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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 light-emitting diodes (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 (SDGs). 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 organise 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 into innovation processes. This, in turn, has enabled the analysis and strengthening of innovation systems. Traditional quantitative innovation indicators mainly include research and development (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 16.3, Box 16.10}

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 proven 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 16.2}

Consistent with innovation system approaches, the sharing of knowledge and experiences between developed and developing countries can contribute to addressing global climate and SDGs. 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 appear 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 SIDS. International diffusion of low-emission technologies is also facilitated by knowledge spillovers from regions engaged in clean R&D (*medium confidence*). {16.6}

The evidence on the role of intellectual property rights (IPR) in innovation is mixed. Some literature suggests that it is a barrier, while other sources suggest 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 address 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 16.9}

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 for 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 SDGs. Acknowledging the systemic nature of technological innovation, which involves 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. Digitalisation 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 digitalisation could play in supporting the achievement of stringent mitigation targets. At present, the understanding of both the direct and indirect impacts of digitalisation 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 16.4, Cross-Chapter Box 12 in this chapter}

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 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). Increased production and consumption of goods and services creates economic benefits through 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 with 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 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), as also discussed 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 achieving mitigation and adaptation targets along with broader Sustainable Development Goals (SDGs), while avoiding undesired consequences of technological change.

The environmental impacts of social and economic activities, including emissions of greenhouse gases (GHGs), 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 increased production and consumption of goods and services through different rebound effects that diminish the potential benefits of reducing the pressure on the environment (Kemp and Soete 1990; Grübler 1998; Sorrell 2007; Barker et al. 2009; Gossart 2015).

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, including 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 (Sachs et al. 2019; Pörtner et al. 2021). 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 (Balvanera et al. 2017; Pörtner et al. 2021).

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 (Kuoljok 2019; Singh et al. 2020). 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 SDGs 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).

The literature has been growing rapidly over the past decades on how, in a systemic way, the barriers to sustainability transition can be overcome in various circumstances. A central element is that national systems of innovation can help achieve both climate change goals and SDGs, by integrating new ideas, devices, resources, new and traditional knowledge, and technological changes for more effective and adaptive solutions (Lundvall 1992). At the organisational level, innovation is seen

Table 16.1 | Overview of challenges to accelerated diffusion of technological innovations. Source: based on Markard et al. (2020).

Challenges	Description	Examples
Innovations in whole systems	Since entire systems are changing, changes in system architecture are also needed, which may not keep pace.	Decentralisation 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, e.g., from unions or workers.	Traditional car industry leading to factory 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.	Reduced 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.	Multilevel governance between European Commission and member states in Energy Union package.

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 organisations (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 result 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 is understood to be the use of soft technologies that brings about transformation through establishing new institutions, new practices, and new models to create a positive societal impact, characterised 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 organised 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 (Chapter 3). The section also describes the different phases of innovation and metrics, such as the widely used but also criticised technology readiness levels (TRLs).

Section 16.3 discusses innovation as a systemic process based on recent literature. While the innovation process is often stylised 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 address potential market failures related to innovation and technology diffusion. The section also assesses the cost-effectiveness of innovation policies as well as other policy assessment criteria introduced in Chapter 13.

Section 16.5 assesses the role of international cooperation in technology development and transfer, in particular the mechanisms established under the UN Framework Convention on Climate Change (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 synthesises 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 the innovation process allows for assessment of technology readiness (Section 16.2.1). Qualitative and quantitative analysis of the main elements underpinning innovation – research and development (R&D), learning by doing, and spillovers – allows for an explanation of past and projected future technological changes (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, Section 16.2.3 reviews the literature of the levers influencing the *direction* of technological change in favour of low- and zero-carbon technologies. Moreover, representation of drivers in mathematical and statistical models from Section 16.2.2 allows integration of its analysis with economic and climate effects

within integrated assessment models (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, that is, 'good enough' innovations that fulfil the needs of non-affluent consumers mostly in developing countries (Hossain 2018), are characterised 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. (Pellicer-Sifres et al. 2018; Dana et al. 2021).

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 roles, 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 and commercialisation is not linear (Section 16.3); it often requires a long time and is characterised by significant bottlenecks and roadblocks. Furthermore, technologies may regress 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 in this report.

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

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 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 – that is, focused on addressing a specific need by marginally improving an 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 function (OECD 2015a). These early stages

Table 16.2 | Stages of the innovation process (Section 16.2.1) mapped onto technology readiness levels (Section 16.2.1.4). Source: adapted from Auerswald and Branscomb (2003), TEC (2017), IEA (2020a).

Stage	Main funding actors	Phases	Related technology readiness levels (TRLs)
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)
			9 – Commercial operation in early environment (solution is commercial available, needs evolutionary improvement to stay competitive)
Deployment and diffusion	Firms Private equity Commercial banks Mutual funds	Commercialisation and scale-up (<i>business</i>)	10 – Integration needed at scale (solution is commercial and competitive but needs further integration efforts)
		International organisations and financial institutions Non-governmental organisations (NGOs)	Transfer

of technological innovation are referred to as the ‘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 (Bento and Wilson 2016; Bento et al. 2018) (Section 16.3).

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 (Weyant 2011; Sagar and Majumdar 2014). 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 the absence of stringent climate policies and targets, incumbent fossil-based energy technologies are characterised by lower financing risk, are heavily subsidised (Davis 2014; Kotchen 2021), and depreciate slowly (Arrow 1962a; Nanda et al. 2016; Semieniuk et al. 2021) (Section 16.2.3). In this context, public research funding 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 (Kammen and Nemet 2007; Anadon et al. 2014; Mazzucato 2015a; Chan and Diaz Anadon 2016; Anadón et al. 2017; Howell 2017; Zhang et al. 2019) (Section 16.4). Public policies also play a role in 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 2015a) (Section 16.3.3, Box 16.3 and 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 projects 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 businesses willing to take the investment risk (Mazzucato 2016). Venture capital, traditionally not tailored for energy investment, can also play an increasingly important role, 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 and 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 need 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 (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 (Gillingham and Sweeney 2012; Corey 2014; Jaffe 2015; Haelg et al. 2018). 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 (Grubler 1996; Rogers 2003). 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 10–90% market share of saturation ranges between 5 to over 70 years (Wilson 2012). Investment in commercialisation 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-lifecycle treatment of products (Cross and Murray 2018) (Section 16.4).

16.2.1.4 Technology Readiness Levels

Technology readiness levels (TRLs) are a categorisation that enables consistent, uniform discussions of technical maturity across different types of technology. They were developed by the National Aeronautics and Space Administration (NASA) in the 1970s (Mankins 1995, 2009) 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 European Union (EU). Most recently, the International Energy Agency (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 (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 extensions (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 organisation 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, commercialisation or the readiness of organisations 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 digitalisation.

16.2.2.1 Learning by Doing and Research and Development

Learning by doing and R&D efforts are two factors commonly used by the literature to explain past and projected 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 more efficient use (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 (Section 16.2.1.1).

Learning by doing and R&D 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. R&D can shift this limit because it allows for replacing the existing technology with a new one. On the other hand, incentives to invest in R&D depend on the future cost of manufacturing, which in turn depends on the scale of learning by doing. The empirical evidence for virtuous circle between cost reduction, market growth and R&D were found in the case of the photovoltaic (PV) market (Watanabe et al. 2000) (Box 16.4), but could also lead to path dependency and lock-in (Erickson et al. 2015). Sections 16.4.4 and 13.7.3.1 discuss how simultaneous use of technology push and pull policies could amplify the effects of research and learning.

The benefits of R&D and learning by doing are larger at the economy level than at the firm level (Arrow 1962b; Romer 1990;). As a result, when left to its own, the market 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 mover¹ 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 categorised 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	Research and development (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)
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 photovoltaic, quotas for electric vehicles in China (F. Wang et al. 2017) and Norway (Pereirinha et al. 2018) Biofuels (Brazil) Social innovation with wind energy (Denmark, Germany)

¹ For example, see Spence (1981) and Bhattacharya (1984) for a discussion of first-mover advantages.

The size of the learning-by-doing effect is quantified in literature using learning rates, that is 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 that learning rates vary across technologies, within technologies, and over time (Nemet 2009a; Rubin et al. 2015; Wei et al. 2017). 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 R&D and other factors (Nemet 2006). Numerous subsequent studies attempted to, among others issues, separate the effect of learning by doing and R&D (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 (Nemet 2006; Kavlak et al. 2018). In addition, the relation could reflect reverse causality: increase in deployment could be an effect (and not a cause) of a drop in price (Nordhaus 2014; Witajewski-Baltvilks et al. 2015). 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 (Fleming and Sorenson 2001; Way et al. 2019). Concentrating investment in narrow sets of technologies (specialisation) 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, and due to 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 a narrow set of technologies, neglecting the benefits of decreasing risk through diversification (Sawulski and Witajewski-Baltvilks 2020).

16.2.2.2 Knowledge Spillovers

Knowledge spillovers drive continuous technological change (Romer 1990; Rivera-Batiz and Romer 1991) and are for that reason relevant to climate technologies as well as incumbent, carbon-intensive technologies. Knowledge embedded in innovations by one innovator

gives 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; Fleming and Sorenson 2001; Olsson and Frey 2002; Tsur and Zemel 2007; Arthur 2009). Recombinant innovations speed up technological change by combining different technological solutions, and make things happen that would be impossible with only incremental innovations (van den Bergh 2008; Safarzyńska and van den Bergh 2010; Frenken et al. 2012). It has been shown that 77% of all patents granted between 1790 and 2010 in the USA are coded by a combination of at least two technology codes (Youn et al. 2015). Spillovers related to energy and low-carbon technologies have been documented by a number of empirical studies (*high confidence*) (Popp 2002; Verdolini and Galeotti 2011; Aghion et al. 2016; Witajewski-Baltvilks et al. 2017; 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. 2016). 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 increases 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 effects, 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*) (Golombek and Hoel 2004; Gerlagh and Kuik 2014). 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 the 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 Digitalisation

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 (Section 5.3.4.1 and Cross-Chapter Box 11 in this chapter).

Several GPTs relevant for climate mitigation and adaptation emerged as a result of digitalisation, namely the adoption or increase in the use of information and communication technologies (ICTs) by citizens, organisations, industries or countries, and the associated restructuring of several domains of social life and of the economy around digital technologies and infrastructures (Brennen and Kreiss 2016; IEA 2017b). The digital revolution is underpinned by innovation in key technologies, for example, 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 pace at which the physical and

digital worlds are converging increases the relevance of disruptive digitalisation in the context of climate mitigation and sustainability challenges (European Commission 2020) (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 greenhouse gas (GHG) emission savings; they also have larger system-wide impacts (Kaack et al. 2021). In industrial sectors, robotisation, 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 (Section 11.3.4.2). Smart mobility is changing transport demand and efficiency (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) (Sections 9.4 and 9.5), and support the shift away from asset redundancy (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 realising flexible and decentralised opportunities through energy-as-a-service concepts and particularly with pay-as-you-go (Section 15.6.8).

Yet, increased digitalisation could 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).

Cross-Chapter Box 11 | Digitalisation: Efficiency Potentials and Governance Considerations

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Digital technologies impact positively and negatively on GHG emissions through: their own carbon footprint; technology application for mitigation; and 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; Huang et al. 2016; IEA 2017b; Jones 2018). 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 smartphone 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 (Avgerinou et al. 2017; Vranken 2017; Stoll et al. 2019; Masanet et al. 2020) (Section 5.3.4.1). Renewable energy can serve as a low-carbon energy provider for the operation of a 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 is estimated at 5 to 10%, with larger savings possible. Approaches include building energy management systems (BEMS), home energy management system (HEMS), demand response

Cross-Chapter Box 11 (continued)

and smart charging (Cross-Chapter Box 11, Table 1). Data centres can also play a role in energy system management, for example, by increasing renewable energy generation through predictive control (Dabbagh et al. 2019), and by helping to 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 (Wahlroos et al. 2017, 2018; Koronen et al. 2020; 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, digitalisation 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 (Section 5.3). Energy and GHG emission impacts from the ubiquitous deployment of smart sensors and service optimisation applications in smart cities 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

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

Sector	Approach	Quantitative evidence	Contribution of digitalisation	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	Zangheri et al. (2019); Buckley (2020); Nawaz et al. (2020); Khanna et al. (2021)
Smart mobility	Shared mobility and digital feedback (ecodriving)	Reduction for shared cycling and shared pooled mobility; increase for ride hailing/ ride sourcing; reduction for eco-driving	– 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	Zeng et al. (2017); OECD and ITF (2020)
Smart cities	Using digital devices and big data to make urban transport and building use more efficient	Precise data about roadway use can reduce material intensity and associated GHG emissions by 90%	++ Big data analysis necessary for optimisation	Efficiency gains are often compensated by more driving and other rebound effects; privacy concerns linked with digital devices in homes	Milojevic-Dupont and Creutzig (2021) (Chapter 10, Box 10.1)
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, optimise crop management, reduce fertilisers 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	Deichmann et al. (2016); Chlingaryan et al. (2018); Soto Embodas et al. (2019); Townsend et al. (2019)
Industry	Industrial internet of things (IIoT)	Process, activity and functional optimisation increases energy and carbon efficiency	++ Increased efficiency ++ 1.3 GtCO ₂ -eq estimated abatement potential in manufacturing + Promote sustainable business models	Optimisation in value chains can reduce wasted resources	GeSI (2012); Wang et al. (2016); Parida et al. (2019); Rolnick et al. (2021)
Load management and battery storage optimisation	Big data analysis for optimising 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 utilisation of generation assets System-wide rebound effects possible	Akorede et al. (2010); Aghaei and Alizadeh (2013); de Sisternes et al. (2016); Voyant et al. (2017); Gür (2018); Hirsch et al. (2018); Sivaram (2018a); Vázquez-Canteli and Nagy (2019) (Chapter 6, Section 6.4)

Cross-Chapter Box 11 (continued)

integrated holistically within policy design (Kunkel and Matthes 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 (Sections 5.4, 5.6 and 9.9).

Broader societal impacts of digitalisation 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*) (Sections 4.4, 5.3 and 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 (Matthes 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). Digitalisation 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; however, open source digital technologies can counter this tendency (e.g., Rotz et al. 2019). Digital technologies play a role in mobilising citizens for climate and sustainability actions (Segeberg 2017; Westerhoff et al. 2018).

Whether the digital revolution will be an enabler or a barrier for decarbonisation will ultimately depend on the governance of both digital decarbonisation pathways and digitalisation 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 (Section 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 digitalisation 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 the participation of rural communities, especially in developing countries, and promote technological leapfrogging, for example, decentralised 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/socio-economic 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 digitalisation as a megatrend (*medium evidence, high agreement*). Digitalisation 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, and so on). Regulations that limit or ban the expropriation and exploitation of behavioural data, sourced via smartphones, represent crucial aspects in digitalisation 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 AI take over ethical choices (Craglia et al. 2018; Rahwan et al. 2019). Appropriate governance is necessary for digitalisation to effectively work in tandem with established mitigation technologies and choice architectures. Consideration of system-wide effects and overall management is essential to avoid runaway effects. Overall governance of digitalisation remains a challenge, and will have large-scale repercussions on energy demand and GHG emissions.

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 realised 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 (Nemet 2006; Kavlak et al. 2018) as well as 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) (Box 16.4), which can also become the case in organic PV technologies (Gambhir et al. 2016; Kavlak et al. 2018).

16.2.3 Directing Technological Change

Technological change is characterised 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 CO₂ emissions (Acemoglu et al. 2012, 2014; Hémous 2016; Grecker et al. 2018). 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. 2016). If there is no close substitute for a 'dirty resource', then its intensity in production could still be reduced by increasing the

efficiency of the dirty resource relative to the efficiency of other inputs (Hassler et al. 2012; André and Smulders 2014; Witajewski-Baltvilks et al. 2017). For instance, energy efficiency improvement leads to a 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 that allow them to economise 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 a 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 with 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 a higher number of low-carbon energy or energy efficiency patents (Newell et al. 1999; Popp 2002; Verdolini and Galeotti 2011; Noailly and Smeets 2015; Ley et al. 2016; Witajewski-Baltvilks et al. 2017; Lin and Chen 2019). Sue Wing (2008) finds that innovation induced by energy prices had a minor impact on the decline in US energy intensity in the last decades of the 20th century, and that autonomous technological change played a more important role. Several studies explore the impact of a carbon tax on green innovation (Section 16.4). However, disentangling the effect of policy tools is complex because the 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 (Section 16.2.3.3).

The value of the market for clean technologies is determined not only by current profit, but also by a firm's expectation of future profits (Alkemade and Suurs 2012; Grecker 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 the rapidly growing economies of Asia and Africa which are on the brink of making major decisions about the type of infrastructure they build as they grow, develop, and industrialise (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. 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 (Taylor 2012; Nemet et al. 2013; 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 ICT and medicine are also reflected in the trends in venture capital funding. Research found that early-stage investments in cleantech companies were more likely to fail and returned less capital than comparable investments in software and medical technology (Gaddy et al. 2017). This led to investors retreating from hardware technologies required for renewable energy generation and storage, and moving 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 characterised by incremental innovations. The role of finance in directing investment is further discussed in Chapter 15, Section 15.6.2.

16.2.3.3 Internationalisation of Green Technological Change

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

The model in Hémous (2016) predicts that such a coalition could induce acceleration of clean technological change through a mix of carbon taxation, 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 goods 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) an 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, provided that the latter regions did not invest in abatement before.

However, this chain breaks if the regions that are behind the 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 spillovers 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).

Research relying on patent citations has indicated that Foreign Direct Investment (FDI) is a mechanism for firms to contribute to the recipient country's innovation output as well as benefit from the recipient country in industrialised 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 a 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).

Table 16.4 | Examples of institutional deficiencies preventing deployment of new technologies in countries behind the 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 organisation 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 mobilising capital for individual firms at large scale	Abramovitz (1986); Aghion et al. (2005)

16.2.3.4 Market Failures in Directing Technological Change

Market forces alone cannot deliver Pareto optimal (i.e., social) efficiency 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 subsidising clean technologies (and not dirty ones) is also necessary to break the lock-in of dirty technological change. Recommendations for technical changes are often 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 Decarbonisation 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 is 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 that estimates the rates of cost reduction 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 (Mercurio et al. 2016; Krey et al. 2019). 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 (Sections 16.2.2 and 16.2.3) or positive

macroeconomic 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 (Criqui et al. 2015; Emmerling et al. 2016; Paroussos et al. 2020) (Section 16.2.2.1), multifactor learning curves (Kahouli 2011; Yu et al. 2011), or other drivers of cost reduction 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 cost 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 (Jamashb 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 (Emmerling et al. 2016; Fragkiadakis et al. 2020). 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, electric vehicles, biofuels, industry materials, batteries and advanced heating and cooking appliances can lead to the following results in a decarbonisation 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 alleviate 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 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 (Marangoni and Tavoni 2014; Baker et al. 2015; Iyer et al. 2015; Napp et al. 2017; Biresselioglu et al. 2020; van Sluisveld 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; Geels et al. 2016; Doukas et al. 2018; Gambhir et al. 2019; Trutnevyte et al. 2019). 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 optimisation (Aleluia Reis et al. 2021). So far, no model can account for all these interactions simultaneously.

Another key aspect of decarbonisation regards issues of acceptability and social inclusion in decision-making. Participatory processes involving stakeholders can be implemented using several methods to incorporate qualitative elements in model-based scenarios on future change (van Vliet et al. 2010; Nikas et al. 2017, 2018; Doukas and Nikas 2020; van der Voorn et al. 2020).

16.2.4.3 Implications for the Modelling of Technical Change in Decarbonisation 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 to 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 IPCC's Sixth Assessment Report (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.

Box 16.1 | Comparing Observed Energy Technology Costs and Deployment Rates with Projections from AR6 Global Modelled Pathways

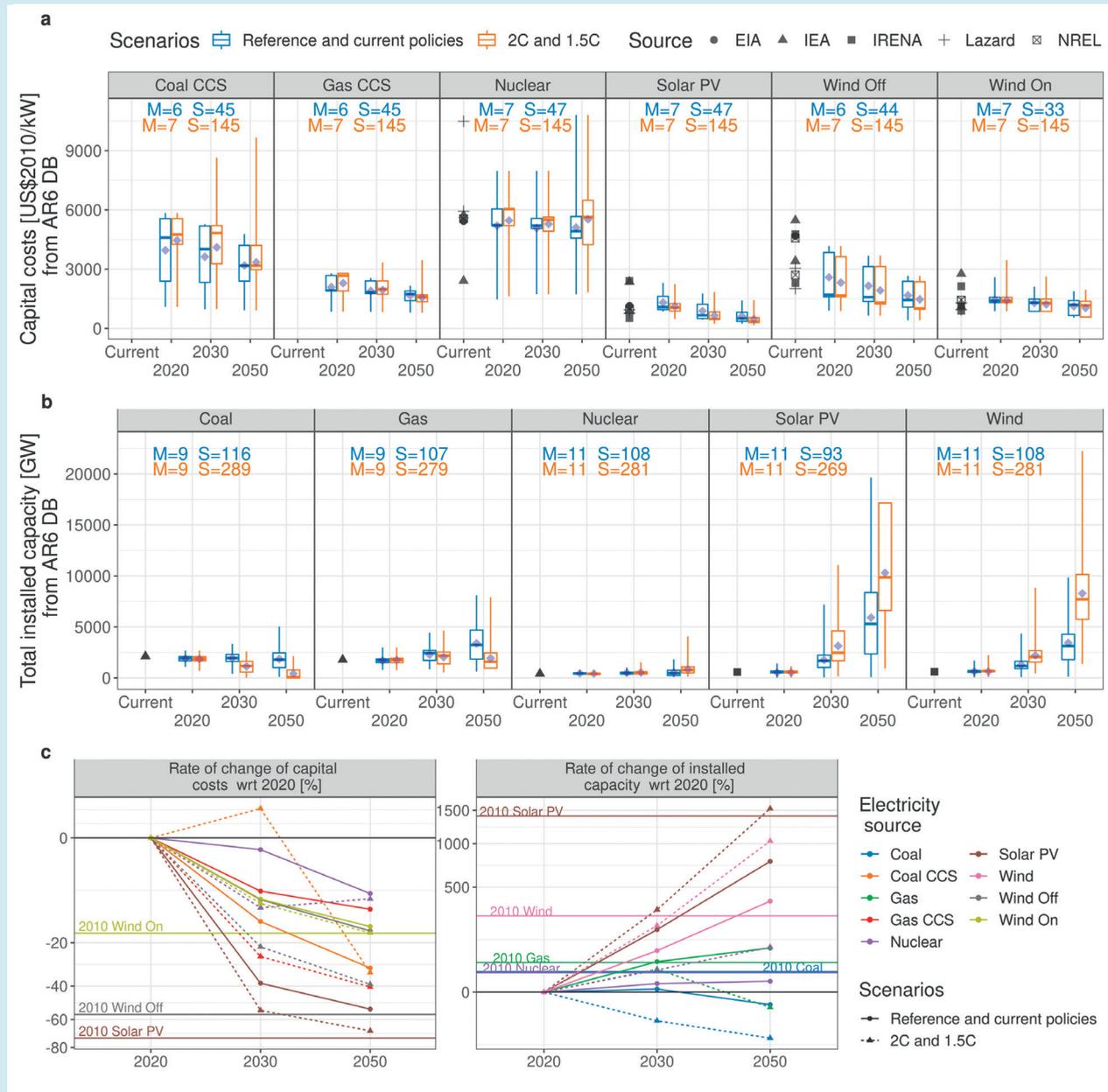
Currently observed costs and deployment for electricity supply technologies from a variety of sources are compared with projections from two different sets of scenarios contained in the AR6 Scenario database: (i) scenarios that limit warming to 3°C (>50%) and scenarios that limit warming to 4°C (>50%), and (ii) scenarios that limit warming to 2°C (>67%) or lower (AR6 Scenarios Database). Global aggregate costs are shown for the following technologies: coal with carbon dioxide capture and storage (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 sets of scenarios (Box 16.1, Figure 1a). For offshore wind 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 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 scenarios that limit warming to 3°C (>50%) and in scenarios that limit warming to 4°C (>50%) (Box 16.1 Figure 1b), where energy and climate policies are implemented in line with NDCs announced prior to COP26. More 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 scenarios that limit warming to 3°C (>50%) and in scenarios that limit warming to 4°C (>50%) is within comparable ranges of that observed in the last decade. In the case of scenarios that limit warming to 2°C (>67%) or lower, capacity installed is higher for renewable technologies and nuclear, and lower for fossil-based technologies (Box 16.1, Figure 1c).

Box 16.1 (continued)

The higher deployment in scenarios that limit warming to 2°C (>67%) or lower cannot be explained solely as a result of technology cost dynamics. In IAMs, technology deployment is also governed by system constraints that characterise both 3°C (>50%) and 4°C (>50%) scenarios, for example, 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 limit 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: (i) scenarios that limit warming to 3°C (>50%) and scenarios that limit warming to 4°C (>50%) ("Reference and current policies"), and (ii) scenarios that limit warming to 2°C (>67%) or lower ("2°C and 1.5°C"). Panel (a) Current capital costs are sourced from Table 1 (Timilsina 2020); distribution of capital costs in 2030 and 2050 (AR6 Scenarios 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 (IEA 2020c; IRENA 2020a, b); distribution of total installed capacity in 2030 and 2050 (AR6 Scenario 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) $(\text{Median}_{\text{year}} - \text{Median}_{2020}) / \text{Median}_{2020} * 100$. 'M' indicates the number of models, 'S' the number of scenarios for which this data is available. 'Reference and current policies' are scenarios that limit warming to 3°C (>50%) and scenarios that limit warming to 4°C (>50%) (C6 and C7 AR6 scenario categories). '2C and 1.5C' are scenarios that limit warming to 2°C (>67%) or lower (C1, C2 and C3 AR6 scenario categories). Each model may have submitted data for more than one model version.

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; the cumulative contribution of incremental innovations over time can be very significant (Kline and Rosenberg 1986). Innovations can come, not just from formal research and development (R&D) but also sources such as production engineers and the shop floor (Kline and Rosenberg 1986; Freeman 1995).

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 conceptualises 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 (Section 1.7.3, Chapter 5 Supplementary Material, 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 in policy analyses is termed an '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, *national innovation systems (NIS)*, highlight the importance of national and regional relationships for determining the technological and industrial capabilities and development of a country (Lundvall 1992; Nelson 1993; Freeman 1995). Nelson (1993) and Freeman (1995) highlight the role of

institutions that determine the innovative performance of national firms as a 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' – that is, notions of interactive learning, in which user-producer relationships are particularly important (Lundvall 1988). Building on this, various other applications of the 'innovation system' framework have emerged in the literature.

Technological innovation systems (TIS), with a technology or a set of technologies (more narrowly or broadly defined in different cases) as the unit of analysis, 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 (Hekkert et al. 2007; Bergek et al. 2008), 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) are 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 innovation systems (RIS) and global innovation systems (GIS), recognise 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...

Table 16.5 | Functions that the literature identified as key for well-performing technological innovation systems. Source: 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

and the economic system of valuation in which markets for the innovation are constructed'.

The relevance of *mission-oriented innovation systems (MIS)*, comes into focus with the move towards mission-oriented programmes 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; Horton and Mackay 2003; Brooks and Loevinsohn 2011; Klerkx et al. 2012), energy (Sagar and Holdren 2002; OECD 2006; Gallagher et al. 2012; Wieczorek et al. 2013; Darmani et al. 2014; Mignon and Bergek 2016), industry (Koasidis et al. 2020b) and transport (Koasidis et al. 2020a), and sustainable development (Anadon et al. 2016b; Clark et al. 2016; Bryden and Gezelius 2017; 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 listed in Table 16.5.

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 Multi-Level 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 of 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 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. This 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, multidirectional and cumulative socio-technical processes playing out at multiple levels over time, with a concomitant expansion in the scale and scope of the transition (Elzen et al. 2004; Geels 2005). There have been numerous studies that draw on the MLP to understand different aspects of climate technology innovation and diffusion (van Bree et al. 2010; Geels 2012; Geels et al. 2017).

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; Altenburg 2009; Lundvall et al. 2009; Tigabu et al. 2015; Tigabu 2018; Choi and Zo 2019) 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. Also, a second main traditional perspective on innovation policy was focused on correcting for 'market failures' (Weber and Truffer 2017) (Section 16.2). 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 Sections 16.3.1 and 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; Negro et al. 2012; Weber and Rohracher 2012; Wieczorek and Hekkert 2012). 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 summarises 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.

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. 2020a, b), 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 programme 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).

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	<ul style="list-style-type: none"> – 'Stop and go policy': lack of continuity and long-term regulations; inconsistent policy and existing laws and regulations – 'Attention shift': policymakers 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	<ul style="list-style-type: none"> – Large-scale criteria – Incremental/near-to-market innovation – Incumbent's dominance 	30
Soft institutions	<ul style="list-style-type: none"> – Lack of legitimacy – Different actors opposing change 	28
Capabilities/capacities	<ul style="list-style-type: none"> – Lack of technological knowledge of policymakers 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	<ul style="list-style-type: none"> – Wrong focus or not specific courses at universities knowledge institutes – Gap/misalignment between knowledge produced at universities and what is needed in practice 	16
Too weak interactions	<ul style="list-style-type: none"> – Individualistic entrepreneurs – No networks, no platforms – Lack of knowledge diffusion between actors – Lack of attention for learning by doing 	13
Too strong interactions	<ul style="list-style-type: none"> – Strong dependence on government action or dominant partners (incumbents) – Networks allows no access to new entrants 	8
Physical infrastructure	<ul style="list-style-type: none"> – No access to existing electricity or gas grid for renewable energy technologies – No decentralised, small-scale grid – No refill infrastructure for biofuels, hydrogen, biogas 	2

Box 16.2 | Standards and Labelling for Energy Efficient Refrigerators and Air Conditioners in India²

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 to promote innovation in energy efficient appliances in 2006 (Sundaramoorthy and Walia 2017). While context-dependent, the programme's design, policies and scale-up contain lessons for addressing systemic failures elsewhere too.

Programme design and addressing of early systemic barriers

To design the S&L programme, 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 programmes. 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 (McNeil et al. 2008).

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).

Box 16.2 (continued)

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 the Indian Institute of Technology (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 multistakeholder 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 programme was conducted from 2006 to 2008 to inform customers about energy-efficient appliances, to enable them to interpret the labels correctly, and to understand their purchase decisions and information sources (Jain et al. 2018; Joshi et al. 2019). BEE initiated a capacity-building programme for retailers to be an information source for customers. 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 International Organization for Standardization (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 programme 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 programme 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.

16.3.3 Indicators for Technological Innovation

Assessing the state of technological innovation helps in understanding the progress of current efforts and policies in meeting stated objectives, and how we might design policies to do better.

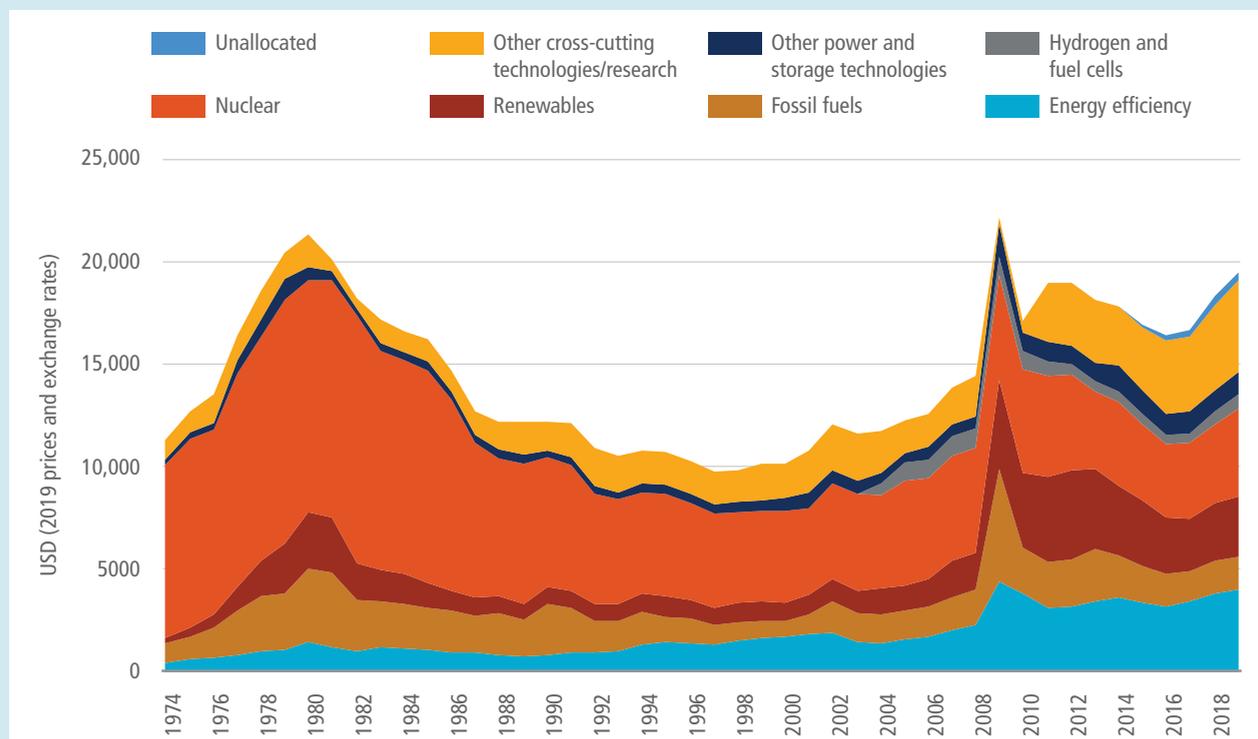
Traditionally, input measures such as research, development and demonstration (RD&D) investments, and output measures such as scientific publication and patents were used to characterise innovation activities (Freeman and Soete 2009). This is partly because of the successes of specialised R&D efforts (Freeman 1995), the predominant linear model of innovation, and because such measures

can (relatively) easily be obtained and compared. In the realm of energy-related innovation, RD&D investments remain the single most-used indicator to measure inputs into the innovation process (Box 16.3). Patent 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) (Veeffink 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 an indicator of innovative activities is complicated by several issues (de Rassenfosse

Box 16.3 | Investments in Public Energy Research and Development

Public energy R&D investments are a crucial driver of energy technology innovation (Sections 16.2.1.1 and 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 only available starting from 2014 and thus not included in Figure 1.

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, carbon dioxide capture, use and storage, 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, is 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: RD&D Database (2019), IEA (2019) (extracted on November 11, 2020).

et al. 2013; Haščič and Migotto 2015; Jaffe and de Rassenfosse 2017), including the fact that the scope of what are 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*) (Jasmab and Pollitt 2005; Jasmab and Pollitt 2008; Sanyal and Cohen 2009; European Commission 2015; American Energy Innovation Council 2017; Gaddy et al. 2017; National Science Board 2018).

Financing firms also play an important role in the energy innovation process, but data availability is 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 cleantech 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 (Anadón 2012; Mazzucato 2013; 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).

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 (Freeman and Soete 1997; Sagar and Holdren 2002; Hu et al. 2018), combined with the functions of technological innovation systems (Miremadi et al. 2018), while also being cognisant 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 on whether a given country/region is committed to strengthen a given technology or phase.

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

Function	Input indicators	Output indicators	Outcome indicators	Actors	Policies	Structural and systemic indicators
Knowledge development	Higher education investments Research and development (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 programmes and strategies Intellectual Property Rights (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 agreements Number of research exchange programmes 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 programmes Strength of linkage among key stakeholders Participation to framework agreements ICT access

Function	Input indicators	Output indicators	Outcome indicators	Actors	Policies	Structural and systemic indicators
Guidance of search	Policy action plans and long-term targets Shared strategies and roadmaps Articulation of interest from lead customers Expectations of markets/profits	Level of media coverage Scenarios and foresight projects	Budget allocations Mission-oriented innovation programmes	Governments Interest groups Media	Targets set by government for industry Innovation policies Credible political support	Media strength
Resource mobilisation	Access to finance Graduate in Science, Technology, Engineering, and Mathematics (STEM) Gross expenditure on R&D/total expenditure Domestic credit to private sector Number of researchers in R&D per capita Public energy R&D expenditure/total expenditure Expenditure on education Investment in complementary assets and/or infrastructure (e.g., charging infrastructure for electric vehicles, smart grids) Venture capital on deals	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/programme evaluation Innovation policies Higher education policies	
Entrepreneurial activities	Number of new entrants Percentage of clean energy start-ups/incumbents Access to finance for cleantech start-ups	Small and medium-sized enterprises (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 Philanthropists	Ease of starting a business Risk-capital policies Start-up support programmes Incubator programmes	Start-up support services
Market formation	Public market support High-tech imports	Market penetration of new technologies Increase in installed capacity Number of niche markets Number of technologies commercialised	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, policymakers, etc.) Greater recognition of benefits	Public opinion Policymaker opinion Executive opinion on regulation Environmental standards and certification	Governments Stakeholders Citizens Philanthropists	Regulatory quality Regulatory instruments Political consistency	Participatory processes

The systemic approach to innovation and transition dynamics (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, there is no available set of quantitative metrics that, collectively, can help get a picture of innovation in a particular energy technology or set of energy technologies. Also we are still lacking an 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 (Dziallas and Blind 2019).

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 (Jaffe et al. 2005; Bürer and Wüstenhagen 2009; Negro et al. 2012; Twomey 2012; Veugelers 2012; Weber and Rohrer 2012) used in what is termed as 'policy mixes' (Rogge and Reichardt 2016; Edmondson et al. 2019, 2020; Rogge et al. 2020). Empirical research shows that, in the energy and environment space, when 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 (*robust evidence, high agreement*) (Bunn et al. 2014; Bergek et al. 2015; Rogge and Reichardt 2016; Nemet 2019). An example of this systemic and dynamic nature of policies is the 70-year innovation journey of solar photovoltaic (PV), covering multiple countries, which is reviewed in Box 16.4.

Box 16.4 | Sources of Cost Reductions in Solar Photovoltaics

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

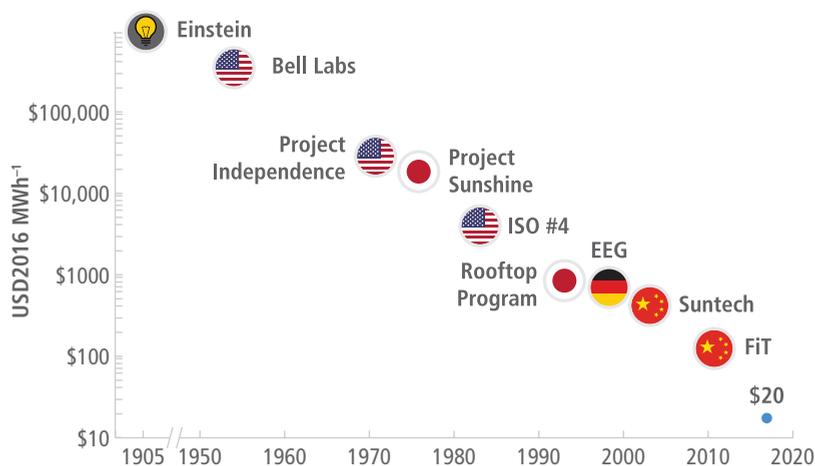
Solar PV has attracted interest for decades, and until recently was seen as an intriguing novelty, serving a niche, but widely dismissed as a serious answer to climate change and other social problems associated with energy use. Since the IPCC's Fifth Assessment Report (AR5), PV has become a substantial 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 six continents, had each installed at least 1GW of solar (IRENA 2020a).

The cost of generating electricity from solar PV is now lower in sunny locations than running existing fossil fuel power plants (IEA 2020c) (Chapter 6). 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 USA, Japan, Germany, Australia, and China – in that sequence (Green 2019; Nemet 2019). As shown in Box 16.4, Figure 1, PV improved as the result of:

- i. scientific contributions in the 1800s and early 1900s, in Europe and the USA, 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);
- ii. a breakthrough at a corporate laboratory in the USA in 1954 that made a commercially available PV device available and led to the first substantial orders, by the US Navy in 1957 (Ohl 1946; Gertner 2013);
- iii. a government R&D and public procurement effort in the 1970s in the USA, that enlisted skilled scientists and engineers into the effort and stimulated the first commercial production lines (Christensen 1985; Blieden 1999; Laird 2001);
- iv. Japanese electronic conglomerates, with experience in semiconductors, serving niche markets in the 1980s and in 1994 launching the world's first major rooftop subsidy programme, with a declining rebate schedule, and demonstrating there was substantial consumer demand for PV (Kimura and Suzuki 2006);
- v. 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);

Box 16.4 (continued)



Box 16.4, Figure 1 | Milestones in the development of low-cost solar photovoltaics. Source: Nemet (2019).

- vi. 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 PVs from 2013 onward (Quitow 2015; Helveston and Nahm 2019); and
- vii. a cohort of adopters with high willingness to pay, accessing information from neighbours, and installer firms that learnt from their installation experience as well as that of their competitors, to lower soft costs (Ardani and Margolis 2015; Gillingham et al. 2016).

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 reduction (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 programme 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 PV's 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 nine 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 telecoms 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 had 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 pointed 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, it took solar PV 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 how to use public policy to speed up innovation over much shorter time frames, for example, 15 or fewer years.

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; (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 for the need to craft policies that affect different actors in the transition, some supporting and some 'destabilising' (Geels 2002; Kivimaa and Kern 2016).

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) (Chapters 1 and 17). This new policy paradigm is opening up a new discursive space, shaping policy outcomes, and giving rise to the emerging idea of transformative innovation policy (Fagerberg 2018; Diercks et al. 2019).

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 a 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 agriculture, forestry and other land-use (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 (Anadon et al. 2016b; Rogge and Reichardt 2016; Åhman et al. 2017; Anadón et al. 2017; Roberts et al. 2018) (*robust evidence, high agreement*). Both technology push (e.g., scientific training, research and development (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*) (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 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 – such as carbon taxes or feed-in tariffs – 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) (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 promote 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 (Section 16.2); demand-pull instruments become more relevant in the later stages of the innovation process (Mowery and Rosenberg 1979; Anadon and Holdren 2009; Nemet 2009b) (Section 16.2).

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 focused 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 prioritises 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 the different types of market or systemic failures or bottlenecks described in Sections 16.2 and 16.3 (OECD 2011a).

Section 16.3 characterised technological innovation as a systemic, non-linear and dynamic process. Figure 16.1 below presents a stylised (and necessarily incomplete) view connecting the innovation process stages presented in Section 16.2, some of the key 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 Section 16.4.4, regulatory policy instruments also shape the early stages of technology development.

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 16.4 (for definitions see Peñasco et al. 2021)
Economic or financial policy instrument types	Research and development (R&D) investments	R&D investments (including demonstration) (Box 16.3)
	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	<i>Not covered</i>
Border carbon adjustments	<i>Not covered</i>	
Offsets	<i>Not covered</i>	
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	<i>Not covered</i>	
Soft policy instruments	Divestment and disclosure	<i>Not covered</i>
	Voluntary agreements (public voluntary programmes and negotiated agreements)	Voluntary agreements
		Energy labels

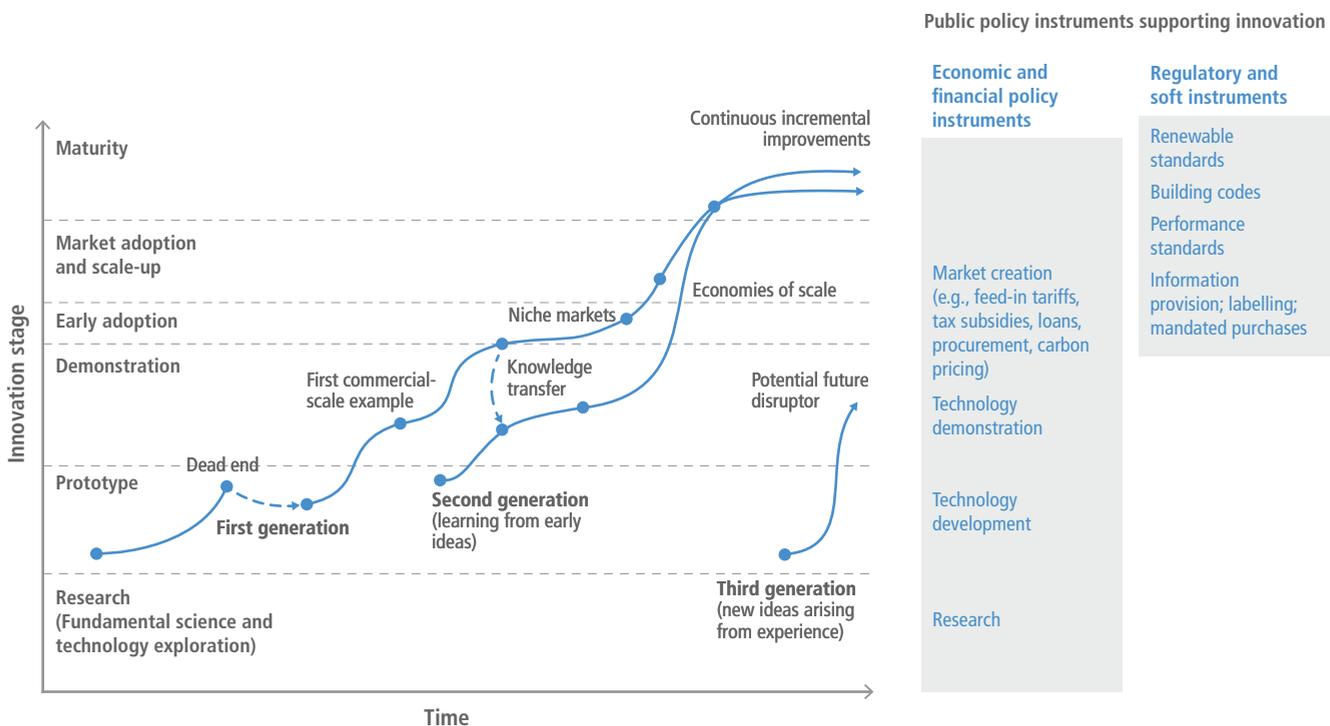


Figure 16.1 | Technology innovation process and the (illustrative) and role of different public policy instruments (on the right-hand side). Source: adapted from IEA (2020a). Note that, as shown in Section 16.4.4, demand-pull instruments in the regulatory instrument category, for instance, can also shape the early stages of the innovation process. Their position on the latter stages is highlighted in this figure 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 (Anadón 2012; Surana and Anadon 2015; Meckling et al. 2017; Matsuo and Schmidt 2019; 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 (Stokes and Warshaw 2017; Deng et al. 2018; Probst et al. 2020). For instance, this was the case for climate and air pollution policies with local content requirements for different types of renewable energy projects in places including China (Qiu and Anadon 2012; Lewis 2014), 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 (Meckling et al. 2015; Schmidt and Sewerin 2017; Stokes and Breetz 2018; Meckling 2019; Meckling and Nahm 2019; Schmid et al. 2020). 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 (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, 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. 2015). When technologies grow out of the niche (second phase), they pose a more serious competition to incumbents who may become more vocal opponents of additional support for innovation in the competing technologies (Geels 2014; Stokes 2016). 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 (Levin et al. 2012; Aklin and Urpelainen 2013).

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, we assess impacts on competitiveness and equity, although we primarily focus on innovation outcomes. Table 16.9 lists the selected set of indicators used to assess the impact of the policy instrument types covered in the right-hand 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.

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 (Section 16.3), there is a large volume of quantitative and qualitative literature aiming to identify such an 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: research and development (R&D) grants, R&D tax credits, prizes, national laboratories, technology incubators (including support for business development, plans), novel direct funding instruments

(e.g., Advanced Research Projects Agency–Energy (ARPA-E)), and innovation procurement.

Public research, development and demonstration (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 focusing on this assessment, only three found no relationship between R&D funding and innovation metrics (Doblinger et al. 2019; Goldstein et al. 2020; Peñasco et al. 2021). Sixteen 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 summarises the evidence available of the impact of ARPA-E (a public institution created in the USA 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 institutions of the Fraunhofer Society.

No evidence has been found regarding the specific impact of R&D tax credits on climate mitigation or adaptation technologies, but it is worth noting that, generally speaking, R&D tax credits are found to incentivise innovation in firms, with a 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 product (GDP) in OECD in 2013 and much more in some

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), Grubb et al. (2021) and Peñasco 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 Chapter 13)
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 percentage 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

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 act 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 six product clusters as part of the government's purchasing in terms of sustainability (PIANOo Expertisecentrum 2020). The six product clusters are: i) automation and telecommunications; ii) energy; iii) ground, road and 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 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 Life Cycle Analysis (LCA) 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 CO₂ 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 was administered among public procurement officers who subscribed to the newsletters of two Dutch associations that provide advice and training to public procurers. This yielded a sample size of more than 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 to bring together relevant information regarding public procurement and provide 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 GPP, innovation-oriented public procurement and the circular economy, but not the other types of public procurement.

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 incentivise 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 programme 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 programmes is relatively limited, and suggests either a positive impact or no impact (Alvarez and Rubio 2015; Baron 2016; Fernández-Sastre and Montalvo-Quizhpi 2019; Peñasco et al. 2021). 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 in both developing and developed countries 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; Baron 2016; ICLEI 2018).

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, and 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 (Doblinger et al. 2019; Goldstein et al. 2020; Peñasco et al. 2021). The majority of the 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 in developed countries (*limited evidence, low agreement*), and none from developing countries. 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), and are focused on the energy sector, and on the USA 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 focused on general technology innovation policy finds that institutions often do not embody the goals of the poor or marginalised (Anadon et al. 2016b).

In the case of the US Department of Energy, block funding that can be quickly allocated to novel projects (such as that allocated to National Labs as part of the Laboratory Directed Research and Development funding) has been found to be associated with improved innovation indicators (Anadon et al. 2016a). Research in 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).

Box 16.6 | ARPA-E – A Novel R&D Funding Allocation Mechanism Focused on an Energy Mission

One approach for allocating public R&D funds in energy involves relying on active programme 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 USA, the Advanced Research Projects Agency for Energy (ARPA-E). This agency was created in 2009 and it was modelled on the experience of Defense Advanced Research Projects Agency (DARPA) – a US government agency funding high-risk, high-reward research in defence-related areas (Bonvillian and Van Atta 2011; US National Academies of Sciences Engineering and Medicine 2017; Bonvillian 2018). DARPA programme 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 model involved programme managers requesting external review as an informational input (Azoulay et al. 2019).

As for DARPA, ARPA-E programme managers use an active management approach that involves empowering programme managers 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 retain some control on the funded projects after the allocation of 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 programme manager level.

Research on ARPA-E also sheds light on the process of project selection, or how programme managers decide what projects to fund. Programme managers do not just follow the rankings of peer reviewers (sometimes projects with very disparate rankings were funded) and in many cases programme 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 of time to assess, early analysis has shown that this mission-orientation and more 'actively managed' R&D funding programme may yield greater innovation patenting outcomes than other US energy R&D funding programmes, and a greater or similar rate of academic publications when compared to other public funding agencies in energy in the USA, ranging from the Office of Science, the more applied Office of Energy Efficiency and Renewable Energy, or the small grants office (US National Academies of Sciences Engineering and Medicine 2017; Goldstein and

Box 16.6 (continued)

Narayanamurti 2018). 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-E approach has been successful in the USA 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*).

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 (Howell 2017; Pless 2019). 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; focusing demonstration projects on learning; incentivising international collaboration in energy research; adopting an adaptive learning strategy; and making funding stable and predictable (Narayanamurti et al. 2009; Narayanamurti and Odumosu 2016; 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 in energy technologies, plays a crucial supporting role (Section 16.2.1). Governments can facilitate knowledge spillovers between firms, between countries, and between technologies (Cohen et al. 2002; Baudry and Bonnet 2019) (Section 16.2).

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; Wilson 2012; Nahm and Steinfeld 2014). Just as 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 Rio 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 (Freeman 1995; Jacobsson et al. 2004; Grubler and Wilson 2013). 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.

Emissions 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 that 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 (quantitative *ex post*, qualitative and theoretical and *ex ante* analysis). Another review focused 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 that there was very little empirical evidence linking innovation with the emissions trading schemes studied to date (Lilliestam et al. 2021). This review focused mainly on papers evaluating the earlier stages of the European Emissions Trading Scheme, which featured relatively low carbon dioxide 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 that (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 emissions trading 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, 10 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). Twenty-four evaluations covered distributional impacts of carbon taxes and other environmental taxes, the majority (15) found the existence of some negative distributional impacts, six found positive impacts, and three found no distributional impacts. Differences in the assessment results stem from the design of the taxes (Peñasco et al. 2021). It is important to note that, once again, the evidence comes from industrialised countries and emerging economies.

Feed-in-tariffs

Many factors affect the impacts of feed-in tariffs (FITs) 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). FITs yield better results if they account for the specificities of the country; or 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 FITs 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 FITs to auctions may favour existing PVs (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 can only 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 (Binz and Anadon 2018). Research comparing China's and India's policies and outcomes on wind energy 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 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). Work comparing renewable energy auctions in different countries in South America generally finds 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 (Geddes et al. 2018). This notwithstanding, the key role of these institutions is in the innovation system (OECD 2015b; Geddes et al. 2018) (Sections 16.2.1 and 16.3) and the belief that they can de-risk scale-up and the testing of business models (Geddes et al. 2018; Probst et al. 2021) (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 that TGCs have had no impact on competitiveness, while two indicate a negative impact and one a positive impact. Only one of the studies was quantitative, and did not identify an impact on competitiveness.

TGCs 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 focused 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 focused 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 a positive impact and three a 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 focused 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 a positive impact and one reports no impact (Peñasco et al. 2021). The impact of white certificates on competitiveness is positive (*limited evidence, high agreement*) while the impact 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. Of the 11 evaluations: seven reported positive impacts (four of them using theoretical methods); three indicated negative impacts (using theoretical methods); and one reported 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 identified positive impacts and one negligible ones) and three studies identified 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 greenhouse gas (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 USA 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, a study by Knittel (2011) 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-emission. 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). As for 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 (*medium evidence, medium agreement*) (Grubb et al. 2021). The introduction or tightening of minimum energy performance standards for appliances (and for buildings, in Noailly (2012)) 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 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 CO₂ 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 USA have highlighted that minimum energy performance standards for vehicles tend to be regressive, with poorer households disproportionately affected (Jacobsen 2013; Levinson 2019), 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 (Gann et al. 1998; Kemp 2005; Ruby 2015; Wesseling et al. 2015).

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 programmes 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, sale bans and financial support.

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 programmes. 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 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 five different grades – 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 and 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. The project also included financial subsidies for the enterprises producing these products. The standard design of these financial subsidies involved the government paying for the price difference of energy-efficient products and general products. The manufacturers that produce the energy-efficient products receive financial subsidies directly from the government (Z. Wang et al. 2017).

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 grade 1 and 2 air conditioners about 80% in 2010 (Z. Wang et al. 2017). According to the information from China's National Institute of Standardization, the energy label system saved more than 1.5 hundred billion kWh power between 2005 and March 2010, equivalent to more than 60 million tonnes of standard coal, 1.4 billion tonnes of carbon dioxide emissions, and 60 tonnes of sulphur dioxide emissions (Zhan et al. 2011), which significantly contributed to energy saving goals of China's 11th Five-Year Plan.

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 Organization for Standardization (ISO 14001 – standard for environmental management) or the European Union's Eco-Management and Auditing Scheme (EMAS), which is partly mandatory. Out of 16 analyses: 70% report positive innovation outcomes in terms of patents, products or processes; 17% report negligible impacts; and 13% report negative impacts. 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 (Inoue et al. 2013; He and Shen 2019; 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 premiums in multiple countries and regions (Fuerst and McAllister 2011; Kahn and Kok 2014; Zhang et al. 2017). Of those studies, 32% were qualitative, associating appliance labelling programmes 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 programmes point to positive impacts (*limited evidence, high agreement*). All four studies that focus on benefits for consumers and tenants report positive impacts (Devine and Kok 2015). Although there are benefits for utility companies and other stakeholders, more research is needed to specifically attribute these benefits to voluntary labels rather than energy efficiency programmes 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). 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.

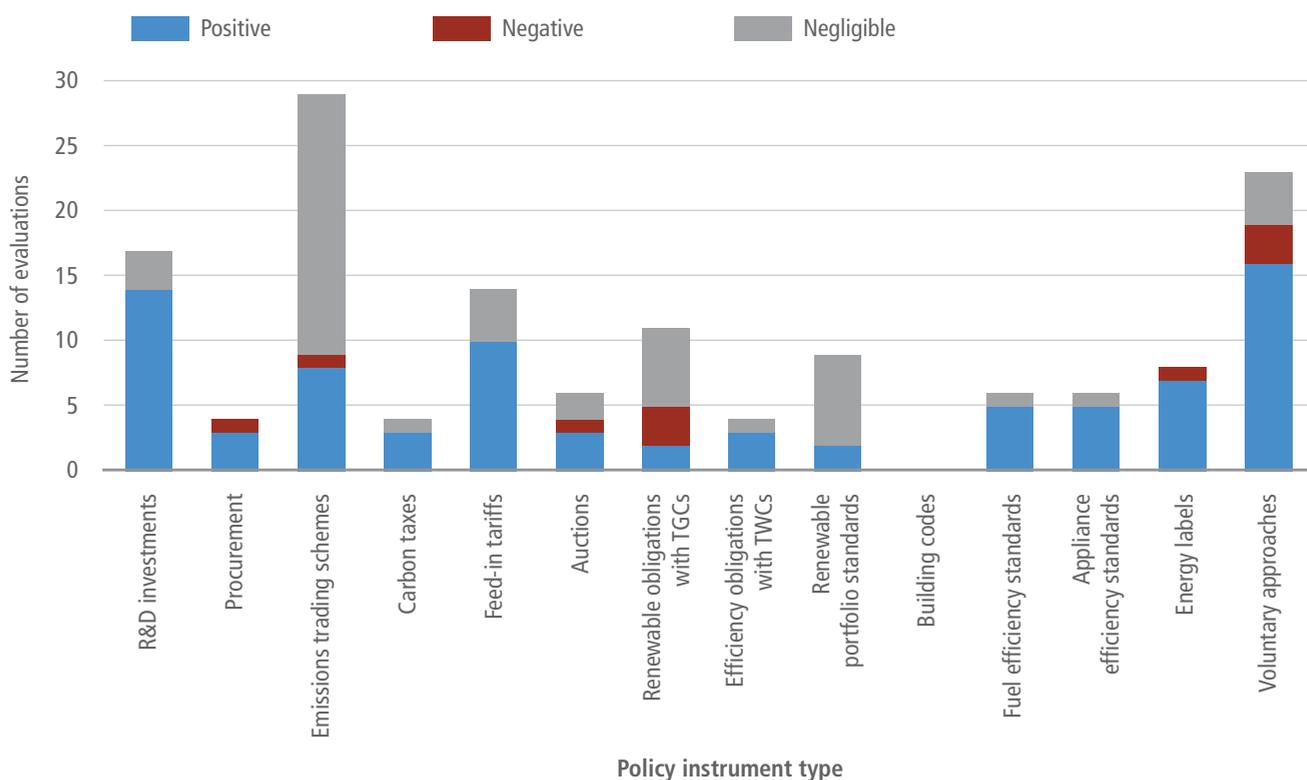


Figure 16.2 | Number of evaluations available for each policy instrument type covered regarding their impact on innovation and direction of the assessment. The vertical axis displays the number of evaluations claiming to isolate the impact of each policy instrument type on innovation outcomes as listed 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 red), and no impact (in grey). It builds on Grubb et al. (2021), Lilliestam et al. (2021) and Peñasco 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 long-standing interest on the impact of Foreign Direct Investment (FDI) on domestic capacity, innovation and environmental outcomes. While this section looks at the impact of trade instruments on innovation, it 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 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 with improved environmental performance and energy efficiency and also innovation outcomes in general (Gao and Zhang 2013). Other work links FDI with increased productivity across firms (not just those engaged in climate-related technologies) through spillovers (Newman et al. 2015). 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. Also, they find that countries with high R&D stocks are the main sources of international technology spillovers and 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). The benefits to the domestic innovation system, 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 rights (IPR) 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 (WIPO 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 (Machlup and Penrose 1950; Nelson and Mazzoleni 1996; 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 R&D. 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 trading patents and issuing licences (Arora et al. 2004). Although IP protections provide incentives to invest in innovation, they can also restrict the use of new knowledge by raising prices or blocking follow-on innovation (Wallerstein et al. 1993; Stiglitz 2008). As institutions, national patent systems 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 such as pharmaceuticals, where investments in developments and clinical trials are high, imitation costs are low, and there is often a one-to-one relationship between a patent and a product, referred to as a ‘discrete’ product industry (Cohen et al. 2000). At the same time, an increasing body of theoretical and empirical literature suggests that the proliferation of patents also discourages innovation (*medium evidence, low agreement*). Theoretical contributions note that a appropriability regime that is too stringent 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 (Machlup 1958; Hall and Helmers 2019). Jaffe and Lerner (2004) and Bessen and Meurer (2009) highlight how IP rights also hamper innovation in a variety of ways. Other contributions in the literature focus on more specific factors. For example, Shapiro (2001) discusses ‘patent thickets’, where overlapping sets of patent rights mean that those seeking to commercialise new technology need to obtain licences 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 – ultimately leading to no one having the 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’.

In general, IP protection and enforcement 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 World Trade Organization (WTO) 1994 Trade-Related Aspects of Intellectual Property Rights (TRIPS) Agreement, entered into by all WTO members, which

sets down minimum standards for the regulation by national governments of many forms of IP 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 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 on growth. It has been argued that the increasingly globalised IP regime through initiatives such as 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 pharmaceuticals, patents are typically used to enable exclusive production of a certain good (and obtain monopoly rents), while in industries such as 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 becoming 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 licence, fair, reasonable and non-discriminatory (FRAND) policies, and statement on licences of right (*high evidence, high agreement*). While patent holders are, 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 licences may be issued in cases of public interest or events of abuse of the patent (WIPO 2008; Biadgleng 2009). 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 choose not to make such a commitment, by doing so, its patent is no longer a candidate 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 files at the patent office and opts for the ‘licence of right’ regime, in return for reduced patent fees, they enter into a contractual agreement that obliges them to license the patent to those who 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 intellectual property rights (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 the USA or China, or with case studies in these and other countries. Research on wind energy in the USA, 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 (Corsatea 2016; Fu et al. 2018; Gao and Rai 2019). Different policies may have different impacts – for example, in the USA, 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 heterogeneous, because of differences in local planning authorities and capabilities (Corsatea 2016; Song et al. 2019).

Sub-national deployment policies have been associated with different impacts on competitiveness metrics (*limited evidence, medium agreement*). Research on green jobs shows positive association between sub-national policies and green jobs or green firms at the metropolitan level as well as the state or provincial level, in both China and the USA (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 USA (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 agreement*). The literature on the impacts of such policies on innovation

and competitiveness is sparse. Some case studies and programme evaluation reports, primarily in the USA, 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 programmes in developed countries, and even more so in India and other developing countries where such programmes have been increasing (Gonsalves and Rogerson 2019; Surana et al. 2020a).

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 – qualitative and quantitative, and in 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 in Chapter 13), it seems relevant to discuss overall findings. Research reviewing renewable energy policies in nine OECD countries concludes that, over time, a broad set of policies characterised 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). This indicates 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 2010; Howlett and del Río 2015; Rogge and Reichardt 2016; del Río and Cerdá 2017). 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 suggests 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. 2020).

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 AR5 (IPCC 2014) and the IPCC Special Report on Global Warming of 1.5°C (SR1.5) (IPCC 2018a). This complements the discussion on international cooperation on science and technology in Chapter 14.

This section first outlines the needs and opportunities for 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 UN Framework Convention on Climate Change (UNFCCC) to support international technology transfer and cooperation. Finally, it discusses emerging ideas for international technology transfer and cooperation, and possible modifications to support the achievement of climate change and Sustainable Development Goals (SDGs), building up to Section 16.6.

16.5.1 International Cooperation on Technology Development and Transfer: Needs and Opportunities

With the submission of their Nationally Determined Contributions (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 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 (Sagar 2009; Ockwell et al. 2015; Ockwell and Byrne 2016). 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), 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. 2018), including industrial development, job creation and economic growth (Porter and Van der Linde 1995; Altenburg and Rodrik 2017; Lema et al. 2020; Pegels and Altenburg 2020) (Section 16.6). The growing complexity of technologies and global competition have made technology development a globalised process involving the flow of knowledge and products across borders (Lehoux et al. 2014; Koengkan et al. 2020). For instance, in electronics production, 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 research and development (R&D), manufacturing or deployment of renewables (Lachapelle et al. 2017). In the case of solar photovoltaic (PV), for example, while many technical innovations emerged from the USA, Japan and China emphasised the manufacture of physical modules (Deutch and Steinfeld 2013) (Box 16.4).

Such globalisation 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 – barriers remain related to finance, environmental performance, human capabilities and cost (Weiss and Bonvillian 2013; Egli et al. 2018), with developing countries being particularly disadvantaged at leveraging these opportunities. The gap in low-carbon technology innovation between countries appears to have reduced only among 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 that international R&D spillovers seem to have benefitted 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. They recommend that innovation efforts be balanced between early-stage R&D spending, and commercialising already low-emission technologies in the demonstration phase and diffusing them globally.

Thus international cooperation on technology development and transfer can enable developing countries to achieve their climate goals more effectively, while also addressing other SDGs – taking advantage, where possible, of the globalisation of innovation and production (Lema et al. 2020). Earlier assessments in 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 (Somanathan et al. 2014; Stavins et al. 2014; IPCC 2018b) 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: (i) promoting collaborative approaches to R&D; and (ii) 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 the North to the South.

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

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 a 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, affect technological diffusion between countries in 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 (Bosetti et al. 2017; Narita and Wagner 2017; Rubio 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 research, development and demonstration (RD&D) through cooperation and knowledge spillovers.

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 the nature of the international engagement and the domestic context. While there has 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). Glachant and Dechezleprêtre (2017) 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 commercialisation 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 – for instance, in a context of market imperfection, clientelist and social exclusive communities and patrimonial and/or marketised 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. This 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), the infrastructure in the country (Kumar et al. 1999), and knowledge and capacity as part of its 'intangible assets' or the 'software' (Ockwell et al. 2015; da Silva et al. 2019; Corsi et al. 2020). For sustainable development, the capacity to plan in an integrated way and implement the SDGs (Khalili et al. 2015; Elder et al. 2016), including using participatory approaches (Disterheft et al. 2015), is a conditional means of implementation. It also is argued that, if human capital were 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 (Ockwell et al. 2015; Hsu 2017; IPCC 2018b; Upadhyaya et al. 2020). In a global analysis of wind energy using econometric analysis, Halleck-Vega et al. (2018) 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 and training, and activities related to technical facilities (Huh and Kim 2018; Khan et al. 2020).

There are multiple studies drawing on empirical work that 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). Olawuyi (2018) discusses the specific 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 transfer of existing knowledge would deliver better results. Despite the understanding of the importance of the capacity issue, significant gaps still remain on this front (TEC 2019) (Section 16.5.4).

16.5.2.2 Enhancing RD&D and Knowledge Spillovers

As mentioned earlier, RD&D can aid 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 (Suzuki 2015; Mission Innovation 2019; TEC 2021). This has resulted in a variety of international initiatives to cooperate on technology in order to create knowledge spillovers and develop capacity. For example, the UNFCCC Technology Mechanism, among 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 (TEC) (TEC 2017). There are numerous multilateral, bilateral and private programmes that have facilitated RD&D, biased mostly towards mitigation (as opposed to adaptation) activities. Many programmes that seemed to be about RD&D were in reality dialogues about research coordination (Ockwell et al. 2015). There are also a variety of possible bilateral and multilateral models and approaches for engaging in joint R&D (Mission Innovation 2019). An update by the TEC (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

The sections below discuss the literature on various categories of international technology cooperation and transfer.

16.5.3.1 UNFCCC Technology and Capacity-building Institutions

Technology development and transfer have been a part of UNFCCC discussions and developments in the context of the international climate negotiations ever since its agreement in 1992, as assessed in AR5 (Stavins et al. 2014). Support on 'Technology Needs Assessment' to developing countries was the first major action undertaken by the UNFCCC, and this has undergone different cycles of learning

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 (TEC) (Ockwell et al. 2015; TEC 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 (IPCC 2012), with potentially significant rates of return (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 least-developed countries) 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 (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 (Basel et al. 2020; Kuhl et al. 2020; Sarker et al. 2020; Vogel et al. 2020; Williams 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. This enables a much easier coupling to early action in response to the information, and a more appropriate response afterwards. Automatic responses to warnings have also been adopted in the humanitarian field for anticipatory action ahead of (rather than simply in response to) disasters triggered by natural hazards (Coughlan de Perez et al. 2015). This has resulted 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).

(Nygaard and Hansen 2015; Hofman and van der Gaast 2019). Since 2009, the UNFCCC discussions on technology development and transfer have focused 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 the TEC and the Climate Technology Centre & Network (CTCN). An independent review of CTCN, evaluated it on five dimensions – relevance, effectiveness, efficiency, impacts and sustainability – and indicated that the organisation 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 [National Designated Entities].' (TEC 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 CTCN's lack of financial sustainability has been a recurring issue, which may potentially be resolved by deepening the linkage between the CTCN and Green Climate Fund (Oh 2020). In the meanwhile, the Green Climate Fund 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 TEC and the CTCN do, however, indicate a broadening of the perspective on technology (CTCN 2019; TEC 2019).

Since the Kyoto Protocol's 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 others indicate

that around 40% of projects feature hardware or other types of international transfer of technology (Seres et al. 2009; Murphy et al. 2015), depending on the nature of technology, the host country and region (Cui et al. 2020) and the project type (Karakosta et al. 2012). The CDM was generally positively evaluated on its contribution to technology transfer. However, 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 in evaluations of technology transfer under the CDM has been criticised (Haselip et al. 2015; Michaelowa et al. 2019). 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 has been 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. In a legal analysis, D'Auvergne and Nummelin (2017) 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 learnt, as well as participatory, cross-cutting and gender-response. They also highlight that it is novel that least-developed countries and Small Island Developing States (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), and was extended by five years at the 25th Conference of the Parties in 2019 (UNFCCC 2020a, b). In its work plan for 2020–2024, its aims include '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 how institutional innovation is combined in the context of adaptation to extreme weather in SIDS can be found in Box 16.8.

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 the Cancun Agreements and the Paris Agreement (TEC 2021). However, much more can be done, given the complexity and magnitude of the requirements in terms of coverage of activities, the amount of committed funding, and its effectiveness. Some assessments of UNFCCC instruments specifically for technology transfer to developing countries have 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 Agreement 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 corrects market failures.

For instance, Mission Innovation 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 seek to foster international collaboration among its members and increase public investments in clean energy R&D with the engagement of the private sector. A recent assessment shows that, although

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 transfers can take place via three primary channels: (i) trade in goods, where technology is embedded in products; (ii) Foreign Direct Investment (FDI), where enterprises transfer firm-specific technology to foreign affiliates; and (iii) patent licences, where third parties obtain the right to use technologies. IPRs are relevant for all these three channels.

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

Box 16.9 (continued)

Several studies argue that, particularly in developing nations, the global IPR 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 (Littleton 2008; Abdel-Latif 2015).

There is little systematic evidence that patents and other IPRs restrict access to environmentally-sound technologies, since these technologies are mostly 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 is also literature suggesting that 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 least-developed countries may be better served by building capacity to absorb and implement technology (Hall and Helmers 2010; Maskus 2010; Sanni et al. 2016; 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 (Hall and Helmers 2010; Maskus 2010; Sanni et al. 2016; 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, IPR may hinder or promote technology transfer (TEC 2012).

In terms of ways forward to meet the challenge of climate change, different suggestions are made in the context of IPR that can help to further improve international technology transfer of climate mitigation technologies, including through the Trade-Related Aspects of Intellectual Property Rights (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; Maskus and Reichman 2017; Dussaux et al. 2018). Others also suggest that distinctions among country groups be made on the basis of levels of technological and economic development, with least-developed countries getting particular attention (Zhuang 2017; Abbott 2018).

expenditures are rising, the aims were 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 for 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 beyond the feasibility study phase due to cooperation and commitment problems between national and local governments, and they highlight the need for ownership and engagement of local residents and recipient governments.

Intellectual property rights (IPR) regimes (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.

16.5.4 Emerging Ideas for International Technology Transfer and Cooperation

As with the broader innovation literature (Section 16.3), and drawing on such literature, there has been an emergence of a greater understanding of, and emphasis on, the role of innovation systems (at national, sectoral, and technological levels) as a way to help

developing countries with the climate technology transition (TEC 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*) (Kumar et al. 1999; Sagar et al. 2009; Ockwell et al. 2018). 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 programmes that are intended to address specific gaps relating to technology development and deployment (Sagar et al. 2009; Ockwell et al. 2018).

There is also an increasing emphasis on the relevance of participative social innovation, local grounding and policy learning as a replacement of the expert-led technological change (Chaudhary et al. 2012; Disterheft et al. 2015; Kowarsch et al. 2016). Others have suggested a shift to international innovation cooperation rather than technology transfer, which implies a 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 multivariiegated in scope and will require the actions of a diverse set of actors to formulate and address the

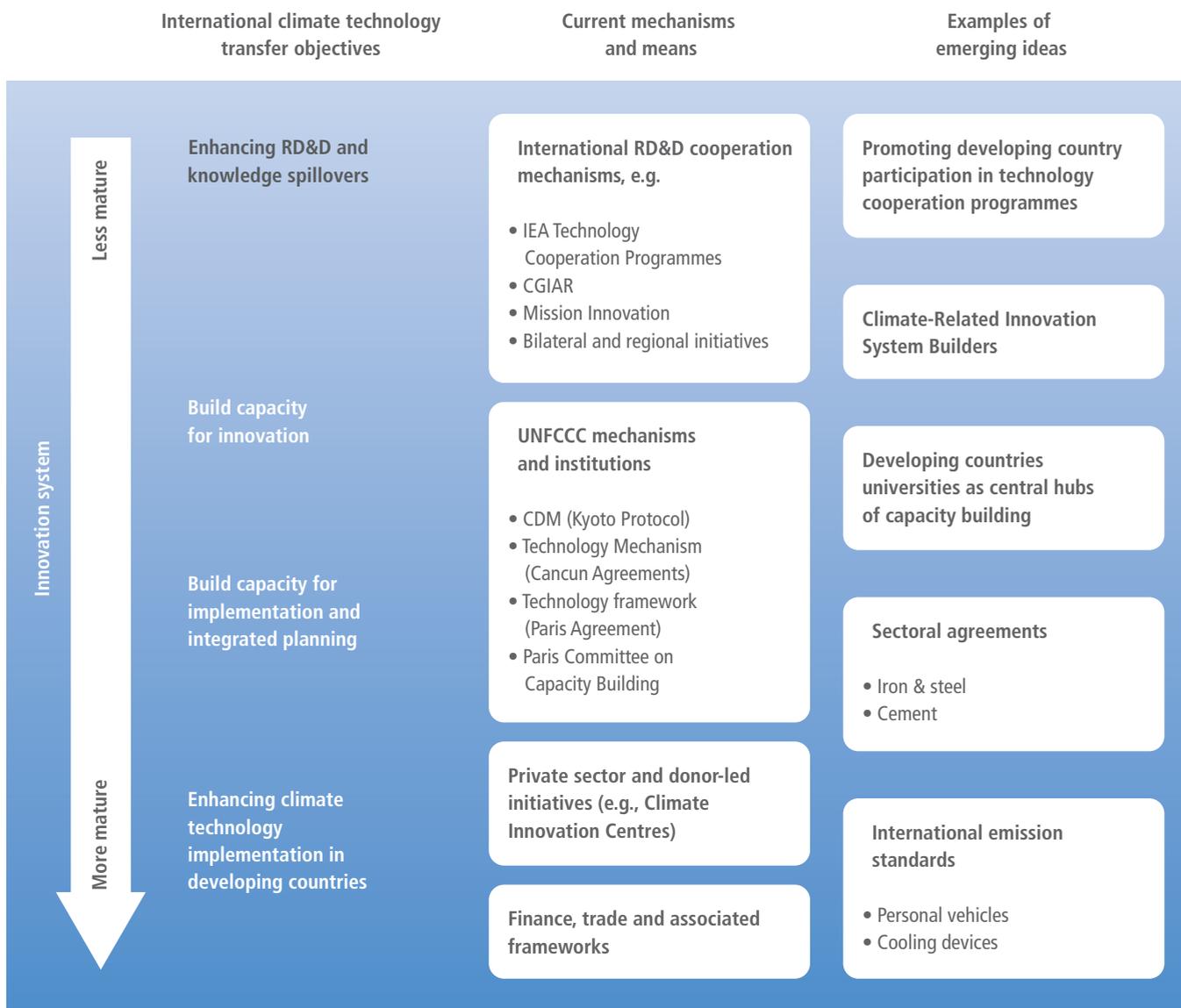


Figure 16.3 | Examples of recent mechanisms and emerging ideas (right column) in relation to level of maturity of the national or technological innovation system, objectives of international climate technology transfer efforts and current mechanisms and means. Sources: Sagar (2009); Ockwell and Byrne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

policy, implying that 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 (Chapter 11), Oberthür et al. (2021) propose that a way forward for the global governance for energy-intensive industry could be through sub-sector ‘clubs’ that include governmental, private and societal actors (Oberthür et al. 2021).

Figure 16.3 summarises examples of emerging ideas for international cooperation on climate technology, their relation to the objectives and existing efforts, and the level of development of the innovation system around a technology (Hekkert et al. 2007; Bergek et al. 2008) or in nations (Lundvall et al. 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 the indirect effects of technological innovation may systematically lead to underestimation of environmental impacts and overestimation of our ability to mitigate climate change (Hertwich and Peters 2009; Arvesen et al. 2011).

Previous sections of 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.

Also, the concentration of technology in few hands has boosted consumption of goods and services which are not necessarily aligned with the Sustainable Development Goals (SDGs) (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: current best practices; guidelines for technological and investment decisions; and 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 SDG implementation gaps reflect, to some extent, inadequate understanding of the complex relationships among the goals (Waiswa et al. 2019; Skene 2020), 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

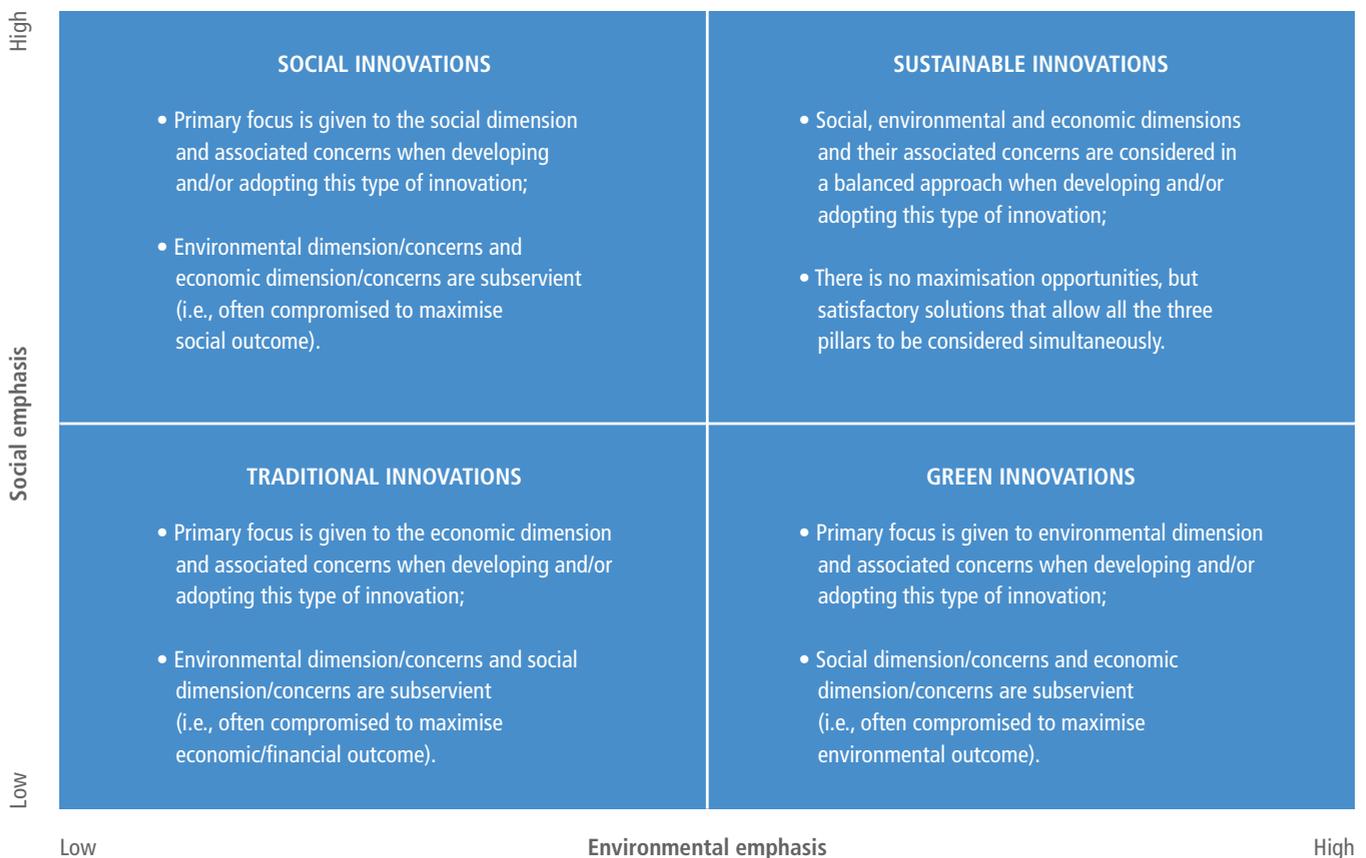


Figure 16.4 | Considerations and typology of innovations for sustainable development. Source: Silvestre and Țircă (2019).

(Gibbons 1999; Jasanoff 2003), to the extent that the two can be separated. From a science, technology and innovation 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 minimised. These include Zero hunger (SDG 2), Clean water and sanitation (SDG 6) and Affordable and clean energy (SDG 7) resources, which continue to rely on production technologies and practices that are eroding ecosystem services, potentially hampering the realisation of SDGs 15 (Life on land) and 14 (Life below water) (Díaz et al. 2019). The second category includes those related to governance and which compete with each other for scarce resources, such as Industry, innovation and infrastructure (SDG 9) and Climate action (SDG 13), which require an interdisciplinary perspective. The third category are those that require maximum realisation, 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 acknowledging the systemic nature of technological innovation, which involves 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 industrialised 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; Lytle et al. 2020; Schindele et al. 2020), and other renewably powered low- to zero-carbon food, water and energy systems (He et al. 2019). Silvestre and Țircă (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 (Figure 16.4).

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 (Haenssger 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 recognise 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 operationalised at sub-national, national and global levels and support integration of resource concerns in policy, planning and implementation (UNEP 2015; Williams et al. 2020).

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

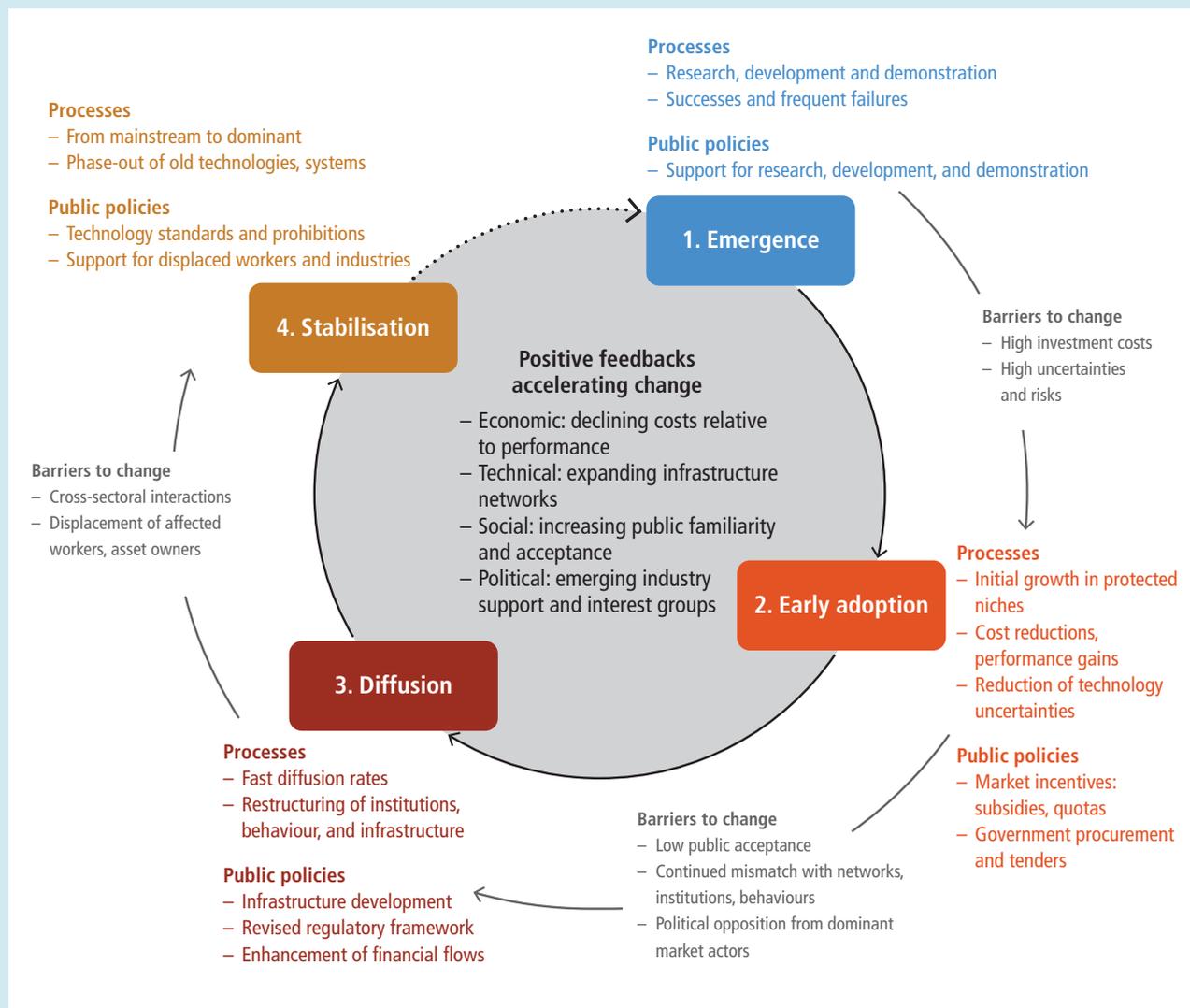
A large volume of literature documents the processes associated with transformational changes in technology and the social systems associated with their production and use (Geels 2019; Köhler et al. 2019). Transformational technological change typically goes hand in hand with shifts in knowledge, behaviour, institutions, and markets (Geels and Schot 2010; Markard et al. 2012); stickiness in these

Cross-Chapter Box 12 (continued)

factors often keeps society 'locked in' to those technologies already in widespread use, rather than allowing a shift to new ones – even those that offer benefits (David 1985; Arthur 1994). Exceptions often follow consistent patterns (Geels 2002; Unruh 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 (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 Supplementary Material 5.5.3 in Chapter 5, and Section 16.3 in Chapter 16), Cross-Chapter Box 12 Figure 1 elaborates on four distinct stages: it portrays these as occurring in a cycle, recognising that even transformative technologies will eventually be replaced with newer ones.

The *emergence* stage is marked by experimentation, innovation in the laboratory, and demonstration in the field, to produce technologies and system architectures (Geels 2005). 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



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

Cross-Chapter Box 12 (continued)

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 (Nemet 2006; Grubb et al. 2021). 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 (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 are effective, including cross-subsidies (such as feed-in tariffs) and market quotas (such as renewable portfolio standards) (Geels et al. 2017b; Patt and Lilliestam 2018; and 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 (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 smartphones 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. (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 standardised 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 policymakers to help those negatively affected, enabling a just transition (McCauley and Heffron 2018; Newell and Simms 2020). Political opposition to the system reconfiguration that comes with integration and stabilisation 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 that have 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 USA, India, and China, leapfrogged directly to the diffusion stage (Chaudhary et al. 2015; Dai and Xue 2015; Lacal-Arántegui 2019). A similar pattern played out for solar power (Nemet 2019). 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 commercialisation 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. For example, public acceptance of meat alternatives leads to firms improving the products, increasing political and economic feedbacks (Section 5.4 and 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 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. (2020) argue that interventions geared towards the social factors driving change can 'activate

Cross-Chapter Box 12 (continued)

contagious processes' leading to 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 (Tziva et al. 2020) (Chapter 5), such as with food systems (Rust et al. 2020) (Section 7.4.5), and can contribute to both resilience and carbon storage (Sendzimir et al. 2011) (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 that contextual factors, including specific configurations of actors, can lead to very different outcomes. Kraus and Koch (2021) found a short-term social shock – such as the COVID-19 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) (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 (Adenle et al. 2015; Pandey et al. 2021). 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 (Marquardt et al. 2016; Bhamidipati et al. 2019), and benefitting little in terms of participating in high value-added activities (Whittaker et al. 2020).

System transitions differ according to context, such as across industrialised and developing countries (Ramos-Mejía et al. 2018), and within countries. Lower levels of social capital and trust negatively impact niche commercialisation (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 marginalising 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 in Chapter 5). 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). On the 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. 2018; IPCC 2018a; Karlsson et al. 2020). 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 (Geels 2014; Meckling et al. 2015; Schmidt and Sewerin 2017; Breetz et al. 2018), increasing legitimacy of environmental sustainability actions (Hansen et al. 2018; Herslund et al. 2018; van Welie and Romijn 2018) and addressing negative socio-economic impacts (Deng et al. 2018; McCauley and Heffron 2018; Eisenberg 2019; Henry et al. 2020).

Summary and gaps in knowledge

Strategies to accelerate climate mitigation can be most effective at accelerating and achieving transformative change when they are synchronised 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; Geels et al. 2017; Köhler et al. 2019). Gaps in knowledge remain on how to tailor policy mixes, the interaction of enabling conditions, the generalisability of socio-technical transition insights to other types of systems, and how to harness these insights to better shift development pathways.

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. 2018) (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 localising low-emission energy technologies value chains as well as 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 materialise far from where activities take place (Ockwell and Byrne 2016; Vasconcellos and Caiado Couto 2021). 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 (Seyfang and Smith 2007; UNCTAD 2019). 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) (Box 16.10). Digital technologies can empower citizens and communities in decentralised energy systems, contributing not only to a more sustainable but also to a more democratic and fairer energy system (Van Summeren et al. 2021) (Section 5.4 in Chapter 5, and Cross-Chapter Box 11 in this chapter).

Therefore, even though science, technology and innovation is an explicit focus of SDG 9, it is 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 (Geels 2014; Meckling et al. 2015; Cross-Chapter Box 12 in this chapter). 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 is usually not 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) (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 (Deng et al. 2018; McCauley and Heffron 2018; Eisenberg 2019; UNCTAD 2019; Henry et al. 2020). 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: 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 (McCauley and Heffron 2018; UNCTAD 2019). 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 decentralised 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 (Calzadilla and Mauger 2018; van Bommel and Höffken 2021).

The opportunities and challenges of technological change can also differ within country regions and between countries (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 information and communication technology (ICT) (Baller et al. 2016) or renewable energy technology (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 (Ockwell and Mallett 2012; Sagar and Majumdar 2014; Ockwell et al. 2018; UNCTAD 2019; Malhotra et al. 2021; Vasconcellos and Caiado Couto 2021). 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 (Ockwell and Byrne 2016; Altenburg and Rodrik 2017; UNCTAD 2019).

16.6.2.2 Challenges to Governing Innovation for Sustainable Development

Dominant economic systems and centralised 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) (Section 5.6 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 society (Jasanoff 2018; Sadras 2020). 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) (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 multilevel 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 the ability to avoid trade-offs with other development objectives – such as 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 and Cross-Chapter Box 12 in this chapter). 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 (Moldaliev 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 mobilising such support has been to portray technological change as a means of minimising 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 (Sections 5.5 and 5.6, Chapter 13, and Cross-Chapter Box 12 in this chapter). Social innovation can contribute to maximising synergies and minimising trade-offs in relation to technological and other innovative practices, but for this to materialise, national, regional and local circumstances need to be taken into account and, if needed, changed. Even in circumstances of high capabilities, the extent that 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 SDGs, but it may also create challenges to the economy, human well-being, and the environment (Schillo and Robinson 2017; Thacker et al. 2019; Walsh et al. 2020). The degree of potential synergies and trade-offs among SDGs differs from country to country and over time (Section 16.6.1.1). These potentials will depend on 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. 2018), 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 is to be achieved in a transformative way (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 that methods for this have been implemented in practice (Douthwaite and Hoffecker 2017).

There are several examples of how to maximise synergies and avoid or minimise 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 include studies raising awareness on solar energy and women's empowerment (Winther et al. 2018) and recycling and waste (Cross and Murray 2018).

Other actions with the potential to maximise synergies are those related to community or grassroots technological innovation. The

importance of the link between technological innovation and community action and its contribution to sustainable development is usually underestimated. Further research is needed on this 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 (Bhamidipati and Hansen 2021; Vasconcellos and Caiado Couto 2021). Actions by policymakers that safeguard environmental and social aspects can boost synergies and maximise those co-benefits (Lema et al. 2021). Given that technological change impacts countries, regions and social groups differently, transition policies can be designed to ensure that all regions and communities are able to take advantage of the energy and other transitions (McCauley and Heffron 2018; Henry et al. 2020).

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.

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 (GHG) emissions, and rising demand for natural resources (UNEP 2013; UNEP 2017; FAO 2018a; Bringezu 2019; Díaz et al. 2019).

Trend analysis indicates that a large share of the global demand for land is projected to be supplied by South America, in particular the Amazon (Lambin and Meyfroidt 2011; TEEB 2018) and Gran 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 GHGs emitted by the beef cattle sector alone represents 65% of the agricultural sector's emissions and 15% of the country's overall emissions (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; TEEB 2018; IPBES 2019).

Technological practices, management and changes in the food chain could help adapt to climate change, reduce emissions and absorb carbon in soil, 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 (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 climate change challenges and food security (WGII-report, Chapter 5, Box 5.10). Small Island Developing States (SIDS) support livelihoods to develop local food value chains that 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, Chapter 5, WGII Box 5.10). Three of the different agroecological approaches are briefly discussed here: agroecological intensification; agroforestry; and biochar use in rice paddy fields.

Box 16.10 (continued)

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 (Tittone 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 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 greening of the Sahel' in Niger. The practice is based on the assisted natural regeneration of trees in cultivated fields, an old method that 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 rice farmers' net income. 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).

The contributions of indigenous people (Díaz et al. 2019), heritage agriculture (Koochafkan 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).

16.6.4 Climate Change, Sustainable 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 progress on mitigation and towards other SDGs. 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 greenhouse gas (GHG) impacts (*high confidence*).

A systemic view of innovation that takes into account the roles of actors, institutions, and their interactions, can contribute to 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 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 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 to better organise innovation systems, 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 towards system transitions for climate change mitigation, and also towards addressing other SDGs. This means taking into account the full lifecycle 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 they: are approached as 'innovation cooperation' that engenders a holistic, systemic view of innovation requirements; are an equitable partnership between donors and recipients; and develop 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 multilevel 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 research and development (R&D) to support policymaking 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; national contexts and local innovation capacity; potential and actual contributions of businesses; literature emphasis on mitigation; indicators to assess innovation systems; non-technical barriers for the feasibility of decarbonisation pathways; the role of domestic intellectual property rights (IPR) policy; digitalisation in low-emissions pathways; and Paris Agreement compliance regarding technology and capacity building.

Representation of developing countries

One of knowledge gaps 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 is true for studies on developing countries, and for authors originating from, or active in, developing country contexts. The evidence of the impact of decarbonisation policy instruments applied to developing countries or Small Island Developing States (SIDS) is limited. Expanding the knowledge base with studies that 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.

National contexts and local innovation capacity

While a growing body of 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. Important knowledge gaps need to be filled 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.

Emphasis on mitigation

Current literature has a strong bias to studies originating from and based on developed countries. Also, innovation and technology literature is skewed to mitigation and, specifically, 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.

Indicators to assess innovation systems

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

Non-technical barriers for the feasibility of decarbonisation pathways

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.

Domestic IPR policy

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.

Digitalisation in low-emissions pathways and digitalisation

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. Studies would benefit from being technology/sector/country-specific.

Further exploration is needed into the way digitalisation influences the framework conditions that cause decarbonisation, the socio-economic and behavioural barriers influencing the diffusion of technologies in the long-term scenarios, and the relationship with society and its effects.

Given the implications of the digital revolution for sustainability, a better characterisation of governance aspects would increase understanding of the implications for policymakers of digitalisation and the possibilities for it and other general-purpose technologies.

Research (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 and accelerate diffusion of climate-related technologies, while taking care not to reduce the incentive for inventors to search for new solutions.

Paris Agreement compliance

An independent assessment is underway to look at the compliance of the Paris Agreement with regard to technology and capacity building as means of implementation. The Enhanced Transparency Framework for action and support is developing a methodology for monitoring, reporting and verification. There is a lack of analysis of the full landscape of international cooperation, of the effectiveness of the UN Framework Convention on Climate Change (UNFCCC) and the Paris Agreement, and what is needed to meet their objectives.

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 within and between countries and regions. This knowledge flow can take the form of exchanging experiences, ideas, skills, and 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 to 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.

Globalisation 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 benefitted from the globalisation of innovation due to different barriers, such as access to finance and technical capabilities. These asymmetries between countries in the globalisation 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 research, development and demonstration, and knowledge spillovers.

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

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