration Lobbying activities Regulatory acceptance and integration Technology support	Level of discussion/debate among key stakeholders (public, firms, policy-makers, etc.) Greater recognition of benefits	Public opinion Policy-maker opinion Executive opinion on regulation Environmental standards and certification	Governments Stakeholders Citizens Philanthropies	Regulatory quality Regulatory instruments Political consistency	Participatory processes

16.3.4 Emerging policy perspectives on systemic transformations

Because of the multiple market, government, system, and other 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 (Twomey 2012; Jaffe et al. 2005; Bürer and Wüstenhagen 2009; Veugelers 2012; Negro et al. 2012; Weber and Rohracher 2012) and used in what is termed as policy mixes (Rogge and Reichardt 2016; Rogge et al. 2020; Edmondson et al. 2020, 2019) . 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 a range of policies that shaped the socio-technical system (Nemet 2019a; Bunn et al. 2014; Rogge and Reichardt 2016; Bergek et al. 2015) (*robust evidence, high agreement*). An example of this systemic and dynamic nature of policies is the 70-year innovation journey of solar PV, covering multiple countries, which is reviewed in Box 16.4.

START BOX 16.4 HERE

Box 16.4 Sources of cost reductions in solar photovoltaics

No single country persisted in developing solar PV. Five countries each made a distinct contribution. Each leader relinquished its lead. The free flow of ideas, people, machines, finance, and products across countries explains the success of solar photovoltaics (PV). Barriers to knowledge flow delay innovation.

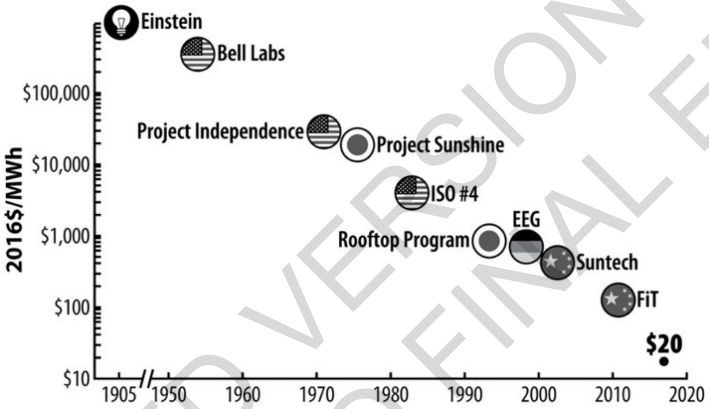
Solar PV has attracted interest for decades, and until recently was seen as an intriguing novelty, serving a niche, but widely dismissed as a serious answer to climate change and other social problems associated with energy use. Since AR5, PV has become a substantial global industry—a truly disruptive technology that has generated trade disputes among superpowers, threatened the solvency of large energy companies, and prompted reconsideration of electric utility regulation rooted in the 1930s. More favourably, its continually falling costs and rapid adoption are improving air quality and facilitating climate change mitigation. PV is now so inexpensive that it is important in an expanding set of countries. In 2020, 41 countries, in 6 continents, had installed at least 1GW of solar each (IRENA 2020a).

The cost of generating electricity from solar PV is now lower in sunny locations than running existing fossil fuel power plants (Chapter 6) (IEA 2020c). Prices in 2020 were below where even the most optimistic experts expected they would be in 2030.

The costs of solar PV modules have fallen by more than a factor of 10,000 since they were first commercialised in 1957. This four orders of magnitude cost reduction from the first commercial application in 1958 until 2018 can be summarised as the result of distinct contributions by the US, Japan, Germany, Australia, and China—in that sequence (Green 2019; Nemet 2019c). As shown in Box 16.4 Figure 1, PV improved as the result of:

1) Scientific contributions in the 1800s and early 1900s, in Europe and the US, that provided a fundamental understanding of the ways that light interacts with molecular structures, leading to the development of the p-n junction to separate electrons and holes (Einstein 1905; Ohl 1941);
2) A breakthrough at a corporate laboratory in the US in 1954 that made a commercially available PV device available and led to the first substantial orders, by the US Navy in 1957 (Gertner 2013; Ohl 1946);
3) A government R&D and public procurement effort in the 1970s in the US, that entrained skilled scientists and engineers into the effort and stimulated the first commercial production lines (Laird 2001; Christensen 1985; Blieden 1999);

4) Japanese electronic conglomerates, with experience in semiconductors, serving niche markets in the 1980s and in 1994 launching the world's first major rooftop subsidy program, with a declining rebate schedule and demonstrating there was substantial consumer demand for PV (Kimura and Suzuki 2006);
5) Germany passing a feed-in tariff in 2000 that quadrupled the market for PV catalysing development of PV-specific production equipment that automated and scaled PV manufacturing (RESA 2001; Lauber and Jacobsson 2016);
6) Chinese entrepreneurs, almost all trained in Australia and using Australian-invented passivated emitter rear cell technology, building supply chains and factories of gigawatt scale in the 2000s. China became the world's leading installer of PV from 2013 onward (Helveston and Nahm 2019; Quitzow 2015).
7) A cohort of adopters with high willingness to pay, accessing information from neighbours, and installer firms that learned from their installation experience, as well as that of their competitors to lower soft costs (Gillingham et al. 2016; Ardani and Margolis 2015).



Box 16.4, Figure 1 Milestones in the development of low-cost solar photovoltaics (Nemet 2019c)

As this evolution makes clear, no individual country persisted in leading the technology and every world leading firm lost its lead within a few years (Green 2019). Solar followed an overlapping but sequential process of technology creation, market creation and cost reductions (comparable to emergence, early adoption, diffusion and stabilisation in Cross-Chapter Box 12 in this chapter). In the technology creation phase examples of central processes include flows of knowledge from one person to another, between firms, and between countries as well as US and Japanese R&D funding in the 1970s and early 1980s. During market creation, PVs modular scale allowed it to serve a variety of niche markets from satellites in the 1950s to toys in the 1980s, when Germany transformed the industry from niche to mass market with its subsidy program that began in 2000 and became important for PV in 2004. The dramatic increase in size combined with its 20-year guaranteed contracts reduced risk for investors and created confidence in PVs long term growth. Supportive policies also emerged outside Germany, in Spain, Italy, California, and China, which spread the risk even as national policy support was more volatile. Rapid and deep cost reductions were made possible by learning-by-doing in the process of operating, optimising, and combining production equipment; investing and improving each manufacturing line to gradually scale up to massive sizes and incremental improvements in the PV devices themselves.

Central to PV development has been its modularity, which provided two distinct advantages: access to niche markets, and iterative improvement. Solar has been deployed as a commercial technology across 9 orders of magnitude: from a 1W cell in a calculator to a 1GW plant in the Egyptian desert, and almost every scale in between. This modular scale enabled PV to serve a sequence of policy-independent niche markets (such as satellites and telecom applications), which generally increased in size and decreased in willingness to pay, in line with the technology cost reductions. This modular scale also enabled a large number of iterations, such that in 2020 over three billion solar panels have been produced. Compared to, for instance, approximately 1000 nuclear reactors that were ever constructed, a million times more opportunities for learning-by-doing were available to solar PV: to make incremental improvements, to introduce new manufacturing equipment, to optimise that equipment, and to learn from failures. More generally, recent work has point to the benefits of modularity in the speed of adoption (Wilson et al. 2020) and learning rates (Sweerts et al. 2020).

While many technologies do not fit into the solar model, some, including micro nuclear reactors and direct air capture, also have modular characteristics that make them suitable for following solar's path and benefit from solar's drivers. However, PV took solar 60 years to become cheap, which is too slow for addressing climate change if a technology is now still at the lab scale. A challenge in learning from the solar model is therefore to how to use public policy to speed up innovation over much shorter time frames, e.g. 15 or less years.

END BOX 16.4 HERE

There are many definitions of policy mixes from various disciplines (Rogge et al. 2017), including environmental economics (Lehmann 2012), policy studies (Kern and Howlett 2009) and innovation studies. Generally speaking, a policy mix can be characterised by a combination of building blocks, namely elements, processes and characteristics, which can be specified using different dimensions (Rogge and Reichardt 2016). Elements include (i) the policy strategy with its objectives and principal plans and (ii) the mix of policy instruments, and (iii) instrument design. The content of these elements is 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 in different policy, governance, geography and temporal context (Rogge and Reichardt 2016). Other aspects in the evaluation of policy mixes include framework conditions, the type of policy instrument and the lower level of policy granularity, namely design elements or design features (del Río 2014; del Río and Cerdá 2017). In addition, many have argued the need to craft policies that affect different actors in the transition, some supporting and some 'destabilising' (see e.g. Kivimaa and Kern (2016) and Geels (2002)).

Learning from the innovation systems literature, some of the recent policy 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 2003; Steneck 2006). Therefore, the aim is to connect innovation policy with societal challenges and transformative changes through engagement with a variety of actors and ideas and incorporating equity, nowadays often referred to as a just transition (Newell and Mulvaney 2013; Swilling et al. 2016; Heffron and McCauley 2018; Jasanoff 2018) (see Chapter 1 and Chapter 17). This new policy paradigm is opening up a new discursive space, shapes policy outcomes, and is giving rise to the emerging idea of transformative innovation policy (Diercks et al. 2019; Fagerberg 2018).

Transformative innovation 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 socio-technical transitions (Elzen et al. 2004; Turnheim and Sovacool 2020) or societal transformations (Scoones 2015; Roberts et al. 2018). Transformative 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 (Gunderson and Holling 2002), eco-innovation (Kemp 2011) and framework for responsible innovation (Stilgoe et al. 2013), value-sensitive design (Friedman and Hendry 2019) and social-technical integration (Fisher et al. 2006).

16.4 Innovation policies and institutions

Building on the frameworks for identifying market failures (Section 16.2) and systemic failures (Section 16.3) in the innovation system for climate-related technologies, Section 16.4 proceeds as follows. First, it considers some of the policy instruments introduced in Chapter 13 that are particularly relevant for the pace and direction of innovation in technologies for climate change mitigation and adaptation. Second, it explains why governments put in place policies to promote innovation in climate related technologies. Third, it takes stock of the overall empirical and theoretical evidence regarding the relationship between policy instruments with a direct and an indirect impact on innovation outcomes (including intellectual property regimes) and also other outcomes (competitiveness and distributional outcomes). Fourth, it assesses the evidence on the impact of trade-related policies and of sub-national policies aiming to develop cleantech industrial clusters.

This section focuses on innovation policies and institutions which are implemented at the national level. Whenever relevant, this section highlights examples of policies or initiatives that delve more deeply into the main high-level sectors: power, transport, industry, buildings, and AFOLU. Whenever 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.

Overall, this section shows that national and subnational policies and institutions are one of the main factors determining the redirection and acceleration of technological innovation and low-emission technological change (Åhman et al. 2017; Rogge and Reichardt 2016; Anadon et al. 2016b; Anadón et al. 2017; Roberts et al. 2018) *(robust evidence, high agreement).* Both technology push (e.g., scientific training, R&D) and demand pull (e.g., economic and fiscal support and regulatory policy instruments), as well as instruments promoting knowledge flows and especially research-firm technology transfer, can be part of the mix *(robust evidence, medium agreement)* (see also Sections 16.2 and 16.3).

Public R&D investments in energy and climate-related technologies have a positive impact on innovation outcomes (*medium evidence, high agreement*). The evidence on procurement is generally positive but limited. The record economic policy instruments that can be classified as market pull instruments when it comes to the competitiveness outcome (at least in the short term) is more mixed. The review of the literature in this section shows that market pull policy instruments had positive but also some negative impacts on outcomes in some instances on some aspects of competitiveness and distributional outcomes (*medium evidence, medium agreement*) (Peñasco et al. 2021). For several of them, carbon taxes or feed-in tariffs for example, the evidence of a positive impact on innovation is more consistent than the others. Evidence suggests that complementary policies or improved policy design can mitigate such short-term negative distributional impacts.

16.4.1 Overview of policy instruments for climate technology innovation

Government policies can influence changes in technologies, as well as changes to the systems they support (Somanathan et al. 2014) (see Chapter 13 and Sections 16.2 and 16.3).

Technology-push policy instruments stimulate innovation by increasing the supply of new knowledge through funding and performing research; increasing the supply of trained scientists and engineers which contribute to knowledge-generation and provide technological opportunities, which private firms can decide to commercialise (Mowery and Rosenberg 1979; Anadon and Holdren 2009; Nemet 2009b; Mazzucato 2013).

Governments can also stimulate technological change through demand-pull (or: market-pull) instruments which support market creation or expansion and technology transfer and thus promoting learning by doing, economies of scale, and automation (Section 16.2). Demand-pull policy instruments include regulation, carbon prices, subsidies that reduce the cost of adoption, public procurement, and intellectual property regulation. Typically, technology push is especially important for early-stage technologies, characterised by higher uncertainty and lower appropriability (see Section 16.2); demand-pull instruments become more relevant in the later stages of the innovation process (Section 16.2) (Mowery and Rosenberg 1979; Anadon and Holdren 2009; Nemet 2009b).

The second column of Table 16.8 summarises the set of policies shaping broader climate outcomes over the past few decades in many countries outlined in Chapter 13 Section 13.6, which groups them into economic and financial, regulatory, and soft instruments. Other policies, such as monetary, banking and trade policies, for instance, can also shape innovation but most government action to shape energy has not focussed on them. As Table 16.8 shows, this section discusses the set of policy instruments on innovation outcomes, or a subset of the 'Transformative Potential' criterion presented in Chapter 13, and thus complements the more general discussion presented there. Table 16.8 specifically prioritizes the impact of the subset of policy instruments on innovation outcomes for which evidence is available. This focus is complemented by a discussion of the impact of the same policy instruments on competitiveness (a subcomponent of the economic effectiveness evaluation criterion) and on distributional outcomes. Many of the policy instrument types listed in Table 16.8 have been implemented or proposed to address different types of market or systemic failures or bottlenecks described in Section 16.2 and Section 16.3 (OECD 2011a).

Table 16.8 Overview of policy instrument types covered in Chapter 13 and their correspondence to the subset of policy instrument types reviewed in Chapter 16 with a focus on innovation outcomes.

High- level categorisation	**Lower level policy instrument type in Chapter 13**	**Policy instrument types reviewed in Section 16.5 (for definitions see Peñasco et al** (2021))
Economic or financial policy instrument types	R&D investments	R&D investments (including demonstration) (see Box 16.4 in Section 16.4)
	Subsidies for mitigation	Feed in tariffs or premia (set administratively)
		Energy auctions
		Other public financing options (public investment banks, loans, loan guarantees)
	Emissions trading schemes	Emissions trading scheme
	Carbon taxes	Taxes/tax relief (including carbon taxes, energy taxes and congestion taxes)
	Government provision	Government provision (focus on innovation procurement)
	Removing fossil fuel subsidies	*Not covered*
	Border carbon adjustments	*Not covered*
	Offsets	*Not covered*
Regulatory policy instrument types	Performance standards (including with tradeable credits)	Renewable obligations with tradeable green certificates
		Efficiency obligations with tradeable white certificates
		Clean energy or renewable portfolio standards (electricity)
		Building codes (building efficiency codes)
		Fuel efficiency standards
		Appliance efficiency standards

	Technology standards	*Not covered*
Soft policy instruments	Divestment and disclosure	*Not covered*
	Voluntary agreements (public voluntary programs & negotiated agreements)	Voluntary agreements
		Energy labels

Section 16.3 characterized technological innovation as a systemic, non-linear and dynamic process. Figure 16.1 below presents a stylized (and necessarily incomplete view) connecting the innovation process stages presented in Section 16.2, some of the key the mechanisms in technology innovation systems, and some of the decarbonisation policy instruments that have been assessed in terms of their impact on technological innovation outcomes in Section 16.4.4. As noted in the caption and discussed in Section16.4.4, regulatory policy instruments also shape the early stages of technology development.

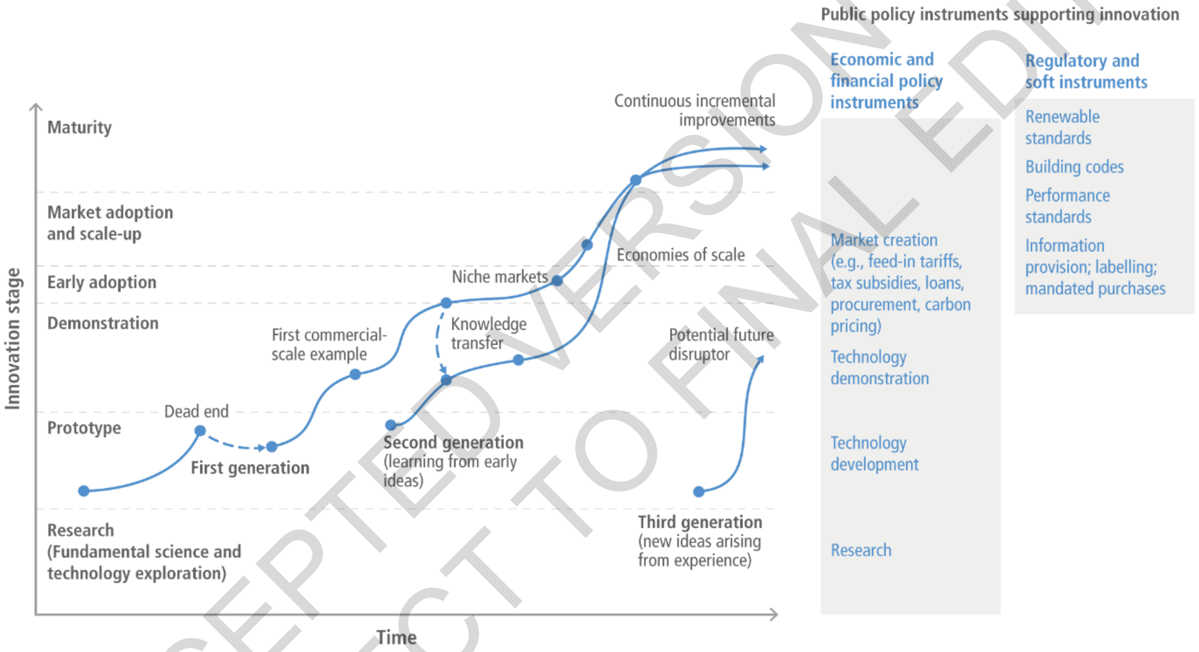


Figure 16.1 Technology innovation process and the (illustrative) and role of different public policy instruments (on the right-hand side). Adapted from IEA (IEA 2020a). Note that, as shown in section 16.4.4, demand pull instruments in the regulatory instrument category, for instance, can also shape the early stages of the innovation process. Their position on the latter stages is highlighted in this figure just because typically these instruments have been introduced in latter stages of the development of the technology.

16.4.2 The drivers and politics of national policies for climate change mitigation and adaptation

Governments around the world implement innovation policies in the energy and climate space with the aim of simultaneously advancing environmental, industrial policy (or competitiveness), and security goals (Surana and Anadon 2015; Meckling et al. 2017; Matsuo and Schmidt 2019; Anadón 2012; Peñasco et al. 2021) (*medium evidence, medium agreement*). Co-benefits of policies shaping technological innovation in climate-related technologies, including competitiveness, health, and improved distributional impacts can be drivers of climate mitigation policy in the innovation sphere

(Deng et al. 2018a; Stokes and Warshaw 2017; Probst et al. 2020). This was the case for climate and air pollution policies with local content requirements for different types of renewable energy projects, for instance. in places including China (Lewis 2014; Qiu and Anadon 2012), India (Behuria 2020), South Africa (Kuntze and Moerenhout 2012), and Canada (Genest 2014) (*robust evidence, medium agreement*).

The emergence of industries and support groups can lead to more sustained support for innovation policies (Schmid et al. 2020; Stokes and Breetz 2018; Meckling 2019; Meckling and Nahm 2019; Meckling et al. 2015a; Schmidt and Sewerin 2017a). Conversely, policies shaping technology innovation contribute to the creation and evolution of different stakeholder groups *(robust evidence, high agreement*). Most of the literature on the role of the politics and interest groups has focused on renewable energy technologies although there is some work on heating in buildings (e.g. Wesche et al. 2019).

As novel technologies become cost-competitive, opposition of incumbents usually grows, as well as the dangers of lock-in that can be posed by the new winner. Addressing this involves adapting policy (*robust evidence, high agreement*).

Three phases of politics in the development of policies to meet climate and industrial objectives can be identified, at the top, the middle and the bottom of the experience curve (Breetz et al. 2018) (see also Figure 16.1 above, and Geels (2002)). 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 et al. 2015a). 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 2014a). 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 and Urpelainen 2013; Levin et al. 2012).

16.4.3 Indicators to assess the innovation, competitiveness and distributional outcomes of policy instruments

If policy instruments are created to (at least partly) shape innovation for systemic transitions to a zero-carbon future, they also need to be evaluated on their impact on the whole socio-technical system (Neij and Åstrand 2006) and a wide range of goals, including distributional impacts and competitiveness and jobs (Stern 2007; Peñasco et al. 2021). Given this and the current policy focus on green recovery and green industrial policy, although we primarily focus on innovation outcomes, we assess also impacts on competitiveness and equity. Table 16.9 lists the selected set of indicators used to assess the impact of the policy instrument types covered in right hand side column in Table 16.8. The table does not include technology diffusion or deployment because these are covered in the technological effectiveness evaluation criterion in Chapter 13. As noted in section 16.2, it is very difficult to measure or fully understand innovation with one or even several indicators. In addition, all indicators have strengths and weaknesses and may be more relevant in some countries and sectors than in others. The literature assessing the impact of different policy instruments on innovation often covers just one of the various indicators listed in the second column of Table 16.9.

Table 16.9 Outcomes (first row) and indicators (second row) to evaluate the impact of policies shaping innovation to foster carbon neutral economies.

Sources: Innovation outcomes indicators are sourced from Del Rio and Cerdá (2014), and Peñasco et al (2021) Grubb et al (2021); the indicators under the competitiveness and distributional effects criteria are sourced from Peñasco et al (2021)

Policy Instrument Outcomes	**Innovation** (part of Chapter 13 'Transformative potential' evaluation criterion)	**Competitiveness** (part of Chapter 13 'Economic effectiveness' evaluation criterion)	**Distributional impacts** (defined in the same way as in Chapter13)
Examples of indicators used for each outcome in the literature	R&D investments, cost improvements, learning rates, patents, publications, reductions in abatement costs, energy efficiency improvements, other performance characteristics, firms reporting carbon saving innovation	Industry creation, net job creation, export of renewable energy technology equipment, economic growth (GNP, GDP), productivity, other investments	Level and incidence of support costs, change in spending on electricity as a % of total household spending, participation of different stakeholders, international equity (e.g., tCO_2-eq per capita), unequal access between large vs. small producers or firms

16.4.4 Assessment of innovation and other impacts of innovation policy instruments

While it is very difficult to attribute a causal relationship between a particular policy instrument implementation and different innovation indicators, given the complexity of the innovation system (see Section 16.3) there is a large quantitative and qualitative literature aiming to identify such impact.

16.4.4.1 Assessment of the impact on innovation of technology push policy instruments: public RD&D investments, other R&D incentives and public procurement

Economic and direct investment policy instrument types are typically associated with a direct focus on technological innovation: 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.

Public RD&D investments have been found to have a positive impact on different innovation in energy and climate related technologies (*robust evidence, high agreement*), but the assessment relies almost entirely on evidence from industrialised countries. Out of 17 publications focussing on this assessment, only three found no relationship between R&D funding and innovation metrics (Peñasco et al. 2021; Goldstein et al. 2020; Doblinger et al. 2019). Sixteen out of them *used ex post* quantitative methods and one relied on theoretical *ex ante* assessment; only two of them included some non-industrialised countries, with one being the theoretical analysis. The evidence available does not point to public R&D funding for climate-related technologies crowding out private R&D (an important driver of innovation) but instead crowding it in. Box 16.6 summarizes the evidence available of the impact of ARPA-E (a public institution created in the United States in 2009 to allocate public R&D funding in energy) on innovation and competitiveness outcomes. Another institution supporting energy R&D that is the subject of much interest is the Fraunhofer Institute.

No evidence regarding the specific impact of R&D tax credits on climate mitigation or adaptation technologies has been found, but it is worth noting that generally speaking, R&D tax credits are found to incentivize innovation in firms in general, with an greater impact on small and medium firms (OECD 2020). This is consistent with the fact that most of the evidence on the positive impact of public R&D support schemes covers small and medium firms (Howell 2017; Doblinger et al. 2019; Goldstein et al. 2020). Although there is a high level of agreement in the literature regarding the impact of R&D

investments on innovation outcomes in climate-related technologies, it is important to note that this evidence comes from industrialised countries. This does not mean that public R&D investments in energy have been found to have no impact on developing countries innovation or competitiveness outcomes, but rather that we were not able to find such studies focussing on developing countries.

Overall, public procurement has high potential to incentivise innovation in climate technologies, but the evidence is mixed, particularly in developing countries (*limited evidence, medium agreement*). Public procurement accounted for 13 % of gross domestic products in OECD in 2013 and much more in some emerging and developing economies (Baron 2016). Its main goal is to acquire products or services to improve public services, infrastructures and facilities and, in some cases, to also incentivize innovation. It is important to implement several steps in the public procurement procedure to improve transparency, minimise waste, fraud and corruption of public fund. These steps range from the assessment of a need, issuance of a tender to the monitoring of delivery of the good or service. Box 16.5 outlines a public procurement program that was implemented in The Netherlands in 2005 with a focus on green technologies. In spite of the fact that green procurement policies have been implemented, the literature assessing the innovation impact of public procurement programs is relatively limited and suggests either a positive impact or no impact (Peñasco et al. 2021; Alvarez and Rubio 2015; Fernández-Sastre and Montalvo-Quizhpi 2019; Baron 2016). The majority of cases where the impact is positive are analyses of industrialised countries, while no impact emerges in the case of a developing country (Ecuador). More empirical research is needed to understand the impact of public procurement, which has the potential to support the achievement of other societal challenges (Edler and Georghiou 2007; Henderson and Newell 2011; ICLEI 2018; Baron 2016) in both developing and developed countries.

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Box 16.5 Green Public Procurement in The Netherlands

In 2005, the Dutch national government acknowledged a move in the House of Representatives to utilise their annual spending power to promote the market for sustainable goods and services as well as to play as a role model. Hence, a policy for environmentally friendly procurement was developed and implemented across the national, local and provincial governments. Subsequently, sustainable public procurement has expanded into a multidimensional policy in the Netherlands, accommodating policies on green public procurement, bio-based public procurement, international social criteria, social return on investment, innovation-oriented public procurement and circular economy.

The Green Public Procurement (GPP) policy is targeted at minimising the negative impacts of production and consumption on the nature environment (Melissen and Reinders 2012; Cerutti et al. 2016). It includes a wide range of environmental criteria for different product groups that public organisations frequently procure such as office equipment, uniforms, road works and catering. There are 45 product groups (Melissen and Reinders, 2012) and 6 product clusters part of the government's purchasing in terms of sustainability(PIANOo Expertisecentrum 2020). The six product clusters are: i) Automation & telecommunications, ii) Energy, iii) Ground, road & hydraulic engineering, iv) Office facilities and services, v) Office buildings, and vi) Transport (PIANOo Expertisecentrum 2020).The GPP 2020 Tender Implementation Plan spells out the terms and conditions for making their green public procurement. Some of these are confidential documents and are not shared online. Others are available for download. The tender implementation plan for the Netherlands is available on https://gpp2020.eu/low-carbon-tenders/open-tenders/. One of the important scenarios is that the public procurers need the details of LCA analysis carried out in a tool called DuboCalc which calculates the environmental impacts of the materials and methods of an infrastructural projects. GPP 2020 has reported that three million tonnes of CO_2 would be saved in the Netherlands alone if all Dutch public authorities applied the national Sustainable Public Procurement Criteria.

Research has been carried out to determine the prime mover for implementing Green Public Procurement. An online survey of was administered among public procurement officers that subscribed to the newsletters of two Dutch associations that provide advice and training to public procurers, yielding a sample size of over 200 (Grandia and Voncken 2019). The first association is called NEVI which is the only organisation in the Netherlands that offers certified procurement training programmes. The second association is called PIANOo which is a public procurement expertise centre paid by the Dutch national government for bringing together relevant information regarding public procurement and providing public procurers with useful tools through their websites, workshops, meetings and annual conferences. The data from the survey was then analysed using structural equations modelling (SEM) and the results show that ability, motivation and opportunities affect the implementation of GPP. Particularly, opportunity was found to affect green public procurement, innovation-oriented public procurement and circular economy but not the other types of public procurement.

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16.4.4.2 Assessment of the impact on competitiveness of technology push policy instruments: public RD&D investments, other R&D incentives and public procurement

Public R&D investments in the energy, renewables, environment space are generally associated with positive impacts on industrial development or 'competitiveness outcome' (*robust evidence, medium agreement*). In a number of cases negligible or negative impacts emerge (Peñasco et al. 2021; Goldstein et al. 2020; Doblinger et al. 2019). The majority of these 15 analyses rely on *ex post* quantitative methods, while only four use *ex ante* modelling approaches. Also, in this case, the vast majority of the evidence is from industrialised countries.

There is limited and mixed evidence regarding the (positive or negative) impact of public procurement for low-carbon or climate technologies and it emerges from developed countries (*limited evidence, low agreement*). All of the four evaluations identified in the Peñasco et al (2021) review relied on qualitative methods. One found a positive impact, another a negative impact and two others found no impact. All of the studies covered European country experiences.

R&D and procurement policies have a positive impact on distributional outcomes (*limited evidence, high agreement*). Peñasco et al (2021) 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).

16.4.4.3 Emerging insights on different public R&D and demonstration funding schemes

The ability of a given R&D policy instrument to impact innovation and competitiveness depends to some extent on policy design features (*limited evidence, high agreement*). As discussed in section 16.4.4.4, this is not unique to R&D funding. Most of these assessments use a limited number of indicators (e.g., patents and publications and follow-on private financing, firm growth and survival, respectively), focusses on the energy sector and on the US and other industrialised countries. Extrapolating to emerging economies and low-income countries is difficult. There is no evidence on the impact of different ways of allocating public energy R&D investments in the context of developing countries.

Block funding, which tends to be more flexible, can lead to research that is more productive or novel, but there are other factors that can affect the extent to which block funding can lead to more or less novel outcomes (*limited evidence, medium agreement*). Research on national research laboratories, which conduct at least 30% of all research in 68 countries around the world (Anadon et al. 2016a), are a widespread mechanism to carry out public R&D and allocate funds, but assessments of their performance is limited to developed countries. R&D priorities are also guided by institutions, and research focussed on general technology innovation policy finds that institutions often do not embody the goals of the poor or marginalized (Anadon et al. 2016b).

In the case of the US Department of Energy, block funding that can be quickly allocated to novel l projects (such as that allocated to National Labs as part of the Laboratory Directed Research and Development—LDRD—funding) has been found to be associated with improved innovation indicators (Anadon et al. 2016a). Research on Japan on R&D funding in general (not for climate-related technologies) however, indicates that R&D funds allocated competitively result in higher novelty for 'high status' (the term used in the paper to refer to senior male researchers), while block funding was associated with research of higher novelty for lower status researchers (e.g., junior female researchers) (Wang et al. 2018).

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Box 16.6 ARPA-E a novel R&D funding allocation mechanism focussed on an energy mission

One approach for allocating public R&D funds in energy involves relying on active program managers and having clear technology development missions that focus on high-risk high-reward areas and projects. This approach can be exemplified by a relatively new energy R&D funding agency in the US, the Advanced Research Projects Agency for Energy (ARPA-E). This agency was created in 2009 and it was modelled on the experience of DARPA (a US government agency funding high risk high reward research in defence-related areas (Bonvillian and Van Atta 2011; Bonvillian 2018; U.S. National Academies of Sciences Engineering and Medicine 2017). DARPA program managers had a lot of discretion for making decisions about funding projects, but since energy R&D funding is usually more politically vulnerable than defence R&D funding, the ARPA-E novel involved program managers requesting external review as an informational input (Azoulay et al. 2019).

Like DARPA, ARPA-E program managers use an 'active management approach that involves empowering program manages to make decisions about funding allocation, milestones and goals. ARPA-E managers also differ from other R&D allocation mechanisms in that ARPA-E staff retained some control on the funded projects after the allocation of the funds. As argued by (Azoulay et al. 2019), even though this relative control over the project can result in a reduction in the flexibility of funded researchers, some 'exploration' happens at the program manager level.

Research on ARPA-E also sheds light on how program managers make decisions about what projects to fund: about the process of project selection. Program managers do not just follow the rankings of peer reviewers (sometimes projects with very disparate rankings were funded) and in many cases program managers reported using information from review comments instead of the rankings (Goldstein and Kearney 2020). Azoulay et al. (2019) suggest that if expert disagreement is a useful proxy for uncertainty in research, then the use of individual discretion in ARPA-E would result in a portfolio of projects with a higher level of uncertainty, as defined by disagreement among reviewers. Moreover, under the premise that uncertainty is a corollary to novelty, individual discretion is an antidote to novelty bias in peer review.

While innovation is notoriously hard to track and, particularly for emerging technologies, it can take a lot time to assess, early analysis has shown that this mission-orientation and more 'actively managed' R&D funding program may yield greater innovation patenting outcomes 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; U.S. National Academies of Sciences Engineering and Medicine 2017). In addition research analysing the first cohort of cleantech start-ups has found that start-ups supported by ARPA-E had more innovative outcomes when compared to those that had applied but not received funding, with others that had not received any government support, and with others that had received other types of government R&D support (Goldstein et al. 2020). Overall, the mission-oriented ARPA approach has been successful in the United States when it comes to innovation outcomes. The extent to which it can yield the same outcomes in other geographies with different innovation and financing environments remains unknown. (*limited evidence, high agreement*).

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Public financing for R&D and research collaboration in the energy sector is important for small firms, at least in industrialised countries, and it does not seem to crowd out private investment in R&D (*medium evidence, high agreement*). Small US and UK firms accrue more patents and financing when provided with cash incentives for R&D in the form of grants (Pless 2019; Howell 2017). US cleantech start-ups which partner with government partners for joint technology development or licensing partnerships accrue more patents and follow on financing (Doblinger et al. 2019).

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 organisations; focussing demonstration projects on learning; incentivising international collaboration in energy research; adopting an adaptive learning strategy; and making funding stable and predictable (Narayanamurti and Odumosu 2016; Narayanamurti et al. 2009; Chan et al. 2017) (*medium evidence, high agreement*).

Without carefully designed public funding for demonstration efforts, often in a cost shared manner with industry, the experimentation at larger scales needed for more novel technologies needed for climate change mitigation may not take place. (*medium evidence, high agreement*). Government funding specifically for technology demonstration projects, for RD&D (research, development and demonstration) in energy technologies plays a crucial supporting role (Section 16.2.1). Governments can facilitate knowledge spill-overs between firms, between countries, and between technologies (see Section 16.2, Cohen et al (2002) and Baudry and Bonnet (2019)).

16.4.4.4 Assessment of the impact on innovation and on competitiveness and distributional outcomes of market pull policy instruments

Demand pull policies such as tradeable green certificates, taxes, or auctions, are essential to support scaling up efforts (Remer and Mattos 2003; Nahm and Steinfeld 2014; Wilson 2012). Just like for R&D investments, research has indicated that effective demand pull needs to be credible, durable, and aligned with other policies (Nemet et al. 2017) and that the effectiveness of different demand pull instruments depends on policy design (del Río and Kiefer 2021). Historical analyses of the relative importance of demand pull and technology push are clear; both are needed to provide robust incentives for investment in innovation. Interactions between them are central as their combination enables innovators to connect a technical opportunity with a market opportunity (Grubler and Wilson 2013; Freeman 1995b; Jacobsson et al. 2004). It is important to note that these market pull policies are often put in place primarily to meet security and/or environmental goals, although innovation and competitiveness are sometimes also pursued explicitly.

Emission Trading Schemes

Overall evidence suggests that the emissions trading schemes, as currently designed, have not significantly contributed to innovation outcomes (*medium evidence, medium/high agreement*).

Penasco et al. (2021) review 20 evaluations: eight identified a positive impact (although in at least two cases the paper indicated the impact was small or negligible), 11 no impact and one was associated with a negative impact on innovation indicators. The studies that found no impact and the studies that found some impact covered all three methods covered (quantitative *ex post*, qualitative and theoretical and *ex ante* analysis). Another review focussed only on empirical studies (mainly quantitative but also qualitative), covered a slightly longer period and identified 19 studies (15 using quantitative methods) (Lilliestam et al. 2021). With a narrower set of indicators of innovation, they concluded there was very little empirical evidence linking the emissions trading schemes studied to date and innovation (Lilliestam et al. 2021). This review focussed mainly on papers evaluating the earlier stages of the European Emissions Trading Scheme, which featured relatively low CO_2 prices and covered a small set of firms, showing that carbon pricing policy design is an important determinant of innovation outcomes. Combining both reviews, there are a total of 27 individual studies, some of them providing mixed evidence of impact, and 23 of them suggest there was no impact or (in a couple of cases) it was small. It is important to note that some researchers note that, for particular subsectors and actors, emissions trading schemes have had an impact on patenting trends (Calel and Dechezleprêtre 2016). Overall the expectation is that higher prices and coverage would result in higher impacts and that, over time, the impact on innovation would grow.

Carbon and environmental taxes

The impact of carbon taxes on innovation outcomes is more positive than that for ETS schemes but the evidence is more limited (*limited evidence, medium agreement*). Assessments of their impact on innovation metrics have been very limited, with only four studies (three quantitative and one *ex ante*). Three of the studies found a positive impact of carbon taxes on innovation outcomes and one found no impact (Peñasco et al. 2021).

Depending on the design (including the value and coverage of the tax), carbon taxes can either have positive, negative or null impact on competitiveness and distributional outcomes (*medium evidence, medium agreement*). The evidence on the impact of carbon taxes on competitiveness is significant (a total of 27 evaluations) and mixed, with six of them reporting some positive impacts, ten reporting no impact, and 11 reporting negative impacts (so 59% were not associated with negative impacts). Most of the evaluations reporting negative impacts were theoretical assessments, and only three *ex post* quantitative analysis (Peñasco et al. 2021). 24 evaluations covered distributional impacts of carbon taxes and other environmental taxes and the majority (15) found the existence of some negative distributional impacts, six found positive impacts and three no distributional impacts. Differences in the result of the assessments stem from the design of the taxes (Peñasco et al. 2021). It is important to note that, once again, the evidence comes from industrialized countries and emerging economies.

Feed-in-Tariffs

Many factors affect the impacts of feed in tariffs on outcomes other than innovation (*robust evidence, high agreement*). While FITs have been generally associated with positive innovation outcomes, some of the differences found in the literature may arise from differences in the evaluation method (Peñasco et al. 2021) or differences in 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. 2016b), and the geographical and temporal context of where the policy was put in place (Section 16.3). Research has also found that, particularly for less mature technologies, a higher technology specificity in the design of FITs is associated with more innovation (Del Río 2012). Feed-in-tariffs yield better results if they account for the specificities of the country; else, the technology and the policy could result in negative distributional and (to a lesser extent) competitiveness impacts. Meckling et al (2017) indicate that an 'enduring challenge' of technology-specific industrial policy such as some feed-in-tariffs is to avoid locking in suboptimal clean technologies—a challenge which, among other options, could be overcome with targeted niche procurement for next generation technologies.

Other authors have cautioned that the move from renewable feed-in-tariffs to auctions may favour existing PV (e.g., polysilicon) over more novel solar power technologies (Sivaram 2018b) such as thin-film PV, amorphous PV, and perovskites.

Policy design, policy mixes, and domestic capacity and infrastructure are important factors determining the extent to which economic policy instruments in industrialised countries and emerging economies can also lead to positive (or at least not negative) competitiveness outcomes and distributional outcomes (*medium evidence, medium agreement*) (Section 16.3). Prioritising low cost energy generation in the design of FIT schemes can result in a lower focus of innovation efforts on more novel technologies and greater barriers to incumbents in less mature technologies (Hoppmann et al. 2013). Similarly, case study research from Mexico and South Africa indicates that focusing on low-cost renewable energy generation only can result in a greater reliance on existing foreign value chains and capital, and thus in lower or negative impacts on domestic competitiveness—in other words, some approaches can hinder the development of the local capabilities that could result in greater long-term benefits domestically (Matsuo and Schmidt 2019). Evidence for developing countries indicates 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).

Energy auctions

The evidence of the impact of renewable energy auctions on innovation outcomes is very small and provides mixed results *(limited evidence, low agreement*). Out of six evaluations, three of them identify positive impacts, two no impacts, and one negative impacts. All of the evaluations but one were qualitative or theoretical and the quantitative assessment indicated no impact (Peñasco et al. 2021). There is more evidence covering emerging economies analysing the impacts of auctions when compared to other policy instrument types. For example, there is work comparing the approaches to renewable energy auctions in South Africa and Denmark (Toke 2015) finding a positive impact on the latter stages of innovation (mainly deployment), and broader work on auctions covering OECD countries as well as Brazil, South Africa and China not finding a significant impact on innovation (Wigand et al. 2016), and work comparing renewable energy auctions in different countries in South America finding generally a positive impact on innovation outcomes (Mastropietro et al. 2014). The body of evidence on the impact of auctions on competitiveness is also limited (six evaluations) and indicates negative outcomes of renewable auctions of competitiveness (*limited evidence, low agreement*). As with other policies, the design of the auctions can affect innovation outcomes (del Río and Kiefer 2021). Only two studies investigated distributional outcomes and both were negative.

Other financial instruments

There is no explicit literature on the ability of green public banks, and targeted loans, and loan guarantees to lead to upstream innovation investments and activities, although there is evidence on their role in deployment (see e.g. Geddes et al (2018)). This notwithstanding the key role of these institutions in the innovation system (Sections 16.2.1 and 16.3) (OECD 2015c; Geddes et al. 2018) and the belief that they can de-risk scale-up and the testing of business models (Probst et al. 2021; Geddes et al. 2018) (see Chapter 17).

Renewable obligations with tradeable green certificates

There is mixed evidence of the impact of tradeable green certificates (TGCs) on innovation (*limited evidence, low agreement)* and competitiveness (*limited evidence, low agreement)*. Out of the 11 evaluations in Peñasco et al (2021), six found no impact, two a positive impact, and three a negative impact. All of them used a qualitative research approach. Of the six studies focusing on competitiveness outcomes, three conclude TGCs have had no impact on competitiveness, while two indicate negative impact and one a positive impact. Only one of the studies was quantitative and did not identify an impact on competitiveness.

TGC are associated with the existence of negative distributional impacts in most applications (*medium evidence, high agreement*). Ten out of 12 studies identify the existence of some negative impacts. All but one of these studies (which focussed on India) are based on analysis of policies implemented in industrialised countries.

Clean Energy and renewable Portfolio Standards
The impact of renewable portfolio standards without tradeable credits on innovation outcomes is negligible or very small (*medium evidence, medium agreement*). Out of the nine studies, seven reported no impact on innovation outcomes and two a positive impact (Peñasco et al. 2021). Most of these papers focussed on patenting and private R&D innovation indicators and not cost reductions. Impact on competitiveness is found to be negligible or positive (*limited evidence, medium agreement*). Out of eight evaluations, five report positive impact and three negligible impact; only two are quantitative studies (Peñasco et al. 2021). Negative distributional impacts from renewable portfolio standards can emerge in some cases (*limited evidence, low agreement*). Out of eight evaluations, four identified positive impacts, and four negative impacts; all of the studies identifying a positive impact were theoretical. There are efforts focussed on clean energy portfolio standards which include technologies beyond renewables.

Efficiency obligations with tradeable credits
The impact of tradeable white certificates in innovation is largely positive, but the evidence is limited (*limited evidence, medium/high agreement*). Out of four evaluations, only one of which was quantitative, three report positive impact and one no impact (Peñasco et al. 2021). The impact of white certificates on competitiveness is positive (*limited evidence, high agreement*) while that on distributional outcomes is very mixed (*limited evidence, low agreement*). Two theoretical studies report positive competitiveness impacts. Out of 11 evaluations of distributional outcomes, eight rely on theoretical *ex ante* approaches. Seven evaluations reported positive impacts (four of them using theoretical methods), three of them (using theoretical methods) indicated negative impacts and one of them no impact.

Building codes
There is evidence of the impact of building codes on innovation outcomes (Peñasco et al. 2021). Only two studies assessed competitiveness impacts (one identifying positive impacts and one negligible ones) and three studies identifying distributional impacts, all positive.

Overall, the evidence on the impact of the market pull policy instruments covered in Section 16.4.4.4 when it comes to the competitiveness outcome (at least in the short term) is more mixed. For some of them, the evidence of a positive impact on innovation is more consistent than the others (for carbon taxes or FITs, for example). Peñasco et al (2021) found that the disagreements in the evidence regarding the positive, negative or no impact of a policy on competitiveness or distributional outcomes can often 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.

16.4.4.5 Assessment of the impact on innovation, competitiveness and distributional outcomes of regulatory policy instruments targeting efficiency improvements

There is medium evidence that the introduction of flexible, performance-based environmental regulation on energy efficiency in general (e.g., efficiency standards) can stimulate innovative responses in firms (Ambec et al. 2013; Popp 2019) *(medium evidence, high agreement)*. Evidence comes from both observational studies that examine patenting, R&D or technological responses to regulatory interventions, and from surveys and qualitative case studies in which firms report regulatory compliance as a driving force for the introduction of environmentally-beneficial innovations (Grubb et al. 2021). While the literature examining the impact of environmental regulation on innovation is large, there have been fewer studies on the innovation effects of minimum energy or emissions performance regulations specifically relating to climate mitigation. We discuss in turn two types of efficiency regulations: on vehicles, and on appliances.

Relationship between automotive efficiency regulations and innovation

The announcement, introduction and tightening of vehicle fleet efficiency or GHG emission standards either at the national or sub-national level positively impacts innovation as measured by patents (Barbieri 2015) or vehicle characteristics (Knittel 2011; Kiso 2019) as summarised in a review by Grubb et al (2021). Detailed studies on the innovation effects of national pollutant (rather than energy) regulations on automotive innovation also indicate that introducing or tightening performance standards has driven technological change (Lee et al. 2010). Some studies in the US that examine periods in which little regulatory change took place have found that the effects of performance standards on fuel economy have been small (Knittel 2011) or not significant relative to the innovation effects of prices (Crabb and Johnson 2010). This is at least in part because ongoing efficiency improvements during this period were offset by increases in other product attributes. For example, Knittel (2011) study observed that size and power increased without a corresponding increase in fuel consumption. It has also been observed that regulatory design may introduce distortions that affect automotive innovation choices: in particular, fuel economy standards based on weight classes have been observed to distort light-weighting strategies for fuel efficiency in both China (Hao et al. 2016) and Japan (Ito and Sallee 2018).

A number of studies have focused on the impacts of a sub-national technology-forcing policy: the California Zero Emission Vehicle (ZEV) mandate. When it was introduced in 1990, this policy required automotive firms to ensure that 2% of the vehicles they sold in 1998 would be zero emissions. In the years immediately after introduction of the policy, automotive firms reported that it was a significant stimulus to their R&D activity in electric vehicles (Brown et al. 1995). Quantitative evidence examining patents and prototypes has indicated that the stringency of the policy was a significant factor in stimulating innovation, though this was in part dependent on firm strategy (Sierzchula and Nemet 2015). Like in the previous instruments, most of the evidence comes from industrialised countries and additional research on other countries would be beneficial.

Relationship between appliance efficiency standards and innovation

Regulation-driven deployment of existing technologies can generate innovation in those technologies, through learning-by-doing, induced R&D and other mechanisms, although not in all cases (Grubb et al. 2021) *(medium evidence, medium agreement)*. The introduction or tightening of minimum energy performance standards for appliances (and in the case of Noailly (2012) for buildings) have driven innovation responses, using direct measures of product attributes (Newell et al. 1999) and patents (Noailly 2012; Kim and Brown 2019), though not all studies have found a significant relationship (Girod et al. 2017). There is also evidence of a correlation between regulation-driven deployment of energy-efficient products with accelerated learning in those technologies (Van Buskirk et al. 2014; Wei et al. 2017).

In addition to observational studies, evidence on the relationship between innovation and regulation comes from surveys in which survey respondents are asked whether they have engaged in innovation leading to energy saving or reduced GHG emissions, and what the motivations were for such innovation. Survey evidence has found that expected or current regulation can drive both R&D investment and decisions to adopt or introduce innovations that reduce energy consumption or CO_2 emissions (Horbach et al. 2012; Grubb et al. 2021). Survey-based studies, however, tend not to specify the type of regulation.

Competitiveness and distributional impacts associated with vehicles and appliance performance standards

Minimum energy performance standards and appliance standards have been known to result in negative distributional impacts *(limited evidence, medium/high agreement*). Several studies focused on the US have highlighted that minimum energy performance standards for vehicles tend to be regressive, with poorer households disproportionately affected (Levinson 2019; Jacobsen 2013), particularly when second-hand vehicles are taken into account (Davis and Knittel 2019). Similar arguments, though with less evidence, have been made for appliance standards (Sutherland 2006).

Overall, the extent to which regulations in energy efficiency result in positive or negative competitiveness impacts in firms is mixed (*limited evidence, high disagreement*). A meta-analysis of 107 studies, of which 13 focused on regulations relating to energy consumption or GHG emissions, found that around half showed that regulations resulted in competitiveness impacts, while half did not (Cohen and Tubb 2018). Cohen and Tubb (2018) also found that studies examining performance-based regulations were less likely to find positive competitiveness impacts than those that examined market-based instruments.

Insights into causal mechanisms and co-evolutionary dynamics from case studies on efficiency regulations

While most of the literature addresses the extent to which regulation can induce innovation, a number of case studies highlight that innovation can also influence regulation, as the costs of imposing regulation are reduced and political interests emerge that seek to exploit competitive advantages conferred by successfully developing energy-efficient or low-carbon technologies (*medium evidence, high agreement*). Case studies map the causal mechanisms relating regulations and innovation responses in specific firms or industries (Ruby 2015; Wesseling et al. 2015; Kemp 2005; Gann et al. 1998).

16.4.4.6 Assessment of the impact on innovation and on competitiveness and distributional outcomes of soft instruments

Energy labels and innovation

The literature specifically focusing on the impacts of labels is very limited and indicates positive outcomes (*limited evidence, high agreement).* Energy labels may accompany a minimum energy performance standard and the outcomes of these policies are often combined in literature (IEA 2015). But again, given the limited evidence more research is needed. Although there are many studies on energy efficiency more broadly and for both standards and labels, only eight studies specifically focus on labels. Furthermore, seven of them report positive outcomes and one negative outcomes. Six of the studies used qualitative methods mentioning the impacts of labelling on the development of new products (Wiel et al. 2006). Research specifically comparing voluntary labels with other mechanisms found a significant and positive relationship between labels and the number of energy-efficient inventions (Girod et al. 2017). More research is needed especially in developing countries that have extensive labelling programs in place, and also with quantitative methods, to develop evidence on the impacts of labelling on innovation. Box 16.7 discusses an example of a combination of policy instruments in China including labelling, bans and financial support.

START BOX 16.7 HERE

Box 16.7 China Energy Labelling Policies, combined with sale bans and financial subsidies

From 1970 to 2001, China was able to significantly limit energy demand growth through energy-efficiency programs. Energy use per unit of gross domestic product (GDP) declined by approximately 5% yr^{-1} during this period. However, between 2002 and 2005, energy demand per unit of GDP increased on average by 3.8% yr^{-1}. To curb this energy growth, in 2005, the Chinese government announced a mandatory goal of 20% reduction of energy intensity between 2006 and 2010 (Zhou et al. 2010; Lo 2014).

An Energy Labelling System was passed in 2004. It requires the manufacturers to provide information about the efficiency of their electrical appliances to consumers. From 2004 to 2010, 23 electrical appliances (including refrigerators, air conditioners and flat-screen TVs) being labelled as energy efficient with 5 different grades, with Grade 1 being the most energy efficient and grade 5 the least efficient. Any appliances with an efficiency grade higher than 5 cannot be sold in the market.

In addition to providing information to consumers, the National Development Reform Commission, which was in charge of designing the policies, and the Ministry of Finance launched in 2009 the "energy-saving products and civilian-benefiting project" (Zhan et al. 2011). It covered air conditioners, refrigerators, flat panel televisions, washing machines, electrical efficient lighting, energy saving and new energy vehicles with the energy grades at 1 or 2 and it consisted of financial subsidies for enterprises producing these products. The standard design of these financial subsidies involved the government paying for the price difference of energy efficiency products and general products. The manufacturers which produce the energy efficient products can get the financial subsidies directly from the government (Wang et al. 2017b).

Before 2008, the market share of grade 1 and grade 2 air conditioners was about 5%, and about 70% of all air conditioners were grade 5 (the most inefficient). Driven by the financial subsidies, the selling price of the highly efficient air conditioners became competitive with that of the general air conditioners. Hence, the sales of energy efficient air conditioners increased substantially, making the market share of air conditioners at grade 1 and 2 to be about 80% in 2010 (Wang et al. 2017b). According to the information from energy efficiency labelling management centre of China National Institute of Standardisation, under the energy label system implemented 5 years ago, more than 1.5 hundred billion kWh power was saved by March 2010, equivalent to more than 60 million tons of standard coal, 1.4 billion tons of carbon dioxide emissions, and 60 tons of sulphur dioxide emissions (Zhan et al. 2011), which significantly contributed to energy saving goals of the 11th Five-Year Plan.

END BOX 16.7 HERE

Voluntary approaches and innovation

Voluntary approaches have a largely positive impact on innovation for those that choose to participate (*robust evidence, medium agreement*). Research on voluntary approaches focuses on firms adopting voluntary environmental management systems that can be certified based on standards of the widely adopted International Standards Organisation (ISO 14001) or the European Union Environmental Management and Auditing Scheme (EMAS), which is partly mandatory today. Out of 16 analyses, 70% report positive innovation outcomes in terms of patents, or product and process innovation. 17% report negligible impacts and 13% report negative impact. Positive innovation outcomes have been linked to firms' internal resource management practices and were found to be strengthened in firms with mature environmental management systems and in the presence of other environmental regulations (He and Shen 2019; Inoue et al. 2013; Li et al. 2019a). Overall, studies are concentrated in a few countries that do not fully capture where environmental management systems have been actually adopted (Boiral et al. 2018). There is a need for research in analyses of such instruments in emerging economies including China and India, and methodologically in qualitative and longitudinal analyses (Boiral et al. 2018).

Competitiveness and distributional outcomes of soft instruments

The outcomes for performance or endorsement labels have been associated with positive competitiveness outcomes *(medium evidence, medium agreement).* Out of 19 studies, 89% report positive impact and 11% negligible impact. Although there are several studies analysing competitiveness related metrics, evidence on most individual metrics is sporadic, except for housing premiums. A large number of studies quantitatively assessing competitiveness find that green labels in buildings are associated with housing price premium in multiple countries and regions (Fuerst and McAllister 2011; Kahn and Kok 2014; Zhang et al. 2017). 32% of the studies were qualitative, associating appliance labelling programs with employment and industry development (European Commission 2018). There is a research gap in analyses of developing countries, and also in quantitatively assessing outcomes beyond housing price premiums.

A few studies on the distributional outcomes of voluntary labelling programs point to positive impacts *(limited evidence, high agreement).* All four studies focusing benefits for consumers and tenants, report positive impacts (Devine and Kok 2015). Although there are benefits for utilities and other stakeholders, more research is needed specifically attribute these benefits to voluntary labels rather than energy efficiency programs in general.

Voluntary agreements are associated with positive competitiveness outcomes *(medium evidence, medium agreement)*, 14 out of 19 evaluations identified were associated with positive outcomes while three were associated with negligible outcomes, and two with negative outcomes. Research found an increase in perceived firm financial performance (de Jong et al. 2014; Moon et al. 2014). Studies also show an association with higher exports as more environmentally conscious trade partners increasingly value environmental certifications (Bellesi et al. 2005). More research is needed to develop evidence on metrics of competitiveness besides firms' financial performance, and especially in developing countries.

Voluntary agreements are associated with a positive impact on distributional outcomes *(limited evidence, high agreement)*. Five studies, mainly using qualitative approaches, report a positive association between a firm adopting an environmental management system and impacts on its supply chains. There is a need for more studies with quantitative assessments and geographical diversity.

16.4.4.7 Summary of the size and direction of the evidence of all policy instrument types on innovation outcomes

Positive impacts have been identified more frequently in some policies than in others. There is also a lot of variation in the density of the literature. Developing countries are severely underrepresented in the decarbonisation policy instrument evaluation literature aiming to understand the impact on innovation. (*high evidence, high agreement).*

Figure 16.2 below indicates the extent to which some decarbonisation policy instruments have been more or less investigated in terms of their impact on innovation outcomes as described in Table 16.9 above. For example, it indicates the extent to which there has been a greater focus of evaluations of the impact of R&D investments, emissions trading schemes and voluntary approaches on innovation. It also shows a limited amount of evidence on procurement, efficiency obligations with tradeable green certificates (TGCs), building codes and auctions.

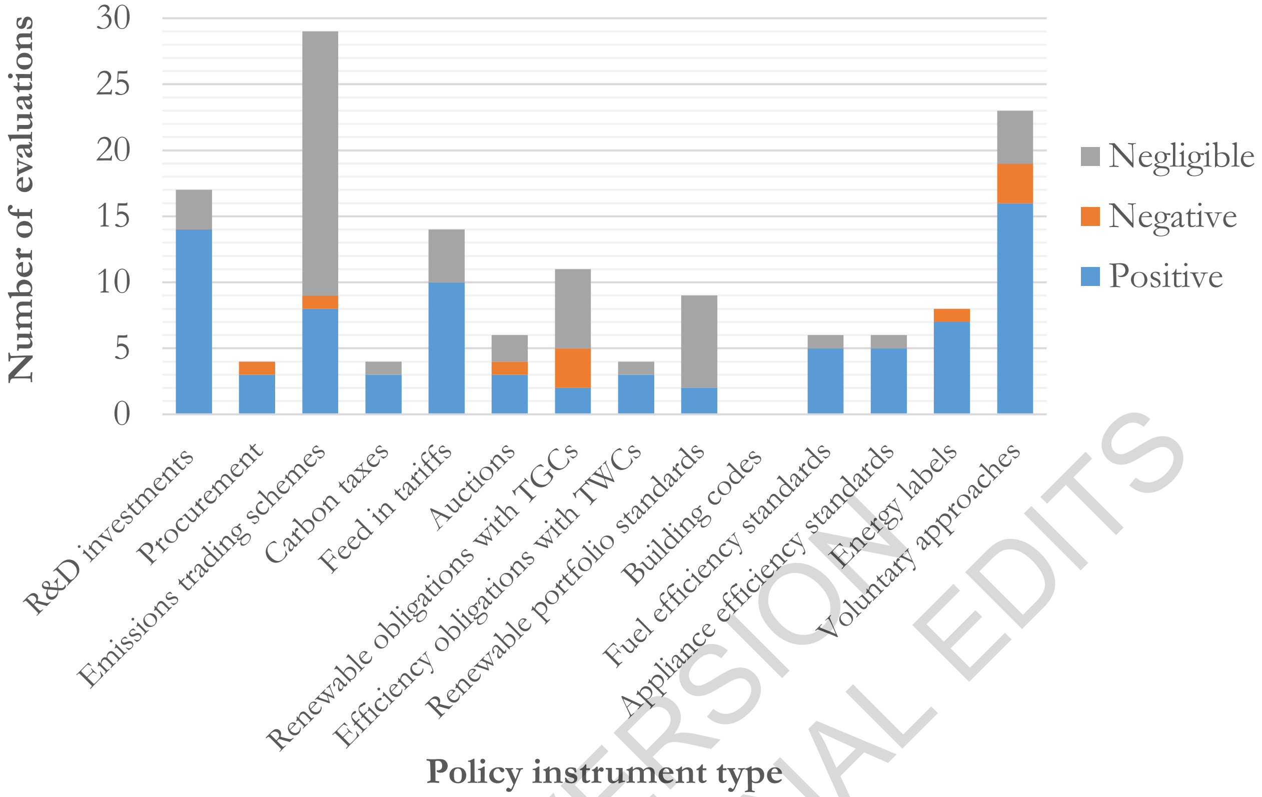


Figure 16.2 Number of evaluations available for each policy instrument type covered regarding their impact on innovation and direction of the assessment. The vertical axis displays the number of evaluations claiming to isolate the impact of each policy instrument type on innovation outcomes as listed in Table 16.9. The colour indicates whether each evaluation identified a positive impact on the innovation outcome (blue), the existence of a negative impact (in orange), and no impact (in grey). It builds on Peñasco et al (2021), Grubb et al (2021), Lilliestam et al (2021) and additional studies identified as part of these reviews. TGC stands for tradeable green certificates. TWC stands for tradeable white certificates.

16.4.5 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. This section does not cover the much larger body of evidence on the relationship between FDI and economic development and growth.

Overall, research indicates that trade can facilitate the entrance of new technologies, but the impact on innovation is less clear (*limited evidence, low agreement*). A recent study 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. 2019b). One analysis on China links FDI not just with improved environmental performance and energy efficiency 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 spill-overs (Newman et al. 2015). In addition, Brandão and Ehrl (2019) indicate that productivity of the electric power industry is more influenced by the transfer of embodied technology from other industries than by investments of the power industry and that countries with high R&D stocks are the main sources of these international technology spillovers and that the source countries may also benefit from the spillover.

Other emerging work investigates the role of local content requirements on innovation outcomes and suggests that it can lead to increased power costs (negative distributional impacts) and the domestic innovation system benefits, measured by patents or exports are unclear if the policies are not part of a holistic and longer lasting policy framework (Probst et al. 2020).

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

Virtually all countries around the world have instituted systems for the protection of creations and inventions, known as Intellectual Property (IP) rights systems (WIPO 2021). While several types of intellectual property exist – patents, copyright, design rights, trademarks, and more –, this section will focus on patents, as the most relevant property right for technological innovations (World Intellectual Property Organization 2008), and hence the most relevant for policy instruments in this context.

Patent systems aim to promote innovation and economic growth, by stimulating both the creation of new knowledge and diffusion of that knowledge (*high evidence, high agreement*). National patent systems, as institutions, play a central role in theories on national innovation systems (*high evidence, strong agreement).* Patent systems are usually instituted to promote innovation and economic growth (Nelson and Mazzoleni 1996; Machlup and Penrose 1950; Encaoua et al. 2006). Some countries explicitly refer to this purpose in their law or legislation – for instance, the US Constitution states the purpose of the US IP rights system to "promote the progress of science and useful arts". Patent systems aim to reach their goals by trying to strike a balance between the creation of new knowledge and diffusion of that knowledge (Scotchmer and Green 1990; Devlin 2010; Anadon et al. 2016b). They promote the creation of new knowledge (e.g. technological inventions) by providing a temporary, exclusive right to the holder of the patent, thus providing incentives to develop such new knowledge and helping parties to justify investments in research and development. They promote the diffusion of this new knowledge via the detailed disclosure of the invention in the patent publication, and by enabling a 'market for knowledge' via the trading of patents and the issuance of licenses (Arora et al. 2004). Although IP protections provide incentives to invest in innovation, they have the double effect of restricting the use of new knowledge by raising prices or blocking follow-on innovation (Stiglitz 2008; Wallerstein et al. 1993). National patent systems, as institutions, feature prominently in models and theories of National Innovation Systems (Edquist 1997; Klein Woolthuis et al. 2005).

The degree to which patent systems actually promote innovation is subject to debate. Patent protection has been found to have a positive impact on R&D activities in patent-intensive industries, but this effect was found to be conditional on access to finance (Maskus et al. 2019). Patents are believed to be especially important to facilitate innovation in selected areas like pharmaceuticals, where investments in developments and clinical trials are high, imitation costs are low, and there is often a 1:1 relationship between a patent and a product, referred to as a "discrete" product industry (Cohen et al. 2000). At the same time, there is an increasing body of theoretical and empirical literature that suggests that the proliferation of patents also discourages innovation (*medium evidence, low agreement)*. Theoretical contributions note that a too stringent appropriability regime may greatly limit the diffusion of advanced technological knowledge and eventually block the development of differentiated technological capabilities within an industry, in what is called an 'appropriability trap' (Edquist 1997; Klein Woolthuis et al. 2005). There has been a long-standing debate on the impact of patents and other IP rights on innovation and economic development (Hall and Helmers 2019; Machlup 1958). Jaffe and Lerner (2004) and Bessen & Meurer (2009) highlight how IP rights also hamper innovation in a variety of ways. Other more specific contributions in the literature focus on specific factors. For example, Shapiro (2001) discusses patent thickets, where overlapping sets of patent rights mean that those seeking to commercialize new technology, need to obtain licenses from multiple patentees. Heller and Eisenberg (1998) argue that a 'tragedy of the anticommons' is likely to emerge when too many parties obtain the right to exclude others from using fragmented and overlapping pieces of knowledge, with ultimately no one having the effective privilege of using the results of biomedical research. Reitzig et al. (2007) describe the damaging effects of extreme business strategies employing patents, such as patent trolling.

IP protection and enforcement in general may have different impacts on economic growth in different types of countries *(limited evidence, high agreement*). There has been a significant degree of harmonisation and cooperation between national IP systems over time. The most recent milestone is the 1994 WTO agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS Agreement) , entered into by all members of the World Trade Organisation (WTO), and which sets down minimum standards for the regulation by national governments of many forms of intellectual property as applied to nationals of other WTO member nations (WTO 1994). Developing countries successfully managed to include some flexibilities into TRIPS both in terms of timing of legislative reform and in terms of the content of the reforms. In an attempt to understand the effects of the introduction of TRIPS, Falvey et al. (2006) find that the effect of IP protection on growth is positively and significantly related to growth for low- and high-income countries, but not for middle-income countries. They argue that low-income countries benefit from increased technology flows, but middle-income countries may have offsetting losses from the reduced scope for imitation. Note that Falvey et al. (2006) do not break down their results in different technological areas and they do not focus on innovation, but instead growth. It has been argued that the increasingly globalised 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 and Reichman 2017).

In principle, patent holders are not required to take their protected invention into use, and neither have the obligation to allow (i.e., license) others to use the inventions in question *(high evidence, high agreement)*. Studies have shown that the way patent holders use their patent differs considerably across industrial sectors: in pharmaceutics, patents are typically used to be the only producer of a certain good (and obtain monopoly rents), while in industries like computers, semiconductors, and communications, patents are often used to strengthen positions in cross-licensing negotiations and to generate licensing income (Cohen et al. 2000; Foray 2004). There are also companies that predominantly obtain patents for defensive reasons: they seek freedom to design and manufacture, and by owning a patent portfolio themselves, they hope to prevent that they become the target of litigation by other patent holders (Hall and Ziedonis 2001). Patents are often used strategically to impede the development and diffusion of competing, alternative products, processes or services, by employing strategies known as 'blanketing' and 'fencing' (Grandstrand 2000), although the research is not specific to the climate space.

There are notable but specific exceptions to the general principle that patent holders are not obliged to license their patent to others. These exceptions include the compulsory license, Fair, Reasonable and Non-discriminatory (FRAND) policies, and statement on licences of right *(high evidence, high agreement).* While patent holders are, as stated above, in principle free to choose not to license their innovation, there are three important exceptions to this. First, most national patent laws have provisions for compulsory licensing, meaning that a government allows someone else to produce a patented product or process without the consent of the patent holder, or plans to use the patent-protected invention itself (WTO 2020). Compulsory licenses may be issued in cases of public interest or events of abuse of the patent (Biadgleng 2009; World Intellectual Property Organization 2008). Compulsory licensing is explicitly allowed in the WTO TRIPS agreement, and its use in context of medicine (for instance to control diseases of public health importance, including HIV, tuberculosis and malaria) is further clarified in the 'DOHA Declaration' from 2001 (Reichman 2009; WHO 2020). Second, standard-setting organisations have policies to include patented inventions in their standards only if the patent holder is willing to commit FRAND licensing conditions for those patents (Contreras 2015). While a patent holder can still choose not to make such a commitment, by doing so, its patent is no candidate anymore for inclusion in the standard. In the (many) fields where standards are of key importance, it is very unusual for patent holders not to be willing to enter into FRAND commitments (Bekkers 2017). Third, when a patent holder, at the time of filing at the patent office, opts for the "licence of right" regime, in return for reduced patent fees, it enters into a contractual agreement that obliges to license the patent to those that request it. While not all national patent systems feature this regime, it is a feature present in the new European Community patent (EPO 2017), and may therefore increase in importance.

For a discussion on the impact of IPR on international technology diffusion, see Box 16.9 in Section 16.5.

16.4.7 Sub-national innovation policies and industrial clusters

Research examining the impacts of sub-national policies on innovation and competitiveness is sporadic – regional variations have been quantitatively assessed in US or China, or with case studies in these and other countries. Research on wind energy in the United States, distributed PV balance of systems in China, and renewable energy technologies in Italy have found that policies that incentivised local demand were associated with inducing innovation, measured with patents (Fu et al. 2018; Gao and Rai 2019; Corsatea 2016). Different policies may have different impacts – for example, in the United States state-level tax incentives and subsidies induced innovation within the state; but for renewable portfolio standards policies in other states were associated with innovation, because of impact on demand, but own-state policies were not (Fu et al. 2018). Research has also noted that the outcomes of policy and regulation on innovation are spatially heterogenous, because of differences in local planning authorities and capabilities (Song et al. 2019; Corsatea 2016).

Sub-national deployment policies have been associated with different impact on competitiveness metrics (*limited evidence, medium agreement)*. Research on green jobs show positive association between sub-national policies and green jobs or green firms at the metropolitan level as well as the state of provincial level, in both China and the United States (Yi 2013; Yi and Liu 2015; Lee 2017), while others find no impact of renewable portfolio standards on green job growth in the state (Bowen et al. 2013). Other examples of competitiveness are in the impact of regional green industrial policy in Brazil's Rio Grande do Sul region in attracting auctioned contracts for wind energy (Adami et al. 2017) or in the changes in net positive state revenues associated with removing tax incentives for wind producers in Idaho in the US (Black et al. 2014).

Sub-national policies also directly support innovation and competitiveness through green incubators and direct grants or R&D funding for local companies working on clean energy, intending to promote local economic development *(limited evidence, medium agreemen*t). The literature on the impacts of such policies on innovation and competitiveness is sparse. Some case studies and program evaluation reports, primarily in the United States, have identified the impacts of sub-national policies on competitiveness — for example, job creation from direct R&D funding in North Carolina (Hall and Link 2015), perceptions for local industry development and support for follow-on financing for companies receiving state-funded grants in Colorado (Surana et al. 2020b), and return on investments for the state in research and innovation spending from the New York state's energy agency (NYSERDA 2020). There is a general paucity of metrics on innovation and competitiveness for systematic assessments of such programs in developed countries, and even more so in India and other developing countries where such programs have been increasing (Surana et al. 2020a; Gonsalves and Rogerson 2019).

Although states and local governments increasingly support clean energy deployment as well as directly support innovation given its link with economic development goals, there is a lack of systematic research on the impacts of these policies at the subnational level. More research—both qualitative and quantitative, and in both developed and developing countries—is needed to systematically develop evidence on these impacts and to understand the reasons behind regional differences in terms of the type of policy as well as the capabilities in the region.

16.4.8 System-oriented policies and instruments

Although previous sections summarised 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 characterise 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. Reviewing renewable energy policies in nine OECD countries, research concludes that, over time, a broad set of policies characterized by a 'balance' metric has been put in place. 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 46 weighted average of six indicators) on renewable capacity (Schmidt and Sewerin 2019), indicating that a neutral conception of balance across all possible policies may not be desirable and that policy mix intensity by itself does not explain technology diffusion.

A growing body of research aims to understand how different policies interact and how to characterise policy mixes (del Río and Cerdá 2017; del Río 2010; Howlett and del Rio 2015; Rogge and Reichardt 2016). The empirical impact on the innovation outcomes is not yet discussed. A more detailed discussion of this literature is located in Chapter 13.

An emerging stream of research in complex systems has suggested that relatively small changes in policy near a possible tipping point in climate impacts in areas including changing strategies related to investments in innovation, could trigger large positive societal feedbacks in the long term (Farmer et al. 2019; Otto et al. 2020a).

16.5 International technology transfer and cooperation for transformative change

This section covers international transfer and cooperation in relation to climate-related technologies, "the flows of know-how, experience and equipment for mitigating and adapting to climate change amongst different stakeholders" (IPCC 2000) as well as innovation to support transformative change compared to the AR5 (IPCC 2014) and the SR1.5 (IPCC 2018a). This complements the discussion on international cooperation on science and technology in Chapter 14.

This section first outlines the needs for and opportunities of international transfer and cooperation on low-emission technologies. It then describes the main objectives and roles of these activities, and then reviews recent institutional approaches within and outside the UNFCCC to support international technology transfer and cooperation. Finally, it discusses emerging ideas on international transfer and cooperation on technology, and possible modifications to support the achievement of climate change and sustainable development goals, building up to Section 16.6.

16.5.1 International cooperation on technology development and transfer: needs and opportunities

With the submission of their NDCs as part of the Paris Agreement, most developing countries are now engaged in climate mitigation and adaptation. While technology is seen as one of the 'means of implementation' of climate action, developing countries often have relatively limited technology innovation capabilities, which requires them to access technologies developed in higher-income countries with stronger innovation systems (Popp 2011; Binz et al. 2012; Urban 2018). In many cases, these technologies require adaptation for the local context and needs (Sagar 2009; Anadon et al. 2016b), and, once again, innovation capabilities are required to suitably adapt these technologies for local use and also to create new markets and business models that are required for successful deployment (Ockwell et al. 2015; Ockwell and Byrne 2016; Sagar 2009). This can lead to dependencies on foreign knowledge and providers (Ockwell and Byrne 2016), negative impacts in terms of higher costs (Huenteler et al. 2016a), and balance of payments constraints and vulnerability to external shocks (Ebeling 2020).

The climate technology transition can also yield other development benefits, for instance better health, increased energy access, poverty alleviation and economic competitiveness (Deng et al. 2018a), including industrial development, job creation and economic growth (Altenburg and Rodrik 2017; Porter and Van der Linde 1995; Lema et al. 2020; Pegels and Altenburg 2020) (See Section 16.6). The growing complexity of technologies and global competition have made the development of a technology into a globalized process involving the flow of knowledge and products across borders (Koengkan et al. 2020; Lehoux et al. 2014). For instance, in production of electronics, Asian economies have captured co-location synergies and dominate production and assembly of product 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 specialising in investments in R&D, manufacturing or deployment of renewables (Lachapelle et al. 2017). In the case of solar PV, for example, while many of the technical innovations emerged from the US, Japan and China emphasized the manufacture of physical modules (Deutch and Steinfeld 2013) (see also Box 16.4).

Such globalization of production and supply chains opens up economic development opportunities for developing countries (Lema et al. 2020). At the same time, not all countries benefit from the globalisation of innovation, as barriers remain related to finance, environmental performance, human capabilities and cost (Egli et al. 2018; Weiss and Bonvillian 2013), with developing countries being particularly disadvantaged at leveraging these opportunities. The gap in low-carbon technology innovation between countries appears to have been reducing only amongst OECD countries (Yan et al. 2017; Du and Li 2019; Du et al. 2019) and the lower-income countries are not able to benefit as much from low-carbon technologies. For instance, in the case of agriculture, Fuglie (2018) notes out that international R&D spillovers seem to have benefited developed countries more than developing countries. Gross et al (2018)also argue that the development timescales for new energy technologies can extend up to 70 years, even within one country, and recommend that innovation efforts be balanced between on the one hand commercialising already low-emission technologies in the demonstration phase, and diffusing them globally, and on the other hand early-stage R&D spending.

Thus international cooperation on technology development and transfer can enable developing countries to achieve their climate goals more effectively, while also addressing other sustainable development goals, taking advantage, where possible, of the globalization of innovation and production (Lema et al. 2020). Earlier assessments in the AR5 and SR1.5 have made it clear that international technology transfer and cooperation could play a role in climate policy at both the international and the domestic policy level (IPCC 2018b; Stavins et al. 2014; Somanathan et al. 2014) and for low-carbon development at the regional level (Agrawala et al. 2014). The Paris Agreement also reflects this view by noting that countries shall strengthen cooperative action on technology development and transfer regarding two main aspects: 1) promoting collaborative approaches to research and development and 2) facilitating access to technology to developing country Parties (UNFCCC 2015). Furthermore, both in literature and in UNFCCC deliberations, South-South technology transfer is highlighted (Khosla et al. 2017) as a complement to the transfer of technology and know-how from North to the South.

This is consistent with literature that suggests that GHG mitigation in developing countries can be enhanced by (1) technology development and transfer collaboration and a 'needs-driven' approach, (2) development of the specific types of capacity required across the entire innovation chain and (3) strengthening of the coordination and agendas across and between governance levels (including domestic and international levels) (Upadhyaya et al. 2020; Zhou 2019; Khosla et al. 2017).

16.5.2 Objectives and roles of international technology transfer and cooperation efforts

International efforts involving technology transfer can have different objectives and roles. These include access to knowledge and financial resources as well as promotion of new industries in both the developed and recipient country (Huh and Kim 2018). Based on an econometric analysis of international technology transfer factors and characteristics of Clean Development Mechanism (CDM) projects, Gandenberger et al (2016) find that complexity and novelty of technologies explain whether CDM project includes hardware technology transfer, and that factors like project size and absorptive capacity of the host country do not seem to be drivers. Halleck 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 this has resulted in low-income countries being largely overlooked.

There is some literature studying whether technology cooperation could complement or replace international cooperation based on emission reductions, such as in the Kyoto Protocol, and whether that would have positive impacts on climate change mitigation and compliance. A handful of papers conducted game-theoretic analysis on technology cooperation, sometimes as an alternative for cooperation on emission reductions, and found partially positive effects (Rubio 2017; Narita and Wagner 2017; Bosetti et al. 2017; Verdolini and Bosetti 2017). However, 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.

While technology cooperation can be aimed at emission reduction through mitigation projects, as indicated above, not all cooperative actions directly result in mitigation outcomes. Overall, technology transfer broadly has focused on i) enhanced climate technology absorption and deployment in developing countries and ii) enhanced RD&D through cooperation and knowledge spill-overs.

16.5.2.1 Enhancing low-emission technology uptake in developing countries

Real-world outcomes in terms of low-emission technology deployment in developing countries may vary significantly depending on both the nature of the international engagement and the domestic context. While there have been some success in the enhancement of technology deployment through technology transfer in some developing countries (de la Tour et al. 2011; Zhang and Gallagher 2016), many others, and particularly least-developed countries, are lagging behind (Glachant and Dechezleprêtre 2017). They indicate that this is due to the lack of participation in economic globalisation and that climate negotiations could facilitate technology transfer to those countries through the creation of global demand for low-emission technologies through stronger mitigation targets that will result in lowering of costs and therefore enhanced technology diffusion. A broader perspective presents a host of other factors that govern technology diffusion and commercialization in developing countries, including, investment; social, cultural and behavioural, marketing and market building; macroeconomics; and support policy (Bakhtiar et al. 2020). Ramos Mejía et al (2018) indicate that the governance of low-emission technology transfer and deployment in developing countries is frequently negatively affected by a mixture of well- and ill-functioning institutions, in a context of, for instance, market imperfection, clientelist and social exclusive communities and patrimonial and/or marketized states. Furthermore, existing interests, such as fossil fuel production, may also impede the deployment of low-emission technologies, as highlighted in case studies of Vietnam and Indonesia (Dorband et al. 2020; Ordonez et al. 2021). It is for such reasons that both domestic efforts and international engagement are seen as necessary to facilitate technology transfer as well as deployment in developing countries (Boyd 2012). The same has been seen as true in the case of agriculture where the very successful international research efforts of the CGIAR (with remarkably favourable benefit-cost ratios (Alston et al. 2021) were complemented by the national agricultural research systems for effective uptake of high-yielding varieties of crops (Evenson and Gollin 2003).

One key area for underpinning effective technology uptake in developing countries relates to capabilities for managing technological change that includes the capabilities to innovate, implement, and undertake integrated planning. There is much research to indicate that the ability of a country's firms to adopt new technologies is determined by its absorptive capacity, which includes its own R&D activities, human capacity (e.g., technical personnel), government involvement (including institutional capacity), and the infrastructure in the country (Kumar et al. 1999), and that knowledge and capacity are part of the 'intangible assets' or the 'software' of a firm or a country (Corsi et al. 2020; da Silva et al. 2019; Ockwell et al. 2015). For sustainable development, capacity to plan in an integrated way and implement the SDGs (Elder et al. 2016; Khalili et al. 2015), including using participatory approaches (Disterheft et al. 2015), are conditional means of implementation. It also is argued that, if human capital were at the focus of international climate negotiations as well as national climate policy, it could change the political economy in favour of climate mitigation, which is needed for developing such capabilities in advance to keep up with the required speed of transformation (Hsu 2017; Upadhyaya et al. 2020; Ockwell et al. 2015; IPCC 2018b). Halleck-Vega et al (2018), in a global analysis of wind energy using econometric analysis, lend quantitative credibility to the claim that a technology skill base is a key determinant of technological diffusion. Activities to enhance capabilities include informational contacts, research activities, consulting, education & training and activities related to technical facilities (Huh and Kim 2018; Khan et al. 2020).

There are multiple studies drawing on empirical work also support this conclusion. For South-South technology transfer between India and Kenya, 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 success (Ulsrud et al. 2018). Specifically for Africa, Olawuyi (2018)discusses the capability gap in Africa, despite decades of technology transfer efforts under various mechanisms and programmes of the UNFCCC. The study suggests that barriers need to be resolved by African countries themselves, in particular inadequate access to information about imported climate technologies, lack of domestic capacities to deploy and maintain imported technologies, the weak regulatory environment to stimulate clean technology entrepreneurship, the absence or inadequacy of climate change laws, and weak legal protection for imported technologies. Moreover, Ziervogel et al (2021) indicate that for transformative adaptation, transdisciplinary approaches and capacity building shifting "the co-creation of contextual understandings" instead of top-down transferal of existing knowledge would deliver better results. Despite the understanding of the importance of the capacity issue, significant gaps still remain on this front (Technology Executive Commitee 2019); see also 16.5.4).

16.5.2.2 Enhancing RD&D and knowledge spill-overs

As mentioned earlier, RD&D can aid both the development of new technologies as well as their adoption for new use contexts. Therefore it is not surprising that international cooperation on RD&D is identified as a mechanism to promote low-carbon innovation (see, for example, Suzuki (2015), Technology Executive Committee (2021), Mission Innovation (2019)). This has resulted in a variety of international initiatives to cooperate on technology in order to create knowledge spill-overs and develop capacity. For example, the UNFCCC Technology Mechanism, amongst other things, aims to facilitate finance for RD&D of climate technologies by helping with readiness activities for developing country actors. In particular preparing early-stage technologies for a smoother transition to deployment and commercialisation has been emphasised in the context of the Technology Executive Committee (Technology Executive Committee 2017). There are numerous programmes, multilateral, bilateral and private, that have facilitated RD&D, biased mostly towards mitigation (as opposed to adaptation) activities, and many programmes that seemed to be about RD&D were in reality dialogues about research coordination (Ockwell et al. 2015). There also are a variety of possible bilateral and multilateral models and approaches for engaging in joint R&D (Mission Innovation 2019). An update by the Technology Executive Committee (2021) reviewing good practices in international cooperation of technology confirmed the conclusions of Ockwell et al(2015), and moreover highlighted that most initiatives are led by the public sector, and that the private sector tended to get involved only in incubation, commercialisation and diffusion phases. It also concluded that, although participation of larger, higher-income developing countries seems to have increased, participation of least-developed countries is still very low.

16.5.3 International technology transfer and cooperation: recent institutional approaches

In the sections below, the literature on various categories of international technology cooperation and transfer is discussed.

16.5.3.1 UNFCCC technology and capacity building institutions

Technology development and transfer are a part of the UNFCCC since its agreement in 1992 and has undergone discussions and developments in the context of the international climate negotiations ever since, as assessed in AR5 (Stavins et al. 2014). The support on "Technology Needs Assessment" to developing countries was the first major action undertaken by the UNFCCC, and has undergone different cycles of learning (Nygaard and Hansen 2015; Hofman and van der Gaast 2019). Since 2009, the UNFCCC discussions on technology development and transfer have focussed on the Technology Mechanism under the Cancun Agreements of 2010, which can be seen as the global climate governance answer to redistributive claims by developing countries (McGee and Wenta 2014). The Technology Mechanism consists of a Technology Executive Committee (TEC) and a Climate Technology Centre and Network (CTCN). An independent review of CTCN evaluated it on five dimensions – relevance, effectiveness, efficiency, impacts and sustainability – indicated that the organization is achieving its mandate in all these dimensions, although there are some possible areas of improvement. The review also specifically noted that "the lack of predictability and security over financial resources significantly affected the CTCN's ability to deliver services at the expected level, as did the CTCN's lack of human and organizational resources and the capacity of NDEs." (Technology Executive Committee 2017). The CTCN has overcome some of the limitations imposed by resource constraints by acting as a matchmaker from an open-innovation perspective (Lee and Mwebaza 2020). The lack of financial sustainability of the CTCN has been a recurring issue, which may potentially be resolved by deepening the linkage between the CTCN and GCF (Oh 2020). In the meanwhile, the GCF is planning to establish the Climate Innovation Facility to support and accelerate early-stage innovations and climate technologies through the establishment of regional innovation hubs and climate accelerators as well as a climate growth fund (Green Climate Fund 2020).

The 'technology' discussion has been further strengthened by the Paris Agreement, in which Article 10 is fully devoted to technology development and transfer (UNFCCC 2015). However, the political discussions around technology continue to be characterised by viewing technology mostly as hardware (Haselip et al. 2015), and relatively limited in scope (de Coninck and Sagar 2017). The workplans of the Technology Executive Committee (TEC) and the CTCN do, however, indicate a broadening of the perspective on technology (CTCN 2019; Technology Executive Commitee 2019).

Since the Kyoto Protocol's Clean Development Mechanism (CDM) has been operational, studies have assessed its hypothesised contribution to technology transfer, including transfer of knowledge. Though not an explicit objective of the CDM, numerous papers have investigated whether CDM projects contribute to technology transfer (Michaelowa et al. 2019). The literature varies in its assessment. Some find extensive use of domestic technology and hence lower levels of international technology transfer (Doranova et al. 2010), while other indicate that around 40% of projects feature hardware or other types of international transfer of technology (Murphy et al. 2015; Seres et al. 2009), depending on the nature of technology, the host country and region (Cui et al. 2020) and the project type (Karakosta et al. 2012). Although the CDM would generally be positively evaluated on the technology transfer contribution, it was also regarded critically as the market-responsiveness and following of export implies a bias to larger, more advanced economies rather than those countries most in need of technology transfer (Gandenberger et al. 2016), although some countries have managed to correct that by directing the projects, sub-nationally, to provinces with the greatest need (Bayer et al. 2016). Also, the focus on hardware transfer of technology in evaluations of technology transfer under the CDM has been criticised (Michaelowa et al. 2019; Haselip et al. 2015). Indeed, although many studies do go beyond hardware in their evaluations (e.g. Murphy et al (2015)), the degree to which the project leads to a change in the national system of innovation or institutional capacity development is not commonly assessed, or assessed as limited (de Coninck and Puig 2015).

There is significantly less literature on capacity building under the UNFCCC, especially as it relates to managing the technology transition. D'Auvergne and Nummelin (2017)(D´Auvergne and Nummelin 2017), in a legal analysis, indicate the nature, scope and principles of Article 11 on capacity building of the Paris Agreement as being demand- and country-driven, following a needs approach, fostering national, subnational and local ownership, and being iterative, incorporating the lessons learned, as well as participatory, cross-cutting and gender-response. They also highlight that it is novel that least-developed countries and SIDS are called out as the most vulnerable and most in need of capacity building, and that it raises a "legal expectation" that all parties "should" cooperate to enhance the capacity in developing countries to implement the Paris Agreement. These aspects are reflected in the terms of reference of the Paris Committee on Capacity Building (PCCB) that was established in 2015 at the 21st Conference of the Parties (UNFCCC 2016; D´Auvergne and Nummelin 2017), which was extended by five years at the 25th Conference of the Parties in 2019 (UNFCCC 2020a,b). In its work plan for 2020-2024, amongst other things, it aims to "identifying capacity gaps and needs, both current and emerging, and recommending ways to address them".

An example of how innovative technologies combined with capacity development and institutional innovation is combined in the context of adaptation to extreme weather in SIDS can be found in Box 16.8.

START BOX 16.8 HERE

Box 16.8 Capacity building and innovation for early warning systems in Small Island Developing States

One of the areas of international cooperation on capacity building is adaptation, which has been highlighted by both the Technology Executive Committee (Technology Executive Committee 2015; Ockwell et al. 2015) and the Paris Committee on Capacity Building (UNFCCC 2020b) as an area where capacity gaps remain, especially in Small Island Developing States (SIDS).

While adaptation was initially conceived primarily in terms of infrastructural adjustments to long-term changes in average conditions (e.g., rising sea levels), a key innovation in recent years has been to couple such long-term risk management to existing efforts to manage disaster risk, specifically including early warning systems enabling early action in the face of climate- and weather-risk at much shorter timescales (e.g., IPCC 2012), with potentially significant rates of return (e.g., Rogers and Tsirkunov 2010; Hallegatte 2012; Global Commission on Adaptation 2019).

In recent years, deliberate international climate finance investments have focused on ensuring that developing countries (and especially SIDS and LDCs) have access to improvements in hydrometeorological observations, modelling, and prediction capacity, sometimes with a particular focus on the people intended to benefit from the information produced (e.g., CREWS 2016). For instance, on the Eastern Caribbean SIDS of Dominica, researchers took a community-based approach to identify the mediating factors affecting the challenges to coastal fishing communities in the aftermath of two extreme weather events (in particular hurricane Maria in 2017) (Turner et al. 2020). Adopting an adaptive capacity framework (Cinner et al. 2018), they identified ‘intangible resources’ that people relied on in their post-disaster response as important for starting up fishery, but also went beyond that framework to conclude that the response ability on the part of governmental organisations as well as other actors (e.g. fish vendors) in the supply chain is also a requirement for rebuilding and restarting income-generating activity (Turner et al. 2020). Numerous other studies have highlighted capacity building as adaptation priorities (Williams et al. 2020; Kuhl et al. 2020; Vogel et al. 2020; Basel et al. 2020; Sarker et al. 2020).

One of several helpful innovations in these efforts is impact-based forecasting (Harrowsmith et al. 2020), which provides forecasts targeted at the impact of the hazard rather than simply the meteorological variable, enabling a much easier coupling to early action in response to the information, enabling a more appropriate response afterwards. Automatic responses to warnings have also been adopted in the humanitarian field for anticipatory action ahead (rather than simply in response to) disasters triggered by natural hazards (Coughlan de Perez et al. 2015), resulting in a rapid scale-up of such anticipatory financing mechanisms to tens of countries over the past few years, and emerging evidence of its effectiveness. Still, the response is lacking in coherence and comprehensiveness, resulting in calls for a more systematic evidence agenda for anticipatory action (Weingärtner et al. 2020).

END BOX 16.8 HERE

From the broader assessment above, despite limitations of available information, it is clear that the number of initiatives and activities on international cooperation and technology transfer and capacity building seem to have been enhanced since both the Cancun Agreements and the Paris Agreement (Technology Executive Committee 2021). However, given the complexity and magnitude of the requirements in terms of coverage of activities, the amount of committed funding, and effectiveness, much more can be done. Some assessments of UNFCCC instruments specifically for technology transfer to developing countries had indicated that functions such as knowledge development, market formation and legitimacy in developing countries’ low-emission technological innovation systems would need much more support to fulfil the Paris goals. (de Coninck and Puig 2015; Ockwell et al. 2015); such areas would benefit from continued attention, given their role in the overall climate technology transition.

16.5.3.2 International RD&D cooperation and capacity building initiatives

Besides the UNFCCC mechanisms, there are numerous other initiatives that promote international cooperation on RD&D as well as capacity building. Some of them are based on the notion of “mission-oriented innovation policy” (Mazzucato and Semieniuk 2017; Mazzucato 2018), which shapes markets rather than merely correcting market failures.

For instance, “Mission Innovation” (MI) is a global initiative consisting of 23 member 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 2°C. The members to seek to increase public investments in clean energy R&D with the engagement of private sectors, and foster international collaboration amongst its members. A recent assessment shows that, although expenditures are rising, the aims are not met by 2020 (Myslikova and Gallagher 2020). 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 commercialisation, developing new technologies now would mean they would be commercially too late for addressing climate change. Huh and Kim (2018) discuss two 'knowledge and technology transfer' projects that were eventually not pursued through beyond the feasibility study phase 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.

The intellectual property right regime (see Box 16.9) can be an enabler or a barrier to energy transition. For more background on IPR and impact on innovation, see Section 16.4.6.

START BOX 16.9 HERE

Box 16.9 Intellectual property rights (IPR) regimes and technology transfer

In the global context of climate mitigation technologies, it has been noted that technologies have been developed primarily in industrialised countries but are urgently required in fast-growing emerging economies (Dechezleprêtre et al. 2011). International technology transfer of such technologies can primarily take place via three channels: (i) trade in goods, where technology is embedded in products; (ii) direct foreign investments (FDI), where enterprises transfer firm-specific technology to foreign affiliates, and (iii) patent licenses, where third parties obtain the right to use technologies. IPRs are relevant for all these three channels.

Not surprisingly, then, the role of IPRs in international technology transfer of climate mitigation technologies has been much discussed but also described as particularly controversial (Abdel-Latif 2015). The relationships between IP rights, innovation, international technology transfer and local mitigation and adaptation are complex (Maskus 2010; Li et al. 2020; Abdel-Latif 2015) and there is no clear consensus on what kind of an IPR regime will be most beneficial for promoting technology transfer.

Several studies argue that, particularly in developing nations, the global IP regime has resulted in delayed access, reduced competition and higher prices (Littleton 2008; Zhuang 2017) and that climate-change-related technology transfer is insufficiently stimulated under the current IPR regime. Compulsory licensing (as already used in medicine) is one of the routes proposed to repair this (Abdel-Latif 2015; Littleton 2008).

There is little systematic evidence that patents and other IPRs restrict access to environmentally sound technologies, since these technologies mostly are in sectors based on mature technologies where numerous substitutes among global competitors are available (Maskus 2010). This might however change in the future, for instance with new technologies based on plants, via biotechnologies and synthetic fuels (Maskus 2010), for which Correa et al (2020) already find some evidence.

There also is literature that suggests weak IPR regimes have a "strong and negative impact on the international diffusion of patented knowledge" (Dechezleprêtre et al. 2013; Glachant and Dechezleprêtre 2017). Also, patents may support market transactions in technology, including international technology transfer, especially to "middle-income" countries and larger developing countries (Maskus 2010; Hall and Helmers 2019) but LDCs may be better served by building capacity to absorb and implement technology (Sanni et al. 2016; Hall and Helmers 2010; Maskus 2010; Glachant and Dechezleprêtre 2017). It is also argued that it is not even clear that the patent system as it exists today is the most appropriate vehicle for encouraging international access (Sanni et al. 2016; Hall and Helmers 2010; Maskus 2010; Glachant and Dechezleprêtre 2017). Given the large variation in perspectives on the role of IPRs in technology transfer, there is a need for more evidence and analysis to better understand if, and under what conditions, IPRs may hinder or promote technology transfer (see also Technology Executive Committee (2012)).

In terms of ways forward to meet the challenge of climate change, different suggestions are made in the context of IPRs that can help to further improve international technology transfer of climate mitigation technologies, including through the TRIPS agreement, by making decisions on IPR to developing countries on a case-by-case basis, by developing countries experimenting more with policies on IPR protection, or through brokering or patent-pooling institutions (Littleton 2009; Dussaux et al. 2018; Maskus and Reichman 2017). Others also suggests that distinctions among country groups be made on basis of levels of technological and economic development, with least developed countries getting particular attention (Abbott 2018; Zhuang 2017).

END BOX 16.9 HERE

16.5.4 Emerging ideas for international technology transfer and cooperation

As with the broader innovation literature (as highlighted in Section 16.3), and, in fact, drawing on such literature, there has been an emergence of a greater understanding of, and emphasis on, the role of innovation systems (at a national, sectoral, and technological level) as a way to help developing countries with the climate technology transition (Technology Executive Committee 2015; Ockwell and Byrne 2016). This has given rise to several proposals, discussed here and summarised in Figure 16.3.

Enhancing deployment and diffusion of climate technologies in developing countries would require a variety of actors with sufficient capabilities (*robust evidence, medium agreement*) (Ockwell et al. 2018; Kumar et al. 1999; Sagar et al. 2009). This may include strengthening existing actors (Malhotra et al. 2021), supporting science, technology, and innovation-based start-ups to meet social goals (Surana et al 2020b), and developing entities and programs that are intended to address specific gaps relating to technology development and deployment (Ockwell et al. 2018; Sagar et al. 2009).

There also is an increasing emphasis on the relevance of participative social innovation, local grounding and policy learning as a replacement of the expert-led technological change (Kowarsch et al. 2016; Chaudhary et al. 2012; Disterheft et al. 2015). Others have suggested a shift to international innovation cooperation rather than technology transfer, which implies donor-recipient relationship. The notion of innovation cooperation also makes more explicit the focus on innovation processes and systems (Pandey et al. 2021). A broad transformative agenda therefore proposes that contemporary societal challenges are complex and multi-variegated in scope and will require the actions of a diverse set of actors to both formulate and address the policy, implying social, institutional and behavioural changes next to technological innovations are the possible solutions (Geels 2004) (see also Cross-Chapter Box 12 in this chapter).

Several authors have proposed new mechanisms for international cooperation on technology. Ockwell and Byrne (2016) argue that a role for the UNFCCC Technology Mechanism could be to support climate relevant innovation-system builders (CRIBs) in developing countries, institutions locally that develop capabilities that "form the bedrock of transformative, climate-compatible, technological change and development". Khan et al (2020) propose a specific variant with universities in developing countries serving as 'central hubs' for capacity building to implement the NDCs as well as other climate policy and planning instruments; they also suggest that developing countries outline their capacity building needs more clearly in their NDCs.

Building on an earlier discussion of technology-oriented and sectoral agreements (Meckling and Chung 2009) and the potential for international cooperation in energy-intensive industry (Åhman et al. 2017), where deep emission reduction measures require transformative changes (see also Chapter 11), Oberthür et al (2021) propose that the global governance for energy-intensive industry through sub-sector 'clubs' that include governmental, private and societal actors could be effective way forward (Oberthür et al. 2021).

Examples of emerging ideas for international cooperation on climate technology, as well as their relation to the objectives and existing efforts, and in relation to the level of development of the innovation system around a technology (Bergek et al. 2008; Hekkert et al. 2007) or in nations (Lundvall et al. 2009) are summarized in Figure 16.3.

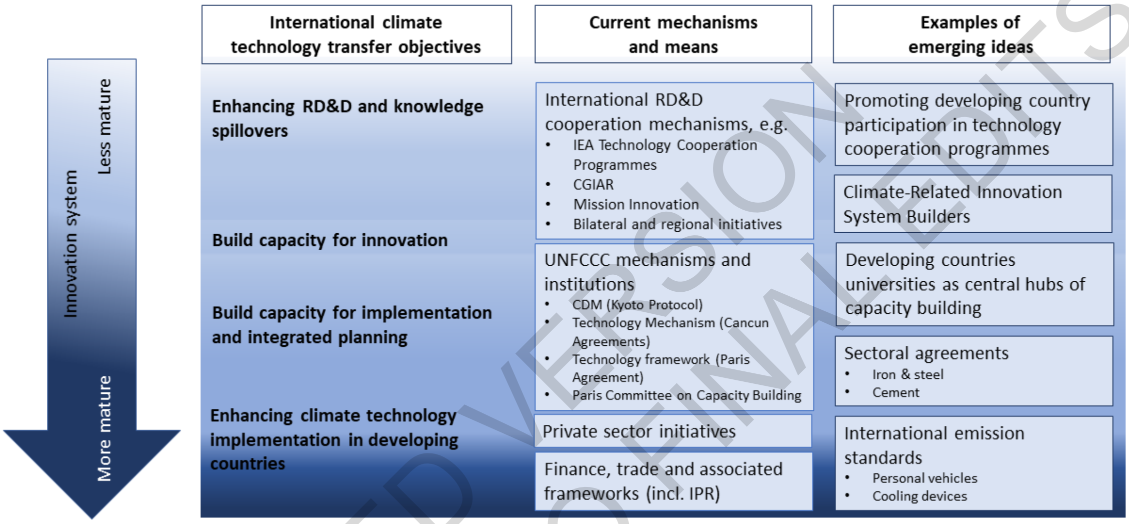


Figure 16.3 Examples of recent mechanisms and emerging ideas (right column) in relation to level of maturity of the national or technological innovation system, objectives of international climate technology transfer efforts and current mechanisms and means. Sources: (Oberthür et al. 2021; Khan et al. 2020; Ockwell and Byrne 2016; Sagar 2009)

16.6 Technological change and sustainable development

This section considers technological innovation in the broader context of sustainable development, recognising that technological change happens within social and economic systems, and therefore technologies are conceived and applied in relation to those systems (Grübler 1998). Simplifications of complex interactions between physical and social systems and incomplete knowledge of technological innovation indirect effects may systematically lead to underestimation of environmental impacts and overestimation of our ability to mitigate climate change (Arvesen et al. 2011; Hertwich and Peters 2009).

In previous sections, the chapter discussed how a systemic approach, appropriate public policies and international cooperation on innovation can enhance technological innovation. This section provides more details on how innovation and technological change, sustainable development and climate change mitigation intertwine.

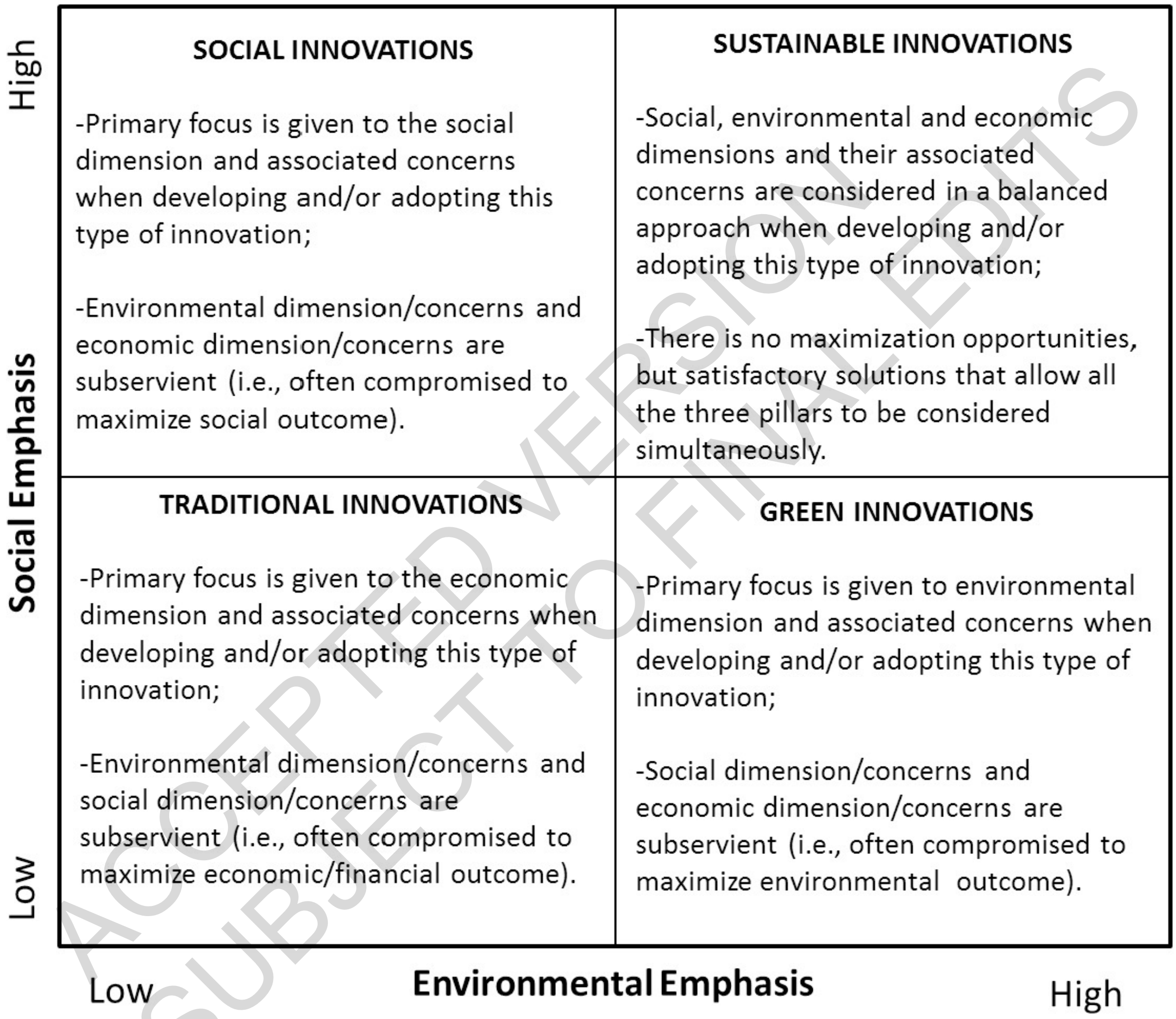
16.6.1 Linking sustainable development and technological change

Sustainable development and technological change are deeply related (UNCTAD 2019). Technology has been critical for increasing productivity as the dominant driving force for economic growth but also, the concentration of technology in few hands has boosted consumption of goods and services which are not necessarily aligned with sustainable development goals (Walsh et al. 2020). It has been suggested that, in order to address sustainable development challenges, science and technology actors would have to change their relation to policymakers (Ravetz and Funtowicz 1999) as well as the public (Jasanoff 2003). This has been further elaborated for the SDGs. The scale and ambition of the SDGs call for a change in development patterns that require a fundamental shift in both current best practices and guidelines for technological and investment decisions and in the wider socio-institutional systems (UNCTAD 2019; Pegels and Altenburg 2020). This is needed as not all innovation will lead to sustainable development patterns (Altenburg and Pegels 2012; Lema et al. 2015).

Current Sustainable Development Goals (SDG) implementation gaps reflect, to some extent, inadequate understanding of the complex relationships among the goals (Skene 2020; Waiswa et al. 2019), as well as their synergies and trade-offs, including how they limit the range of responses available to communities and governments, and potential injustices (Thornton and Comberti 2017). These relationships have been approached by focusing primarily on synergies and trade-offs while lacking the holistic perspective necessary to achieve all the goals (Nilsson et al. 2016; Roy et al. 2018).

A more holistic framework could envisage the SDGs as outcomes of stakeholder engagement and learning processes directed at achieving a balance between human development and environmental protection (Gibbons 1999; Jasanoff 2003), to the extent that the two can be separated. From a science, technology and innovation (STI) perspective, Fu et al (2019) distinguish three categories of SDGs. The first category comprises those SDGs representing essential human needs for which inputs that put pressure on sustainable development would need to be minimized. These include food (SDG 2), water (SDG 6) and energy (SDG 7) resources, which continue to rely on production technologies and practices that are eroding ecosystem services, hampering the realization of SDG goals 15 (land) and 14 (oceans) (Díaz et al. 2019). The second are those related to governance and which compete with each other for scarce resources, such as infrastructure (SDG 9) and climate action (SDG 13), which require an interdisciplinary perspective. The third category are those that require maximum realization, include no poverty (SDG 1), quality education (SDG 4) and gender equality (SDG 5) (Fu et al. 2019).

Resolving tensions between the SDGs requires adoption and mainstreaming of novel technologies that can meet needs while reducing resource waste and improving resource-use efficiency, and while acknowledging the systemic nature of technological innovation, which involve many levels of actors, stages of innovation and scales (Anadon et al. 2016b). Changes in production technology have been found effective to overcome trade-offs between food and water goals (Gao and Bryan 2017). Innovative technologies at the food, water and energy nexus are transforming production processes in industrialized and developing countries, such as developments in agrivoltaics, which is co-development of land for agriculture and solar with water conservation benefits (Barron-Gafford et al. 2019; Schindele et al. 2020; Lytle et al. 2020), and other renewably powered low- to zero-carbon food, water and energy systems (He et al. 2019). Silvestre and Ţîrcă (Silvestre and Ţîrcă 2019) indicate that maximising both social and environmental aims is not possible, but that sustainable innovations include satisfactory solutions for social, environmental and economic pillars (see Figure 16.4).



SOCIAL INNOVATIONS

-Primary focus is given to the social dimension and associated concerns when developing and/or adopting this type of innovation;

-Environmental dimension/concerns and economic dimension/concerns are subservient (i.e., often compromised to maximize social outcome).

SUSTAINABLE INNOVATIONS

-Social, environmental and economic dimensions and their associated concerns are considered in a balanced approach when developing and/or adopting this type of innovation;

-There is no maximization opportunities, but satisfactory solutions that allow all the three pillars to be considered simultaneously.

TRADITIONAL INNOVATIONS

-Primary focus is given to the economic dimension and associated concerns when developing and/or adopting this type of innovation;

-Environmental dimension/concerns and social dimension/concerns are subservient (i.e., often compromised to maximize economic/financial outcome).

GREEN INNOVATIONS

-Primary focus is given to environmental dimension and associated concerns when developing and/or adopting this type of innovation;

-Social dimension/concerns and economic dimension/concerns are subservient (i.e., often compromised to maximize environmental outcome).

Figure 16.4: Considerations and typology of innovations for sustainable development (Silvestre and Ţîrcă 2019).

There is evidence that technological changes can catalyse implementation of the reforms needed to the manner in which goods and services are distributed among people (Fu et al. 2019). A recently developed theoretical framework based on a capability approach (CA) has been used to evaluate the quality of human life and the process of development (Haenssgen and Ariana 2018). Variations of the CA have been applied to exploratory studies of the link between technological change, human development, and economic growth (Mayer 2001; Mormina 2019). This suggests that the transformative potential of technology as an enabling condition is not intrinsic, but is assigned to it by people within a given technological context. A failure to recognize and account for this property of technology is a root cause of many failed attempts at techno-fixing sustainable development projects (Stilgoe et al. 2013; Fazey et al. 2020).

The basic rationale for governance of technological change is the creation and maintenance of an enabling environment for climate and SDG-oriented technological change (Avelino et al. 2019). Such an environment poses high demands on governance and policy to coordinate with actors and provide a direction for innovation and technological change. Cross-Chapter Box 12 illustrates how the dynamics of socio-technical transitions and shifting development pathways towards sustainable development offer options for policymakers and other actors to accelerate the system transitions needed for both climate change mitigation and sustainable development. Governance interventions to implement the SDGs will need to be operationalized at sub-national, national and global levels and support integration of resource concerns in policy, planning and implementation (UNEP 2015; Williams et al. 2020).

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Cross-Chapter Box 12 Transition Dynamics

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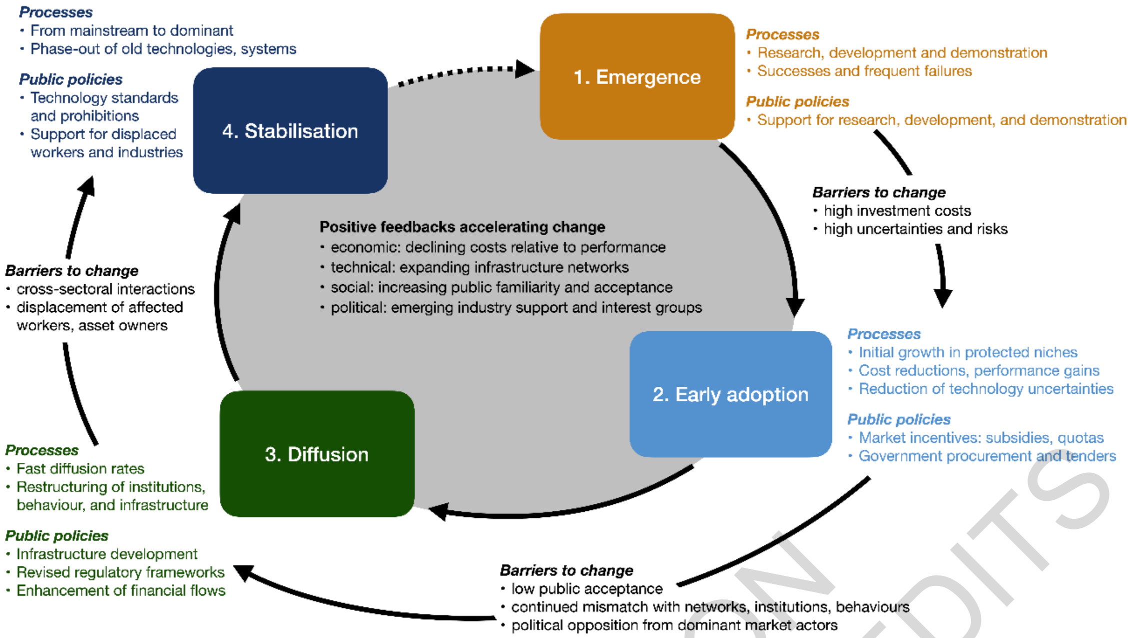
Introduction: Numerous studies suggest that transformational changes would be required in many areas of society if climate change is to be limited to 2°C warming or less. Many of these involve shifts to low carbon technologies, such as renewable energy, which typically involve changes in associated regulatory and social systems; others more explicitly concern behavioural shifts, such as towards plant-based diets or cleaner cooking fuels, or, at the broadest level, a shift in development pathways. Chapter 1 establishes an analytic framework focusing on transitions, which chapters 5, 13, 14, 15 and 16 further develop. In this cross-chapter box, we provide a complementary overview of the dynamics of different kinds of transformational changes for climate mitigation and sustainable development. We first focus on insights from socio-technical transitions approaches, and then expand to broader system transitions.

Dynamics of socio-technical transitions: A large literature documents the processes associated with transformational changes in technology and the social systems associated with their production and use (Köhler et al. 2019; Geels 2019). Transformational technological change typically goes hand-in-hand with shifts in knowledge, behaviour, institutions, and markets (Markard et al. 2012, p. 956; Geels and Schot 2010); stickiness in these factors often keeps society "locked-in" to those technologies already in widespread use, rather than shift to new ones, even those that offer benefits (David 1985; Arthur 1994). Exceptions often follow consistent patterns (Unruh 2002; Geels 2002); since AR5 a growing number of scholars have suggested using these insights to design more effective climate policies and actions (Geels et al. 2017). Chapter 1 (see Section 1.7 and Figure 1.6) represents technology diffusion and a corresponding shift in policy emphasis as a continuous process; it is also useful to identify a sequence of distinct stages that typically occur, associating each stage with a distinct set of processes, challenges, and effective policies (Patt and Lilliestam 2018; Victor et al. 2019). Consistent with elsewhere in this report (section 5.5.2 and SM.5.5.3 in Chapter 5, and section 16.3 in Chapter 16), Cross-Chapter Box 12 Figure 1 elaborates four distinct stages. Recognizing that even transformative technologies will eventually be replaced with newer ones, the figure portrays these as occurring in a cycle.



Cross-Chapter Box 12, Figure 1 Stages of socio-technical transition processes

The *emergence* stage is marked by experimentation, innovation in the laboratory, and demonstration in the field, to produce technologies and system architectures (Geels 2005a). By its very nature, experimentation includes both successes and failures, and implies high risks. Because of these risks, especially in the case of fundamentally new technologies, government funding for research, development and demonstration (RD&D) projects is crucial to sustaining development (Mazzucato 2015b).

The second stage is *early adoption*, during which successful technologies jump from the laboratory to limited commercial application (Pearson and Foxon 2012). Reaching this stage is often described as crossing the "Valley of Death", because the cost/performance ratio for these new market entrants is too low for them to appear viable to investors (Murphy and Edwards 2003). A key process in the early adoption phase is induced innovation, a result of incremental improvements in both design and production processes, and of mass-production of a growing share of key components (Grubb et al. 2021; Nemet 2006). There is diversity across classes of technologies, and learning tends to occur faster for technologies that are modular (Wilson et al. 2020), such as photovoltaics, and slower for those that require site- or context-specific engineering, such as in the shift to low carbon materials production (Malhotra and Schmidt 2020). Public policies that create a secure return on investment for project developers can lead to learning associated with industry expansion (See Chapter 16, Figure 16.1); typically these are economically and politically viable when they promote growth within a market "niche", causing little disruption to the mainstream market (Roberts et al. 2018). Direct support mechanisms, including cross-subsidies, such as feed-in tariffs, and market quotas such as renewable portfolio standards, are effective (Patt and Lilliestam 2018; Geels et al. 2017b; see Chapter 9 for assessment of early adoption policies in the building sector). The value of these policies is less in their immediate emissions reductions, but more in generating the conditions for self-sustaining transformational change to take place as technologies later move from niche to mainstream (Hanna and Victor 2021).

The third stage, *diffusion*, is where niche technologies become mainstream, with accelerating diffusion rates (see Chapter 1, Sections 1.7 and 16.4), and is marked by changes to the socio-technical "regime", including infrastructure networks, value chains, user practices, and institutions. This stage is often the most visible and turbulent, because more widespread adoption of a new technology gives rise to structural changes in institutions and actors' behaviour (e.g. increased adoption of smart phones to new payment systems and social media), and because when incumbent market actors become threatened, they often contest policies promoting the new technologies (Köhler et al. 2019). In the diffusion stage, policy emphasis is shifted from financial support during the early adoption stage, towards supporting regime-level factors needed to sustain, or cope with, rapid and widespread diffusion (Markard 2018). These factors and policies are context specific. For example, Patt et al. (Patt et al. 2019) document that the policies needed to expand residential charging networks for electric vehicles depend on the local structure of the housing market.

The fourth stage is *stabilisation*, in which the new technologies, systems, and behaviours are both standardized and insulated from rebound effects and backsliding (Andersen and Gulbrandsen 2020). Sectoral bans on further investment in high carbon technologies may become politically feasible at this point (Breetz et al. 2018; Economidou et al. 2020). The decline of previously dominant products or industries can lead to calls for policy-makers to help those negatively affected, enabling a just transition (Newell and Simms 2020; McCauley and Heffron 2018). Political opposition to the system reconfiguration that comes with integration and stabilization can also be overcome by offering incumbent actors an attractive exit strategy (de Gooyert et al. 2016).

Because different sectors are at different stages of low-carbon transitions, and because the barriers that policies need to address are stage- and often context-specific, effective policies stimulating socio-technical transitions operate primarily at the sectoral level (Victor et al. 2019). This is particularly the case during early adoption, where economic barriers predominate; during diffusion, policies that address regime-level factors often need to deal with cross-sectoral linkages and coupling, such as those between power generation, transportation, and heating (Patt 2015; Bloess 2019; Fridgen et al. 2020). The entire cycle can take multiple decades. However, later stages can go faster by building on the earlier stages' having taken place elsewhere. For example, early RD&D into wind energy took place primarily in Denmark, was followed by early adoption in Denmark, Germany, and Spain, before other countries, including the United States, India, and China leapfrogged directly to the diffusion stage (Lacal-Arántegui 2019; Chaudhary et al. 2015; Dai and Xue 2015). A similar pattern played out for solar power (Nemet 2019b). International cooperation, geared towards technology transfer, capacity and institution-building, and finance, can help ensure that developing countries leapfrog to low-carbon technologies that have undergone commercialization elsewhere (Adenle et al. 2015; Fankhauser and Jotzo 2018)(see also Chapter 5, Box 5.9, Chapter 15, Section 15.5 and Section 16.5 in this chapter)..

This report contains numerous examples of the positive feedbacks in the centre of Cross-Chapter Box 12, Figure 1, predominantly arising during the early adoption and diffusion stages, and leading to rapid or unexpected acceleration of change. Public acceptance of alternatives for meat leads to firms improving the products, increasing political and economic feedbacks (Chapter 5, Section 5.4, Box 5.5). Declining costs in solar and wind cause new investment in the power generation sector being dominated by those technologies, leading to increased political support and further cost reductions (Chapter 6). In buildings (Chapter 9) and personal mobility (Chapter 10), low-carbon heating systems and electric passenger vehicles are gaining public acceptance, leading to improved infrastructure and human resources, more employment in those sectors, and behavioural contagion. Some have argued that technologies cross societal tipping points on account of these feedbacks (Obama 2017; Sharpe and Lenton 2021).

Dynamics between enabling conditions for system transitions: Abson et al. (2017) argue that it is possible to make use of "leverage points" inherent in system dynamics in order to accelerate sustainability transitions. Otto et al. (2020b) argue that interventions geared towards the social factors driving change can "activate contagious processes" leading towards the transformative changes required for climate mitigation. These self-reinforcing dynamics involve the interaction of enabling conditions including public policy and governance, institutional and technological innovation capacity, behaviour change, and finance. For example, Mercure et al. (2018) simulated financial flows into fossil-fuel extraction, and showed how investors' taking into account transition risk in combination with technological innovation would lead to the enhancement of investments in low-carbon assets and further enhanced innovation. As another example, behaviour, lifestyle, and policy can also initiate demand-side transitions (Chapter 5) (Tziva et al. 2020), such as with food systems (Rust et al. 2020) (Chapter 7, section 7.4.5), and can contribute to both resilience and carbon storage (Sendzimir et al. 2011) (Chapter 16, Box 16.5).

In the urban context, the concept of sustainability experiments has been used to examine innovative policies and practices adopted by cities that have significant impact on transition towards low-carbon and sustainable futures (Bai et al. 2010; Castán Broto and Bulkeley 2013). Individual innovative practices can potentially be upscaled to achieve low-carbon transition in cities (Peng and Bai 2018), leading to a process of broadening and scaling innovative practices in other cities (Peng et al. 2019). Such sustainability experiments give rise to new actor networks, which in some cases may accelerate change, and in others may lead to conflict (Bulkeley et al. 2014). As in the diffusion phase in Cross-Chapter Box 12, Figure 1, contextual factors play a strong role. Examining historical transitions to cycling across European cities, Oldenziel et al. (2016) found contextual factors including specific configurations of actors to lead to very different outcomes. Kraus and Koch (2021) found a short-term social shock – the COVID crisis – to lead to differential increases in cycling behaviour, contingent on other enabling conditions.

Linking system dynamics to development pathways and broader societal goals: Transition dynamics insights can be broadened to shifting development pathways. Development paths are characterised by particular sets of interlinking regime rules and behaviours, including inertia and cascading effects over time, and are reinforced at multiple levels, with varied capacities and constraints on local agency occurring at each level (Burch et al. 2014)(See also Cross-Chapter Box 5 in Chapter 4). This is also observed by Schot and Kanger (2018), who identify a needed change in a "meta-regime", crossing sectoral lines in linking value-chains or infrastructure and overall development objectives. In the context of the UN climate change regime, international cooperation can bring together such best practices and lessons learnt (Pandey et al. 2021; Adenle et al. 2015). This is especially relevant for developing countries, which often depend on technologies and financial resources from abroad, witnessing their pace and direction influenced by transnational actors (Bhamidipati et al. 2019; Marquardt et al. 2016), and benefiting little in terms of participating in high value-added activities (Whittaker et al. 2020).

System transitions differ according to context, such as across industrialized and developing countries (Ramos-Mejía et al. 2018), and within countries. Lower levels of social capital and trust negatively impact niche commercialization (Lepoutre and Oguntoye 2018). In contexts of poverty and inequality, stakeholders' – including users' – capabilities for meaningful participation are limited and transition outcomes can end up marginalizing or further excluding social groups (Osongo and Schot 2017; Hansen et al. 2018). Many studies of transitions in developing countries make note of the importance of innovation in the informal sector (Charmes 2016, Box 5.10). Facilitating informal sector access to renewable energy sources, safe and sustainable buildings, and finance can advance low-carbon transitions (McCauley et al. 2019; Masuku and Nzewi 2021). Contrary, disregarding its importance can result in misleading or ineffective innovation and climate strategies (Maharajh and Kraemer-Mbula 2010; Mazhar and Ummad 2014; de Beer et al. 2016; Masuku and Nzewi 2021).

Policies shifting innovation in climate-compatible directions can also reinforce other development benefits, for instance better health, increased energy access, poverty alleviation and economic competitiveness (Deng et al. 2018b; Karlsson et al. 2020; IPCC 2018a). Development benefits, in turn, can create feedback effects that sustain public support for subsequent policies and hence help to secure effective long-term climate mitigation (Meckling et al. 2015b; Geels 2014b; Schmidt and Sewerin

2017b; Breetz et al. 2018), increasing legitimacy of environmental sustainability actions (Hansen et al. 2018; van Welie and Romijn 2018; Herslund et al. 2018) and addressing negative socio-economic impacts (Eisenberg 2019; McCauley and Heffron 2018; Henry et al. 2020a; Deng et al. 2018b).

Summary and gaps in knowledge: Strategies to accelerate climate mitigation can be most effective at accelerating and achieving transformative change when they are synchronized with transition processes in systems. They address technological stage characteristics, take advantage of high-leverage intervention points, and respond to societal dynamics (Abson et al. 2017; Köhler et al. 2019; Geels et al. 2017). Gaps in knowledge remain on how to tailor policy mixes, the interaction of enabling conditions, the generalizability of socio-technical transition insights to other types of systems, and how to harness these insights to better shift development pathways.

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16.6.2 Sustainable development and technological innovation: Synergies, trade-offs and governance

16.6.2.1 Synergies and trade-offs

Policies that shift innovation in climate compatible directions can promote other development benefits, for instance better health, increased energy access, poverty alleviation and economic competitiveness (Deng et al. 2018a, see also Cross-Chapter Box 12). Economic competitiveness co-benefits can emerge as climate mitigation policies trigger innovation that can be leveraged for promoting industrial development, job creation and economic growth, both in terms of localizing low-emission energy technologies value chains as well as of increased energy efficiency and avoided carbon lock-ins (Section 16.4). However, without adequate capabilities, co-benefits at the local level would be minimal, and they would probably materialize far from where activities take place (Vasconcellos and Caiado Couto 2021; Ockwell and Byrne 2016). Innovation and technological change can also empower citizens. Grass-roots innovation promotes the participation of grass-roots actors, such as social movements and networks of academics, activists and practitioners, and facilitate experimenting with alternative forms of knowledge creation (UNCTAD 2019; Seyfang and Smith 2007). Examples of ordinary people and entrepreneurs adopting and adapting technologies to local needs to address locally defined needs have been documented in the development literature (van Welie and Romijn 2018) (See also Box 16.10). Digital technologies can empower citizens and communities in decentralized energy systems contributing not only to a more sustainable but also to a more democratic and fairer energy system (Van Summeren et al. 2021) (See also Cross-Chapter Box 11 in this chapter, and Section 5.4 in Chapter 5).

Therefore, even though STI is an explicit focus of SDG 9, it is in fact an enabler of most SDGs (UNCTAD 2019). Striving for synergies between innovation and technological change for climate change mitigation with other SDGs can help to secure effective long-term climate mitigation, as development benefits can create feedback effects that sustain public and political support for subsequent climate mitigation policies (Meckling et al. 2015a; Geels 2014a, also Cross-Chapter Box 12). However, innovation is not always geared to sustainable development, for instance, firms tend to know how to innovate when value chains are left intact (Hall and Martin 2005), which tend to not be the case in systemic transitions.

A comprehensive study of these effects distinguishes among "…anticipated-intended, anticipated-unintended, and unanticipated-unintended consequences" (Tonn and Stiefel 2019). Theoretical and empirical studies have demonstrated that unintended consequences are typical of complex adaptive systems, and while a few are predictable, a much larger number are not (Sadras 2020). Even when unintended consequences are unanticipated, they can be prevented through actor responses, for instance rebound effects following the introduction of energy efficient technologies. Other examples of unintended consequences include worse-than-expected physical damage to infrastructure and resistance from communities in the rapidly growing ocean renewable energy sector (Quirapas and Taeihagh 2020), and gaps between expected and actual performance of building integrated photovoltaic (BIPV) technology (Boyd and Schweber 2018; Gram-Hanssen and Georg 2018). In the agricultural sector, new technologies and associated practices that target the fitness of crop pests have been found to favour resistant variants. Unintended consequences of digitalisation are reported as well (Lynch et al. 2019) (see Cross-Chapter Box 11 in this chapter).

Innovation and climate mitigation policies can also have negative socio-economic impacts and not all countries, actors and regions around the world benefit equally from rapid technological change (UNCTAD 2019; Eisenberg 2019; McCauley and Heffron 2018; Henry et al. 2020b; Deng et al. 2018a). In fact, socio-technical transitions often create winners and losers (Roberts et al. 2018). Technological change can reinforce existing divides between women and men, rural and urban populations, and rich and poor communities, as older workers displaced by technological change will not qualify for jobs if they were unable to acquire new skills, weak educational systems may not prepare young people for emerging employment opportunities, and disadvantaged social groups, including women in many countries, often have fewer opportunities for formal education (UNCTAD 2019; McCauley and Heffron 2018). That is a risk regarding technological change for climate change mitigation, as emerging evidence suggests that the energy transition can create jobs and productivity opportunities in the renewable energy sector, but will also lead to job losses in fossil fuel and exposed sectors (Le Treut et al. 2021). At the same time these new jobs may use more intensively high-level cognitive and interpersonal skills compared to regular, traditional jobs, requiring higher levels of human capital dimensions such as formal education, work experience and on-the-job training (Consoli et al. 2016). Despite the empowerment potentials of decentralized energy systems, not all societal groups are equally positioned to benefit from energy community policies, with issues of energy justice taking place within initiatives, between initiatives and related actors, as well as beyond initiatives (van Bommel and Höffken 2021; Calzadilla and Mauger 2018).

The opportunities and challenges of technological change can also differ within country regions and between countries (e.g. Garcia-Casals et al. 2019). Within countries, Vasconcellos and Caiado Couto (2021) show that, in the absence of policies and capacity building activities which promote local recruiting, a significant part of total benefits of wind projects, especially high-income jobs and high value-added activities, is captured by already higher income regions. Between countries, developing countries usually have lower innovation capabilities, which means they need to import low-emission technology from abroad and are also less able to adapt these technologies to local conditions and create new markets and business models. This can lead to external dependencies and limit opportunities to leverage economic benefits from technology transfer (Section 16.5.1).

This means that in countries below the technological frontier, the contribution of technological change to climate change mitigation can happen primarily through the adoption and less through the development of new technologies, which can reduce potential economic and welfare benefits from rapid technological change (UNCTAD 2019). The adoption of consumer ICT technologies (Baller et al. 2016) or renewable energy technologies (Lema et al. 2021) cannot bring least developed economies close to the technological frontier without appropriate technological capabilities in other sectors and an enabling innovation system (UNCTAD 2019; Malhotra et al. 2021; Vasconcellos and Caiado Couto 2021; Sagar and Majumdar 2014; Ockwell and Mallett 2012; Ockwell et al. 2018). It has been argued widely that both hard and soft infrastructure, as well as appropriate policy frameworks and capability building, would facilitate developing countries engagement in long-term technological innovation and sustainable industrial development, and eventually in achieving the SDGs (UNCTAD 2019; Ockwell and Byrne 2016; Altenburg and Rodrik 2017).

16.6.2.2 Challenges to governing innovation for sustainable development

Dominant economic systems and centralized governance structures continue to reproduce unsustainable patterns of production and consumption, reinforcing many economic and governance structures from local through national and global scales (Johnstone and Newell 2018). Technological change, as an inherently complex process (Funtowicz 2020), poses governance challenges (Bukkens et al. 2020) requiring social innovation (Repo and Matschoss 2019) (See also Section 5.6 in Chapter 5, and Chapter 13).

Prospects for effectively governing SDG-oriented technological transformations require at a minimum balanced views and new tools for securing the scientific legitimacy and credibility to connect public policy and technological change in our society (Sadras 2020; Jasanoff 2018). Many frameworks of governance have been proposed, such as reflexive governance (Voss et al. 2006), polycentric governance (Ostrom 2010), collaborative governance (Bodin 2017), adaptive governance (Munene et al. 2018) and transformative governance (Rijke et al. 2013; Westley et al. 2013) (see also Chapters 13 and 14).

A particular class of barriers to the development and adoption of new technologies comprises entrenched power relations dominated by vested interests that control and benefit from existing technologies (Chaffin et al. 2016; Dorband et al. 2020). Such interests can generate balancing feedbacks within multi-level social-technological regimes that are related to technological lock-in, including allocations of investment between fossil and renewable energy technologies (Unruh 2002; Sagar et al. 2009; Seto et al. 2016).

Weaker coordination and implementation capacity in some developing countries can undermine ability to avoid trade-offs with other development objectives, like reinforced inequalities or excessive indebtedness and increased external dependency, and can limit the potential of leveraging economic benefits from technologies transferred from abroad (Section 16.5, Cross-Chapter Box 12). Van Welie and Romijn (2018) show that in a low-income setting the exclusion of some local stakeholders from the decision-making process may undermine sustainability transitions efforts. Countries with high levels of inequality can be more prone to elite capture, non-transparent political decision making processes, relations based on clientelism and patronage, and no independent judiciary (Jasanoff 2018), although in particular contexts, non-elites manage to exert influence (Moldalieva and Heathershaw 2020). The dominance of incumbents however implies that sustainable technological transitions could be achieved without yielding any social and democratic benefits (Hansen et al. 2018). In the cultural domain, a recurrent policy challenge that has been observed in most countries is the limited public support for development and deployment of low carbon technologies (Bernauer and McGrath 2016). The conventional approach to mobilizing such support has been to portray technological change as a means of minimizing climate change. Empirical studies show that simply reframing climate policy is highly unlikely to build and sustain public support (Bernauer and McGrath 2016).

Finally, there is a link between social and technological innovation; any innovation is grounded in complex socio-economic arrangements, to which governance arrangements would need to respond (see Sections 5.5 and 5.6, Chapter 13, and Cross-Chapter Box 12 in this chapter). Social innovation can contribute to maximizing synergies and minimizing trade-offs in relation to technological innovation and other innovative practices, but for this to materialize, national, regional and local circumstances need to be taken into account and, if needed, changed. Even in circumstances of high capabilities, the extent social innovation might help to promote synergies and avoid trade-offs is not easy to evaluate (Grimm et al. 2013).

16.6.3 Actions that maximise synergies and minimise trade-offs between innovation and sustainable development

Technological innovation may bring significant synergy in pursuing sustainable development goals, but it may also create challenges to the economy, human well-being, and the environment (Thacker et al. 2019; Schillo and Robinson 2017; Walsh et al. 2020). The degree of potential synergies and trade-offs among SDG differs from country to country and over time (see section 16.6.1.1). These potentials will depend upon available resources, geographical conditions, development stage and policy measures. Even though synergies and trade-offs related to technological innovation have received the least attention from researchers (Deng et al. 2018a), literature show that higher synergy was found where countries' policies take into account the linkages between sectors (Mainali et al. 2018). For technology innovation to be effective in enhancing synergies and reducing trade-offs, its role and nature in production and consumption patterns, as well as in value chains and in the wider economy, requires clarification. Technology ownership and control together with its current orientation and focus towards productivity needs to be revised if a meaningful contribution to the implementation of the SDGs in a transformative way is to be achieved (Walsh et al. 2020). Responsible innovation, combining anticipation, reflexivity, inclusion and responsiveness, has been suggested as a framework for conducting innovation (Stilgoe et al. 2013). Also inclusive innovation (Hoffecker 2021) could make sure that unheard voices and interests are included in decision-making, and methods for this have been implemented in practice (Douthwaite and Hoffecker 2017).

There are several examples on how to maximize synergies and avoid or minimize trade-offs when bringing technological innovation to the ground. When implementing off-grid solar energy in Rwanda, synergies were found between 80 of the 169 SDG targets, demonstrating how mainstreaming off-grid policies and prioritising investment in the off-grid sector can realise human development and well-being, build physical and social infrastructures, and achieve sustainable management of environmental resources (Bisaga et al. 2021). Another example is related to wind power in Northeast of Brazil where the creation of direct and indirect jobs has been demonstrated in areas where capabilities are high, as well as associated improvements in wholesale and retail trade and real estate activities, though this also emphasises the need for capacity development along with international collaboration projects (Vasconcellos and Caiado Couto 2021). Other examples are studies raising awareness on solar energy and women empowerment (Winther et al. 2018) and recycling and waste (Cross and Murray 2018).

Other actions with the potential to maximize synergies are those related to community or "grassroot" technological innovation. The importance of the link between technological innovation and community action and its contribution to sustainable development is usually underestimated, and requires further research and, most importantly, its inclusion in the political agenda on sustainable development (Seyfang and Smith 2007). On the other hand, when technological innovation occurs far from where is implemented and participation in the production, and hence training activities of local actors is minimal, co-benefits and synergies among SDGs are limited and usually far below expectations (Vasconcellos and Caiado Couto 2021; Bhamidipati and Hansen 2021). Actions by policymakers that safeguard environmental and social aspects can boost synergies and maximize those co-benefits (Lema et al. 2021). Given that technological change impacts countries, regions and social groups differently, just transition policies can be designed to ensure all regions and communities are able to take advantage of the energy and other transitions (Henry et al. 2020b; McCauley and Heffron 2018).

Box 16.10 provides insights on how a systemic approach to technological innovation can contribute to reconcile synergies and trade-offs to achieve sustainable development and mitigation goals.

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Box 16.10 Agroecological approaches: the role of local and indigenous knowledge and innovation

Major improvements in agricultural productivity have been recorded over recent decades (FAO 2018a). However, progress has also come with social and environmental costs, high levels of greenhouse gas emissions and rising demand for natural resources (UNEP 2017; Bringezu 2019; UNEP 2013; Díaz et al. 2019; FAO 2018a).

Trend analysis indicate that, of global demand for land, a large share is projected to be supplied by South America, in particular the Amazon (Lambin and Meyfroidt 2011; TEEB 2018) and Chaco forests (Grau et al. 2015). In developing countries, land use change for satisfying international meat demand is leading to deforestation. In Brazil, the amount of GHG emitted only by the beef cattle sector represents 65% of the emissions of the agricultural sector and 15% of the overall emissions of the country (May 2019).

Agricultural and food systems are complex and diverse; they include traditional food systems, mixed food systems and modern food systems (Pengue et al. 2018). Multiple forms of visible and invisible flows of natural resources exist in global food systems (Pascual et al. 2017; IPBES 2019; TEEB 2018).

Technological practices, management and changes in the food chain could help adapt to climate change, reduce emissions and absorb carbon in the soils, thus contributing to carbon dioxide removal (IPCC, 2018, 2019). A range of technologies can be implemented, from highly technological options such as transgenic crops resistant to drought (González et al. 2019), salt or pesticides resistance (OECD 2011b; Kim and Kwak 2020) or smart and 4.0 agriculture (Klerkx et al. 2019), to more frugal, low-cost technologies such as agroecological approaches adapted to local circumstances (Francis et al. 2003; FAO 2018b). These agroecological approaches are the subject of this box.

For developing countries, agroecological approaches could tackle both climate change challenges and food security (WGII-report, Chapter 5, Box 5.10). In SIDSs, they support livelihoods to develop local food value chains can promote sustainable management of natural resources, preserve biodiversity and help build resilience to climate change impacts and natural disasters (FAO 2019). Other advantages of agroecological practices include their adaptation to different social, economic and ecological environments (Altieri and Nicholls 2017), the fact that they are physical and financial capital-extensive, and are well-integrated with the social and cultural capital of rural territories and local resources (knowledge, natural resources, etc.), without leading to technological dependencies (Côte et al. 2019).

Agroecology is a dynamic concept that has gained prominence in scientific, agricultural and political discourses in recent years (Wezel et al. 2020; Anderson et al. 2021) (Chapter 7 - Agroecology (including Regenerative Agriculture); Chapter 5 WGII Box 5.10). There are different agroecological approaches, three of which will be briefly discussed here: agroecological intensification, agroforestry and biochar use in rice paddy fields.

Agricultural intensification provides ways to use land, water and energy resources to ensure adequate food supply while also addressing concerns about climate change and biodiversity (Cassman and Grassini 2020). The term ecological intensification (Tittonell 2014) focuses on biological and ecological processes and functions in agroecosystems. In line with the development of the concept of agroecology, agroecological intensification integrates social and cultural perspectives (Wezel et al. 2015). Agroecological intensification (Mockshell and Villarino 2019) for sub-Saharan Africa aims to address both employment and food security challenges (Pretty et al. 2011; Altieri et al. 2015).

Another example of an agroecological approach is agroforestry. Agroforestry provides examples of positive agroecological feedbacks, such as ‘the regreening of the Sahel’ in Niger. The practice is based on the assisted natural regeneration of trees in cultivated fields, an old method which was slowly dying out but which innovative public policies (the transfer of property rights over trees from the state to farmers) helped restore (Sendzimir et al. 2011).

Rice paddy fields are a major source of methane. Climate change impacts and adaptation strategies can affect rice production and net income of rice farmers. Biochar use in rice paddy fields has been advocated as a potential strategy to reduce GHG emissions from soils, enhance soil carbon stocks and nitrogen retention, and improve soil function and crop productivity (Mohammadi et al. 2020).

Contributions of indigenous people (Díaz et al. 2019), heritage agriculture (Koohafkan and Altieri 2010) and peasants agroecological knowledge (Holt-Giménez 2002) to technological innovation offer a wide array of options for management of land, soils, biodiversity and enhanced food security without depending on modern, foreign agricultural technologies (Denevan 1995). In farming agriculture and food systems, innovation and technology based on nature could help to reduce climate change impacts (Griscom et al. 2017). Evidence suggests that there are benefits to integrating tradition with new technologies in order to design new approaches to farming, and that these are greatest when they are tailored to local circumstances (Nicholls and Altieri 2018).

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16.6.4 Climate change, sustainability development and innovation

This section gives a synthesis of this chapter on innovation and technology development and transfer, connecting it to sustainable development.

In conjunction with other enabling conditions, technological innovation can support system transitions to limit warming, help shift development pathways, and bring about new and improved ways of delivering goods and services that are essential to human well-being *(high confidence)*. At the same time, however, innovation can result in trade-offs that undermine both progress on mitigation and progress towards other sustainable development goals. Trade-offs include negative externalities such as environmental impacts and social inequalities, rebound effects leading to lower net emission reductions or even increases in emissions, and increased dependency on foreign knowledge and providers *(high confidence)*. Digitalisation, for example, holds both opportunity for emission reduction and emission-saving behaviour change, but at the same time causes significant environmental, social and GHG impacts *(high confidence)*.

A systemic view of innovation, that takes into account the roles of actors, institutions, and their interactions, can contribute to both enhanced understanding of processes and outcomes of technological innovation, and to interventions and arrangements that can help innovation. It can also play a role in clarifying the synergies and trade-offs between technological innovation and the SDGs. Effective governance and policy, implemented in an inclusive, responsible and holistic way, could both make innovation policy more effective, and avoid and minimise misalignments between climate change mitigation, technological innovation, and other societal goals *(medium evidence, high agreement)*.

A special feature is the dynamics of transitions. Like other enabling conditions, technological innovation plays both a balancing role, by inhibiting change as innovation strengthens incumbent technologies and practices, and a reinforcing role, by allowing new technologies and practices to disrupt the existing socio-technical regimes *(high confidence)*. Appropriate innovation policies can help organise innovation systems better, while other policies (technology push and demand pull) can provide suitable resources and incentives to support and guide these innovation systems towards societally-desirable outcomes, ensure the innovations are deployed at scale, and direct these dynamics not just towards system transitions for climate change mitigation, but also towards addressing other SDGs. This means taking into account the full life-cycle or value chain as well as analysis of synergies and trade-offs.

Against this backdrop, international cooperation on technological innovation is one of the enablers of climate action in developing countries on both mitigation and adaptation *(high confidence)*. Experiences with international cooperation on technology development and deployment suggest that such activities are most effective when approached as "innovation cooperation" that engenders a holistic, systemic view of innovation requirements, is done in equitable partnership between donors and recipients, and develops local innovation capabilities *(medium evidence, high agreement)*.

Chapter 17, in particular Section 17.4, connects technological innovation with other enabling conditions, such as behaviour, institutional capacity and multi-level governance, to clarify the actions that could be taken, holistically and in conjunction, to strengthen and accelerate the system transitions required to limit warming to be in line with the Paris Agreement and to place countries in sustainable development pathways.

16.7 Knowledge gaps

Filling gaps in literature availability, data collection, modelling, application of frameworks and further analysis in several sectors will improve knowledge on innovation and technology development and transfer, including R&D to support policy making in climate change mitigation as well as adaptation. These policies and related interventions need to benefit from data and methodologies for the ex-post evaluation of their effectiveness.

This section addresses identified knowledge gaps related to what extent developing countries are represented in studies on innovation and technology development and transfer; to national contexts and local innovation capacity; to potential and actual contributions of businesses; to literature emphasis on mitigation; to indicators to assess innovation systems; to non-technical barriers for the feasibility of decarbonisation pathways; to the role of domestic IPR policy; to digitalisation in low-emissions pathways; to the compliance of Paris Agreement in regard to technology and capacity building.

One of knowledge gap identified when assessing the literature is on the representation of developing countries in studies on innovation and technology development and transfer. This includes the conceptual core disciplines of the economics of innovation, innovation systems and sustainability transitions. This goes both for studies on developing countries, and for authors originating from, or active in, developing countries contexts. The evidence of the impact of decarbonisation policy instruments applied to developing countries or SIDS is limited. Expanding the knowledge base with studies with a focus on developing countries would not only allow for testing whether the theories (developed by predominantly by developed-country researchers for industrialised countries) hold in developing country contexts, but also yield policy insights that could help both domestic and international policymakers working on climate-related technology cooperation.

While a growing literature has shown how technology characteristics and complexity, national context and innovation capacity can influence the capacity of a country's innovation ecosystem as a result of incentive and attraction policies, more research is needed to help prioritise and design policies in different national contexts while filling important knowledge gaps regarding the impact of "green" public procurement, lending, "green" public banking and building code policies on innovation outcomes.

There is also a superficial understanding of the potential and actual contributions of businesses, educational institutions and socially responsible programmes, particularly in developing countries, as sources of innovation and early adopters of new technologies, and a notable lack of knowledge about indigenous practices.

Besides the strong bias of literature to studies originating from and based on developed countries, innovation and technology literature is also skewed to mitigation, and within mitigation to energy. Literature on technology innovation for adaptation is largely missing.

In the area of innovation studies, data are limited on the different indicators used to assess the strength of the innovation system, even for energy, including global figures on R&D and demonstration spending, also for developing countries, and their effectiveness. There is also a lack of a comprehensive framework and detailed data to assess the strengths of low-emission innovation systems, including interactions among actors, innovation policy implementation, and strength of institutions.

Another gap in knowledge remains between the results from energy-climate-economy models and those emerging from systems transition and sustainability transition approaches, empirical case studies, and the innovation system literature. If this gap is filled, the understanding of the feasibility of decarbonisation pathways in light of the many non-technical barriers to technology deployment and diffusion could be improved.

In the field of policy instruments, existing evaluations provide insufficient evidence to assess the impact of decarbonisation policy instruments on innovation, as these evaluations mainly focus on environmental or technological effects. The potential positive or negative role of domestic IPR policy in technology transfer to least developed countries remains unclear as the literature does not show agreement. Moreover, gaps remain in impact evaluations of sub-national green industrial policies, which are of growing importance. The interaction between subnational and national decarbonisation policies to advance innovation would also benefit from further research, particularly in developing countries.

The understanding of the role of digitalisation in decarbonisation pathways is lacking and needs to be studied from several angles. Existing studies do not sufficiently take into account knowledge on the energy impact of digital technologies, in particular the increase in energy demand by digital devices, and the increase in energy efficiency. They would benefit from being technology/sector/country-specific.

The way in which digitalisation will influence the framework conditions under which decarbonisation will occur, the socio-economic and behavioural barriers influencing the diffusion of technologies in the long-term scenarios and the relationship with society and its effects need to be further explored.

Given the implications of the digital revolution for sustainability, a better characterisation of governance aspects would increase understanding of the implications and possibilities of digitalisation and other GPTs for policymakers.

Relatedly, research (both theoretical and empirical) on the impacts of imitation, or adaptation of new technological solutions invented in one region and used in other regions, could fill knowledge gaps, in order to accelerate the diffusion of climate-related technologies, while taking care not to reduce the incentive for inventors to invest in the search for new solutions.

Lastly, an independent assessment about the compliance of the Paris Agreement with regard to technology and capacity building as means of implementation is starting under the Enhanced Transparency Framework for action and support, where a methodology of monitoring, reporting and verification are being developed. There is also a lack of analysis of the full landscape of international cooperation, of what is needed to meet the objectives of the UNFCCC and the Paris Agreement, and of its effectiveness.

Frequently Asked Questions (FAQs)

FAQ 16.1 Will innovation and technological changes be enough to meet the Paris Agreement objectives?

The Paris Agreement stressed the importance of development and transfer of technologies to improve resilience to climate change and to reduce greenhouse gas emissions. However, innovation and even fast technological change will not be enough to achieve Paris Agreement mitigation objectives. Other changes are necessary across the production and consumption system and the society in general, including behavioural changes.

Technological changes never happen in a vacuum, they are always accompanied by, for instance, people changing habits, companies changing value chains, or banks changing risk profiles. Therefore, technological changes driven by holistic approaches can contribute to accelerate and spread those changes towards the achievement of climate and sustainable development goals.

In innovation studies, such systemic approaches are said to strengthen the functions of technological or national innovation systems, so that climate-friendly technologies can flourish. Innovation policies can help respond to local priorities and prevent unintended and undesirable consequences of technological change, such as unequal access to new technologies across countries and between income groups, environmental degradation and negative effects on employment.

FAQ 16.2 What can be done to promote innovation for climate change and the widespread diffusion of low-emission and climate-resilient technology?

The speed and success of innovation processes could be enhanced with the involvement of a wider range of actors from the industry, research and financial communities working in partnerships at national, regional and international levels. Public policies play a critical role to bring together these different actors and create the necessary enabling conditions, including financial support through different instruments as well as institutional and human capacities.

The increasing complexity of technologies requires cooperation if their widespread diffusion is to be achieved. Cooperation includes the necessary knowledge flow between within and between countries and regions. This knowledge flow can take the form of exchanging experiences, ideas, skills, practices, among others.

FAQ 16.3 What is the role of international technology cooperation in addressing climate change?

Technologies that are currently known but not yet widely used need to be spread around the world, and adapted to local preferences and conditions. Innovation capabilities are required not only to adapt new technologies for local use but also to create new markets and business models. International technology cooperation can serve that purpose.

In fact, evidence shows that international cooperation on technology development and transfer can help developing countries to achieve their climate goals more effectively, and if this is done properly can also help addressing other sustainable development goals. Many initiatives exist both regionally and globally to help countries in achieving technology development and transfer through partnerships and research collaboration that include developed and developing countries, with a key role for technological institutions and universities. Enhancing current activities would help an effective, long-term global response to climate change, while promoting sustainable development.

Globalization of production and supply of goods and services, including innovation and new technologies, may open up opportunities for developing countries to advance technology diffusion; however, so far not all countries have benefited from the globalisation of innovation due to different barriers such as access to finance and technical capabilities. These asymmetries between countries in the globalization process can also lead to dependencies on foreign knowledge and providers.

Not all technology cooperation directly results in mitigation outcomes. Overall, technology transfer broadly has focused on enhancing climate technology absorption and deployment in developing countries as well as RD&D and knowledge spill-overs.

Paris Agreement also reflects this view by noting that countries shall strengthen cooperative action on technology development and transfer regarding two main aspects: 1) promoting collaborative approaches to research and development and 2) facilitating access to technology to developing country Parties.

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