# Chapter 16: Innovation, technology development and transfer

**Coordinating Lead Authors:** Gabriel Blanco (Argentina), Heleen de Coninck (the Netherlands)

**Lead Authors:** Lawrence Agbemabiese (Ghana/the United States of America), El Hadji Mbaye Madien Diagne (Senegal), Laura Diaz Anadon (Spain/United Kingdom), Yun Seng Lim (Malaysia), Walter Alberto Pengue (Argentina), Ambuj Sagar (India), Taishi Sugiyama (Japan), Kenji Tanaka (Japan), Elena Verdolini (Italy), Jan Witajewski-Baltvilks (Poland)

**Contributing Authors:** Lara Aleluia Reis (Portugal), Rudi Bekkers (the Netherlands), Paolo Bertoldi (Italy), Luisa F. Cabeza (Spain), Brett Cohen (Republic of South Africa), Felix Creutzig (Germany), María Josefina Figueira Meza (Venezuela/Denmark), Maria Figueroa (Venezuela), Clara Galeazzi (Argentina), Kirsten Halsnæs (Denmark), Joni Jupesta (Indonesia), Şiir Kilkiş (Turkey), Michael Koenig (Germany), Abhishek Malhotra (India), Eric Masanet (the United States of America), William McDowall (United Kingdom), Greg Nemet (the United States of America), Joyashree Roy (India/Thailand), Karolina Safarzynska (Poland), Ayyoob Sharifi (Iran/Japan), Kavita Surana (India), Maarten van Aalst (the Netherlands)

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

**Chapter Scientists:** Muneki Adachi (Japan), Clara Caiafa (Brazil/Italy/the Netherlands), Daniela Keesler (Argentina), Eriko Kiriyama (Japan)

**Date of Draft**: 16/01/2021

# Table of Contents

Chapter 16: Innovation, technology development and transfer ....16-1

Executive summary ....16-4

16.1 Introduction ....16-7

16.2 Technological change and sustainable development ....16-8

16.2.1 Contemporary perspectives on sustainable development and technological change .16-8

16.2.2 Technological change for meeting essential needs ....16-9

16.2.3 A catalytic role for capabilities and technological change ....16-10

16.2.4 Governance of technological change ....16-10

16.2.5 The nexus of technological change and sustainable development ....16-11

16.3 Fundamental elements, drivers and incentives of technology innovation processes ....16-12

16.3.1 Stages of the innovation process ....16-12

16.3.2 Drivers of innovation processes ....16-15

Cross-Chapter Box 8: Digitalisation: efficiency potentials and governance considerations ...16-19

16.3.3 Determinants of direction of technological change trajectory ....16-24

16.3.4 Representation of the innovation process in modelled decarbonisation pathways ..16-26

16.4 A systemic view of technological innovation process ....16-31

16.4.1 Frameworks for analysing technological innovation processes ....16-31

16.4.2 Identifying systemic failures to innovation in climate-related technologies ....16-33

16.4.3 Low-emission innovation activity in the private sector ....16-37

16.4.4 Emerging policy perspectives on systemic transformations ....16-38

16.4.5 Systemic indicators for technological innovation ....16-41

16.5 Innovation policies and institutions ....16-44

16.5.1 Overview of policy instruments for climate technology innovation ....16-45

16.5.2 Drivers of national policies for climate change mitigation and adaptation ....16-47

16.5.3 Innovation, competitiveness and distributional outcomes ....16-48

16.5.4 Assessment of innovation and other impacts of innovation policy instruments ....16-48

16.5.5 Trade instruments and their impact on innovation ....16-60

16.5.6 Intellectual property rights, legal framework and the impact on innovation ....16-60

16.5.7 Sub-national innovation policies and industrial clusters ....16-62

16.5.8 System-oriented policies and instruments ....16-63

16.6 International technology cooperation for transformative change ....16-63

16.6.1 Current state and recent developments in global innovation processes ....16-64

16.6.2 Objectives and functions of international technology transfer and cooperation ....16-64

16.6.3 Assessment of international technology transfer and cooperation ....16-66

16.6.4 Emerging ideas for international technology transfer and cooperation ....16-70

16.7 Knowledge gaps ........ 16-71
Frequently Asked Questions (FAQs) ........ 16-72
References ........ 16-75

# Executive summary

**Technology can contribute to decoupling growth in human well-being from worsening environmental impacts and increasing natural resources demand. Yet, current patterns of technological change may also lead to higher emissions or other side-effects, for instance through the so-called rebound effects (*robust evidence, medium agreement*).** Technology is one of the main elements of the climate and the sustainable development agendas, which is why it has its own article in the Paris Agreement. {16.1, 16.2, 16.6}

**In addition to research, development and demonstration (RD&D), deployment and diffusion of new and improved technologies are necessary to achieve climate and sustainable development goals. The more effective approaches to enable such deployment and diffusion involve adoption of public policies with a holistic perspective, encompassing all aspects of the innovation process along with sustainable development goals. (*robust evidence, medium agreement*)** This includes not only technology-push and market-pull policies, but also tailoring innovation policies to local development priorities and context, and overcoming both market and innovation system failures. Nature also offers technological solutions that can contribute to fix carbon, reduce emissions, and guarantee food security. {Box 16.5, 16.4.5}

**Appropriate mixes of climate, industrial and trade policies could induce progress of low-carbon technologies, with spill-over across regions leading to global reduction of emissions and attaining sustainable development goals.** There is an increasing interest in the role of industrial policy promoting innovation in green technologies to building and sustain public support for climate efforts (*medium evidence, high agreement*). The extent to which different countries may be able to domestically produce clean technologies depends on various factors, including the complexity of the technologies, domestic capabilities, and the policy framework (*low evidence/high agreement*). {16.3, 16.4.2, 16.4.4, 16.5,}

**Different public policy instruments have been used to promote technological innovation in climate related technologies directly (mainly public RD&D investments and innovation procurement) or indirectly (through economic or regulatory instruments). Direct policy instruments have had a positive impact on innovation outcomes as measured by patents, publications or cost reductions (*robust evidence, medium agreement*).** Emerging research indicates that public R&D funding and support has been valuable for fostering innovation in small to medium cleantech firms (*medium evidence, high agreement*). Indirect policy instruments such as feed-in tariffs, auctions, emissions trading schemes, taxes and renewable portfolio standards have generally been associated with positive or negligible innovation outcomes, although in some cases specific designs have resulted in some negative distributional outcomes (*medium evidence/medium agreement*). A sustained and comprehensive effort is most likely to lead to more innovation and domestic capacity (*medium evidence/medium agreement*). Although the evidence from developing countries and small island states is growing, most of the evidence available is from industrialised countries and emerging economies {16.3, 16.5.4}.

**Recent years have seen lower cost, improved performance, and faster deployment rates of many technologies that can contribute to climate change mitigation on both the supply and the demand side (*high confidence*).** These often have been driven by governments through a range of policy instruments, as well as by private-sector responses. In order to achieve climate and sustainable development objectives, though, the relevant innovation systems have to be strengthened significantly. This includes greater public and private investments (*inter alia*, in RD&D, early deployment, and diffusion), enhanced capacity of all innovation and societal actors, and improved institutional and governance arrangements.{16.4, 16.5}

**In the last 20 years, public energy-related RD&D funding in OECD countries has risen slowly, and is currently reaching levels comparable with the peak of energy RD&D investments following the two oil crises. Although data are limited, patchy evidence suggests that spending on energy RD&D in least-developed countries is a fraction of that in developed countries (*high confidence*). The overall effectiveness of reported RD&D spending is not available.** Public investment in energy RD&D has been an important driver of innovation in energy. There are various ways to evaluate the state of innovation and technology development in countries. Qualitative frameworks include innovation systems, while quantitative indicators include patents and RD&D spending. Over time, the portfolio of energy technologies which are funded has changed. In 2019, around 80% of all public energy R&D spending was on low-carbon technologies – energy efficiency, CCUS, renewables, nuclear, hydrogen, energy storage and cross-cutting issues such as smart grids. Since the mid-1970s public investments in OECD countries in energy RD&D have seen large swings, with a peak after the oil crisis of the 1970s at USD2019 21.3 billion and of USD 22.2 billion in 2009 as part of government efforts following the financial crisis. {16.5.4, Box 16.4}

**Appropriate innovation and transfer of climate supporting general purpose technologies can help achieve both climate and sustainable development goals in a synergistic mode. This would entail taking into account, and responding to, adverse, unanticipated externalities of technological transitions (*robust evidence, high agreement*).** Such externalities could include livelihood loss, environmental damages or increased production and consumption of goods and services. {16.2, 16.3.2.2, Cross-Chapter Box 4 in Chapter 4}

**The process of technological change is represented in a stylised way in mitigation pathways generated by climate-energy-economy models. In reality the process of technological change is complex, given its social, economic, environmental, financial, institutional, infrastructural, capacity, and behavioural dimensions (*high confidence*).** Improving the model representation of various aspects of technology development and diffusion processes has been – and can continue to be – useful for understanding interactions between innovation, emissions and decarbonisation pathways. Most models do not include detailed representations of innovation policies and practices to support the climate and SD transitions. {16.3.4, Box 16.1}

**International cooperation in technology development and transfer can play an important role in addressing global climate and sustainable development goals and needs by helping both developed and developing countries to share knowledge and experiences (*high confidence*)**. The way international cooperation arrangements are developed and implemented determines their effectiveness. In the past, the market-based Clean Development Mechanism has led to some technology transfer, especially to larger developing countries that have planned for it (*robust evidence, medium agreement)*. The effectiveness and societal benefits of technology transfer under market conditions seems mainly determined by the local capabilities and policy regime, suggesting that capacity building remains needed, especially in least-developed countries and SIDSs. {16.6.3.1; Box 16.9}

**The implementation of current arrangements for technology development and transfer, as well as capacity building, including those in the Paris Agreement, are insufficient to meet climate objectives and contribute to sustainable development**. Enhancing financial support through these arrangements may contribute to improving their performance. Emerging ideas such as sectoral agreements, climate-related innovation builders in developing countries and enhanced capacity building. The evidence on the role of intellectual property rights in the diffusion of climate-related technologies is mixed, suggesting that countries with well-developed capabilities may benefit but countries with limited capacity might face greater barriers {16.6.3., 16.6.4}.

**Gaps in knowledge include both theoretical frameworks and empirical studies applicable to developing countries contexts, innovation studies on adaptation and mitigation other than energy, data on the indicators used to assess the strength of the climate technological innovation systems,**

**and ex-post assessments of the effectiveness of various innovation-related policies and interventions, including R&D. {16.7}**

# 16.1 Introduction

Technological innovation is a main element of both the climate and the sustainable development agenda. This is why, for the first time in the history of the IPCC Assessment Reports, a full chapter is dedicated to innovation and technology development and transfer. To set the ground for further discussions Chapter 16 covers the major aspects of these topics in relation to the multiple dimensions of sustainable development in sections 16.2 and 16.3.

In the past, the IPCC has discussed innovation and technology development and transfer scattered across reports and chapters. In the AR5, (Somanathan et al. 2014) assessed national and sub-national innovation policy instruments, (Agrawala et al. 2014) discussed regional and supra-regional initiatives and proposals for technology-focussed cooperation and technology transfer, and (Stavins et al. 2014) in their chapter on international cooperation concluded that technology-related policies could lower mitigation costs and increase the likelihood that countries commit to reducing GHG emissions. (de Coninck et al. 2018) in the SR1.5 discuss technology and innovation as one of six necessary enabling conditions for the systems transitions that would be needed to limit global warming to 1.5°C.

This chapter builds on these previous IPCC reports by assessing the literature around innovation and technological changes in the broader framework of sustainable development, discussing the benefits and trade-offs of development and implementation of existing and new technologies. In particular, the focus is on technologies for mitigation, but some adaptation technologies are also covered. The chapter includes a discussion on how policy interventions at international, national and subnational levels can foster the innovation process, and looks at international cooperation and capacity building.

Across the chapter, innovation is understood as the commercial or industrial application of a new product, process or method of industrial production, of a new market or source of supply, or of a new form of commercial, business or financial organisation (Schumpeter 1934). This considers innovation involving inventing and discovering new ideas by building on prior knowledge and realising them at large scale affecting how we live and work (Scotchmer 1991; Arthur 2009). The chapter also adopts a definition of technology as the subset of knowledge that includes the full range of devices, methods, processes, and practices that can be used "to fulfil certain human purposes in a specifiable and reproducible way" (Brooks 1980) or "a means to a purpose" (Arthur 2009).

Discussing innovation and technological changes in a sustainable development context requires addressing the overall social, environmental and economic consequences, positive or negative, of technological change and how public policy can intervene. Section 16.2 describes the role of technology in sustainable development, including unintended effects of technological changes, such as impacts on the labour market and unemployment rates, on soil yields and productivity, on competitiveness and trade, and on distribution of wealth. It also refers to the so-called "rebound effect" that occurs at different levels of the economy and can prevent achieving the full potential of technological changes in relation to energy savings and emissions reductions.

Drivers and enablers, but also barriers and constrictions, of the innovation process are discussed in Section 16.3. This section also describes the different phases of innovation and metrics, such as the widely used but also criticised technology readiness levels (TRLs), and the way technological changes are represented in mitigation pathways generated by climate-energy-economy models.

Contrary to earlier, more linear models of innovation, over the past quarter of a century, the innovation systems literature has emerged. The literature now professes to assess and study innovation in a systemic way, regarding innovation as an outcome of a constellation of institutional, behavioural and social factors in different local contexts that may slow or accelerate technology diffusion. The literature on this is assessed in Section 16.4.

Innovation and technology policy is discussed in Section 16.5, including technology push (e.g., publicly funded R&D) and demand-pull (e.g., governmental procurement programmes) instruments that addresses potential market failures related to innovation and technology diffusion. The section also assesses the cost-effectiveness and other policy assessment criteria introduced in Chapter 13 of technology support policies that have promoted substantial innovation and diffusion of new technologies.

In Section 16.6, the chapter assesses the role of international cooperation in technology development and transfer, in particular the technology mechanisms established under the UNFCCC, but also other international mechanisms for technology cooperation. The discussion on international cooperation includes information exchange, research, development and demonstration cooperation, access to financial instruments, as well as promotion of domestic capacities and capacity building. Finally, Section 16.7 discusses gaps in knowledge emerging from this chapter.

# 16.2 Technological change and sustainable development

Technological change (TC) is a necessary condition for achieving the climate and sustainable development goals (IPCC 2014). Though mentioned in AR5, a coherent picture of the relationship among the Sustainable Development Goals (SDGs), and between the SDGs and technological change did not emerge. This section presents key findings that collectively advance understanding of technological changes and their implications for achieving climate and sustainable development goals.

## 16.2.1 Contemporary perspectives on sustainable development and technological change

By most accounts, the current outlook for sustainable development remains uncertain (Díaz et al. 2019). Some literature suggests that addressing the SDGs coherently means taking a systems approach based on the Earth System, requiring new knowledge about the complex relationships among the goals is needed (Skene 2020).

Studies have explored this from various perspectives, including nexus frameworks (Dai et al. 2018; Bazilian et al. 2011), context-sensitive goal interactions (Cottrell et al. 2018; Nilsson et al. 2018), social networks (Chen et al. 2019; Kim et al. 2018; Kolleck 2019; Rover et al. 2017) and computer simulation models (Collste et al. 2017), increasingly leveraging big data and artificial intelligence(Milojevic-Dupont and Creutzig 2021; Quan et al. 2019; Vinuesa et al. 2020; Kim et al. 2018). A widely recognised common weakness of these approaches has been their focus primarily on synergies and trade-offs while lacking the holistic perspective necessary to achieve all the goals (Nilsson et al. 2016).

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. Fu et al (2019) distinguishes three categories of SDGs: 1) those representing essential human needs for which inputs that put pressure on sustainable development would need to be minimised, 2) those related to governance and which compete with each other for scarce resources, and 3) those that require maximum realisation (see Table 16.1). These can be linked to academic disciplinary homes and applied to technological change.

**Table 16.1 A categorisation of SDGs and their linkages to technological change based on (Fu et al., 2019)**

| | SDGs<br>(Agenda 2030) | Main disciplinary home | Implications for, and/or linkages to, technological change |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Essential Needs *Minimum Inputs* | - Food<br>- Water<br>- Energy<br>- Resources & oceans<br>- Terrestrial ecosystem | Natural sciences and engineering | Innovation in resource efficiency and sustainable technologies |
| Governance C*ompromise in competition* | - Infrastructure<br>- Urbanisation<br>- Consumption and production<br>- Climate<br>- Global partnership | Transdisciplinary science and policy | Integrative governance approaches (Soto Golcher and Visseren-Hamakers 2018) can mediate competing goals and trade-offs |
| Expected Objectives<br>*Maximum Realisation* | - No poverty<br>- Health<br>- Equal education<br>- Gender equality<br>- Economic and labour rights<br>- Equality<br>- Safe society | Social science and ethics | Innovation as a systemic inclusive effort, co-determined by institutional, behavioural and societal capability factors. |

### 16.2.2 Technological change for meeting essential needs

Efforts at global and national levels to meet growing needs for food (SDG 2), water (SDG 6) and energy (SDG 7) resources continue to rely on technologies and practices that are eroding ecosystem services, hampering the realisation of SDGs 15 (land) and 14 (oceans) (Díaz et al. 2019). Transition to more sustainable solutions require adoption and mainstreaming of novel technologies that can meet needs while reducing resource waste and improving resource-use efficiency, and while acknowledging the systemic nature of technological innovation, which involve many levels of actors, stages of innovation and scales (Anadon et al. 2016b). Changes in production technology have been found to be an effective measure by which to overcome trade-offs between food and water SDGs(Gao and Bryan 2017). A growing array of innovative technologies at the food, water energy nexus, is transforming production processes in industrialised and developing countries. Some literature has strived to identify universal criteria that may guide technological change in the water, food and energy sectors (Bolisetty et al. 2019).

There are examples of technological changes in these three sectors that are worth mentioning: Novel irrigation technologies are helping food producers augment and improve water supplies, raise water productivity, and improve effectiveness of water demand management and irrigation system maintenance (Reinders 2020); new technologies such as nanoparticles that can significantly enhance the efficiency of agricultural inputs (Singh et al. 2020); agrivoltaics that co-develop land for agriculture and solar with water conservation benefits (Barron-Gafford et al. 2019; Schindele et al. 2020; Lytle et al. 2020)

A direct consequence of adopting this kind of technologies, combined with progressive improvements in energy efficiency, has been the gradual 'decoupling' of well-being or economic growth from resource use and environmental impact, through resource productivity increases (UNEP 2013). The evidence on decoupling is mixed. While some say it recently accelerated for various countries (Newman 2017) and in cities (Gao and Newman 2018), others indicate that the historical records show that there is no clear evidence that absolute decoupling is actually taking place (Chitnis et al. 2014).

Technological changes that lead to productivity increases, however, can also cause increased output (and consumption) of goods and services and, thus, strengthen the pressures on the environment. Those environmental impacts depend not only on what technologies are used, but also on how they are used (Grübler 1998). The incomplete knowledge of those impacts and other indirect effects, and of interactions between the physical and social sub-systems, systematically leads to overly optimistic assessments (Hertwich and Peters 2009). In addition, according to (Grübler 1998) "technological change is not exogenous to social and economic systems, in fact technologies are not conceived, selected, and applied autonomously" (see also Section 16.4).

### 16.2.3 A catalytic role for capabilities and technological change

A recently developed theoretical framework based on a capability approach (CA) has been used to evaluate the quality of human life and the process of development (Haenssgen and Ariana 2018). Drawing on Amartya Sen's seminal definition of development as an expansion of humans' ability and freedom to live the life they value (Sen 1990), CA offers a perspective on how 'development' can be evaluated. CA has recently been applied to impact assessments of development processes and interventions on people's lives as well as to exploratory studies of the link between technology, human development, and economic growth (Mayer 2001; Mormina 2019).

Studies suggest that the transformative potential of technological change is not intrinsic to a given technology, but is assigned to it by people within a given technological context. Several empirical studies (Rogers 2003; Lansing 1987; Haenssgen and Ariana 2018, p. 103) illustrate this subtle phenomenon in the context of Pakistani and Indonesian agriculture: "…Punjabi farmers in Pakistan acquired tractors for agricultural work; yet because the local technological knowledge only related to the use of bullocks, the maintenance of tractors reflected the care they gave to their animals. Consequently, they covered tractor hoods with blankets to keep them warm during winter at the risk of overheating and machine breakdown." Lansing (1987, p. 339) reports the case of complex yet effective irrigation systems using a network of 'water temples' in Bali [Indonesia], which was not even recognised ('indeed invisible') as an irrigation technology by Western agricultural consultants. [W]hat counts as technical object and how it relates to other inputs depends on the specific socio-technological context." There are several examples of people adopting and adapting technologies to local needs to address locally defined needs; replicating and scaling up such success stories in developing countries and regions would require increased flows of technical assistance and investments from their more developed counterparts (Fu et al. 2019).

### 16.2.4 Governance of technological change

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 will need to encourage the implementation of relevant technological changes directly supportive of SDGs goals related to infrastructure, urbanisation, patterns of consumption and production, climate mitigation and adaptation, and strengthened global partnerships.

Governance interventions to implement the SDGs will necessarily be operationalised at sub-national and national levels (Guo et al. 2020). Regulatory and institutional frameworks that support integration of resource concerns in policy, planning and implementation could set the stage for a net positive outcomes in terms of progress towards the SDGs (UNEP 2015). Innovation and technological change, as an inherently complex processes (Funtowicz 2020), poses governance challenges (Bukkens et al. 2020) requiring social innovation (Repo and Matschoss 2019). The complex adaptive systems perspective has gained traction among development scholars for exploring issues of technological change (Rihani 2002) across the three categories of SDGs (Table 16.1).

Besides evaluating the role of governance as a guide and enabler of SDG-oriented technological change, several scholars have drawn attention to an increasingly important domain of governance concern: unintended consequences (UCs) of technological change. 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). A comprehensive study of these effects distinguishes among "…anticipated-intended, anticipated-unintended, and unanticipated-unintended consequences" (Tonn and Stiefel 2019). From an engineering standpoint, there are "…behaviours that are not intentionally designed into an engineered system yet occur even when a system is operating nominally, that is, not in a failure state as conventionally understood…[T]he primary cause for this difference is the bounded rationality of human designers" Walsh, et al (2019, p. 2441).

In the energy sphere, examples of UCs include: the rapidly growing ocean renewable energy sector, UCs that have been reported, include worse-than-expected physical damage to infrastructure, and resistance from communities (Quirapas and Taeihagh 2020); gaps between expected and actual performance of building integrated photovoltaic (BIPV) technology have been documented some studies (Boyd and Schweber 2018; Gram-Hanssen and Georg 2018). In the agricultural sector, examples include: the new technologies and associated practices that target the fitness of crop pests have been found to favour resistant variants with unintended effect not limited to chemical treatments but also to "…putatively more sustainable approaches" (Sadras 2020). In the health sector, the introduction of health information technology in some clinical settings have increased the likelihood of patient harm (Coiera et al. 2016), failed expectations, saturation of electronic health records (EHR) markets, innovation vacuums, physician burnout, and data obfuscation (Colicchio et al. 2019).

Building on extant theoretical and empirical work, Tonn and Stiefel (2019) propose a framework guide governance actors' responses to UCs that links four constructs, namely: causes, initiators, consequences and effects, and actions to mitigate or adapt. Prioritisation is achieved on the basis of the number of systems affected by given events, trends and forecasts, and systems (initiators), the level of mitigation and adaptive actions, and the unmet obligations to future generations. This approach can help governance actors determine traditionally unknowable consequences as well as the plausible magnitude, direction, and timing of what is to come, enabling governance actors such as researchers, analysts, policy makers make sound decisions on ways to mitigate and adapt to emerging risks of technological change (Tonn and Stiefel 2019).

Despite its advantages, participatory governance can produce perverse results in a contemporary society where dysfunctional cultural phenomena such as fake news, misinformation, and disinformation – themselves arguably unintended consequences of social media technology -- prevail in the public sphere (Iyengar and Massey 2019). Prospects for effectively governing SDG-oriented technological transformations, require at a minimum new tools for securing the scientific legitimacy and credibility to connect public policy and technological change in our society (Sadras 2020).

### 16.2.5 The nexus of technological change and sustainable development

Recent research offers new insights into the challenges hindering technological change in terms of socio-economic processes and associated modes of decision-making, namely behavioural, neoclassical, evolutionary economics (Grubb et al. 2015). Various studies highlight the importance of cultural factors on the pace and direction of technological change (Munene et al. 2018). However, new opportunities to change future pathways have emerged. On balance, the potential for effecting transformative actions at global, national and subnational levels is high (Chaffin et al. 2016; de Haan and Rotmans 2018; Avelino et al. 2019).

An important class of policy challenges hindering the development and adoption of environmental technologies comprises *entrenched power relations* dominated by vested interests that control and benefit from existing technologies (Chaffin et al. 2016). Such interests are largely responsible for stabilising feedbacks within multi-level social-technological regimes (Chaffin et al. 2016).

Human factors, primarily cultural, behavioural and cognitive limits reside at the roots of many challenges to transformative policy change. Studies have demonstrated deficits in innate abilities of people to question dominant social-structuring paradigms (Westley et al. 2011). Although the human capacity for imagination is great, we have difficulty conceptualising ideas beyond the physical senses. Sustainability challenges, manifesting as they do on multiple scales, transcend anything humanity has had to deal with before (Grubb et al. 2015).

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).

A closely related behavioural barrier to climate change is the tendency of citizens to be loss averse, disliking losses far more than similarly sized gains. Recent research on the impact of gain-and-loss framed arguments on climate change activism and technology adoption find that the former are less mobilising, even when they are otherwise persuasive, than gain-framed arguments (Levine and Kline 2019), and that policies can be made so the diversity of actors is used (Knobloch and Mercure 2016). The SDGs offer could build a reliable framework for prioritising and allocating scarce resources for sustainability-focused technological change (Romero-Lankao et al. 2018).

# 16.3 Fundamental elements, drivers and incentives of technology innovation processes

## 16.3.1 Stages of the innovation process

The innovation cycle is commonly thought of as having three distinct innovation phases on the path between basic research and commercial application: Research and Development (R&D), demonstration, and deployment and diffusion (IPCC 2007). Each of these phases differs with respect to the kind of activity carried out, the type of actors involved and their role, financing needs and the associated risks and uncertainties. All phases involve a process of trial and error, and failure is common; the share of innovation that successfully reaches the deployment phase is small. The path occurring between basic research to commercialisation often requires a long time and is characterised by significant bottlenecks and roadblocks. Successfully passing from each stage to the next one in the innovation cycle requires overcoming "valleys of deaths" (Auerswald and Branscomb 2003; Technology Executive Committee 2017), which is considered most challenging for the demonstration phase (Frank et al. 1996; Weyant 2011; Nemet et al. 2018). As time passes, a given (dominant) technology will reach the obsolescence phase, as new and improved technologies are discovered, but this is not discussed here.

The different innovation phases and main funding actors are summarised in Table 16.2, which also provides mapping to the technology readiness levels (TRLs) discussed in Section 16.3.1.4.

**Table 16.2 Stages of the innovation process (16.3.1) mapped onto Technology Readiness Levels (16.3.1.4)**

| **Stage** | **Main funding actors** | **Phases** | **Related TRL**<br>**(*EU Definition*)** |
|---|---|---|---|
| Research and development | Governments<br>Firms | Basic research | TRL 1 – Basic principles observed |
| | | Applied research and technology development | TRL 2 – Technology concept formulated |
| | | | TRL 3 – Experimental proof of concept |
| | | | TRL 4 – Technology validated in lab |

| | | | |
|---|---|---|---|
| | | | TRL 5 – Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies) |
| Demonstration | Governments<br>Firms<br>Venture Capital<br>Angel investors | Experimental pilot project or full scale testing | TRL 6 – Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies) |
| | | | TRL 7 – System prototype demonstration in operational environment |
| | | | TRL 8 – System complete and qualified |
| | | | TRL 9 – Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space) |
| Deployment and diffusion | Firms<br>Private equity<br>Commercial banks<br>Mutual funds | Commercialisation and scale up<br>*(business)* | |
| | International financial institutions | Transfer | N.A. |

Adapted from: (Auerswald and Branscomb 2003), Technology Executive Committee (2017), IEA (2010, p. 14)

### *16.3.1.1 Research and Development*

This phase of the innovation process is focused on both generating knowledge and solving particular problems, i.e., creating a combination of artefacts that is intended to perform a particular function, or to achieve a specific goal. R&D activities comprise basic research, applied research and technology development. Basic research brings specific knowledge on a phenomenon or law of nature; it is often aimed at advancing knowledge rather than solving a problem. Applied research uses the scientific method to solve specific practical issues affecting a given technology, product, or service, including proof-of-concept to verify the viability of a given innovation. Technology development, often leading to prototyping, consists of generating a working model of the technology that is usable in the real world, proving the usability and customer desirability of the technology and giving an idea of its design, features and functioning (OECD 2015a).

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 1996). This risk to funders (Goldstein and Kearney 2020) translates into underinvestment in R&D due to low appropriability (Sagar and Majumdar 2014; Weyant 2011). Private investment in R&D is particularly challenging for climate mitigation technologies due to the presence of a negative environmental externalities and of incumbent fossil-based energy technologies whose financing risk is lower, and which are heavily subsidised and depreciate slowly (see Section 16.3.2) (Nelson 1959; Arrow 1962a; Griliches 1992; Nanda et al. 2016). Public research funding therefore plays a key role in supporting high-risk R&D both in developed and developing economies: it can provide patient and steady funding not tied to short-term investment returns (see Section 16.5) (Anadon et al. 2014; Mazzucato 2015; Howell 2017; Zhang et al. 2019). Public policies also play a role increasing private incentives in energy research and development funding (Nemet 2013).

R&D priorities are also guided by institutions, which often do not embody the goals of the poor or marginalised (Anadon et al. 2016b).

#### *16.3.1.2 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). For energy and industry technologies, government funding often plays a larger role in technology demonstration projects than in other sectors, such as health or agriculture, because scaling up hardware energy technologies is not only expensive, but also risky (Brown and Hendry 2009; Hellsmark et al. 2016). Governments' engagement in the demonstration phase of low-carbon energy technologies also signals support for business willing to take the investment risk (Mazzucato 2016). Venture capital, traditionally not tailored for energy investment, can play an increasingly important role also thanks to the incentives (e.g., through de-risking) provided by public funding and policies (Gaddy et al. 2017; IEA 2017a).

#### *16.3.1.3 Deployment and diffusion*

Deployment entails producing a technology at large scale and scaling up its adoption use across individual firms or households in a given market, and across different markets (Jaffe 2015). In the context of climate change mitigation and adaptation technologies, the purposeful diffusion to developing countries, is referred to as "technology transfer". Transfer of technology is an important component of stringent mitigation strategies as well as international agreements (see Section 16.6).

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

Technologies have been shown to penetrate the market with a gradual non-linear process in a characteristic logistic (S-shaped) curve (Grübler 1996; Rogers 2003). The time needed to reach widespread adoption varies greatly across technologies relevant for adaptation and mitigation, with the formative phase ranging between 5 years to over 200 years (Bento and Wilson 2016; Bento et al. 2018) with 5 to over 70 years for technologies getting from a 10 to 90% market share of saturation (Wilson 2012). While investment in commercialisation of low-emission technology is largely provided by private financiers, governments play a key role in ensuring incentives through supportive policies, including the incentives provided by public policies in investing in certain technologies as opposed to others (Haelg et al. 2018), pricing carbon dioxide emissions, information diffusion through information campaigns, public procurement and technology standards (see Section 16.5).

#### *16.3.1.4 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 NASA in the 1970s (Mankins 2009, 1995) and are currently widely used by engineers, business people, research funders and investors. 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. TRLs range from 1 to 9, with 9 indicating the most mature.

The purpose of TRLs is to support decision making regarding the development and transition of a given technology. In the field of energy technologies, they are applied to avoid the premature application of technologies, which would lead to increased costs and project schedule extension (US Department of Energy 2011). They are thus 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).

Yet, the usefulness of TRLs is limited by several factors: their practical application in complex technologies or systems is limited; they were developed to measure technical product development, and do not define deployment or obsolescence, nor account for manufacturability, commercialisation or the readiness of organisations to implement innovations (European Association of Research Technology Organisations 2014). Finally, they do not consider factors such as the relevance of the products' operational environment to the system under consideration, or any type of technology-system mismatch (Mankins 2009).

## 16.3.2 Drivers of innovation processes

### *16.3.2.1 Learning-by-doing and research and development*

Productivity could be increased and the cost of technology could be reduced by the accumulation of knowledge in the process of R&D as well as learning-by-doing. R&D is the process of looking for new solution (e.g., blueprint) that could increase the efficiency of existing production methods or result in new product or services. In contrast to investment in capital, investment in R&D results in knowledge which is non-rival, i.e., exploiting it by one firm or person does not limit others to exploit it too (Romer 1990). Learning-by-doing results from the interaction of workers with new machines that allows them to use them more efficiently. The higher is the stock of capital in the economy, the more intensive is the interaction with machines and the larger is the stock of knowledge and productivity (Arrow 1962b).

The size of learning-by-doing could depend positively on the size of research and development and vice-versa. Young (1993) postulates that learning-by-doing cannot continue forever and is bounded by an upper physical productivity limit of a given technology. This upper bound could be shifted by new inventions that could replace the existing technology with a new one (learning-by-searching). However, these inventions require R&D activity. Incentives to invest in R&D depend on costs of production, which in turn depend on the scale of learning-by-doing. The empirical evidence for virtuous circle between prices, market growth and R&D were found in the case of PV market (Watanabe et al. 2000), but could also lead to path dependency and lock-in (Erickson et al. 2015). Section 16.5.4 discusses how simultaneous use of technology push and pull policies could amplify effects of research and learning.

The benefits of R&D and learning-by-doing are larger at the economy level than at the firms level (Romer 1990; Arrow 1962b). Knowledge gained due to investment of one firm can be often appropriated by others. Since actors making investment decisions do not internalise the benefits of others, equilibrium level of investment is below its social optimum.

Moreover, if learning-by-doing is necessary to drive the cost of technology down, there is a risk that this technology will not be adopted by the market even if its adoption could bring societal benefits. Initially new technologies are often expensive or characterised by low technological and environmental performance and cannot compete with the incumbent technologies (Cowan 1990). Large numbers of adopters could lower this cost via learning-by-doing to a level sufficient to beat the incumbent technology (Gruebler et al. 2012). However, firms could hesitate to be the first adopter and bear the high cost (Isoard and Soria 2001). If this disadvantage overwhelms the advantages of being a first mover (see e.g. Spence, (1981), and Bhattacharya, (1984) for discussion of first mover advantages) 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. Technology push and demand pull policies are commonly mentioned to correct these market failures. The role of these policies is explained in Table 16.3. Section 16.5 discusses individual policy instruments in greater detail.

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

| | What it refers to: | What promotes technological change | What slows down technological change | Examples |
|---|---|---|---|---|
| Technology Push | Support the creation of new knowledge to make it easier to invest in innovation | R&D, funding and performance of early demonstrations (Brown and Hendry 2009; Hellsmark et al. 2016) | Inadequate supply of trained scientists and engineers (Popp and Newell 2012); gap with demand pull (Grübler et al. 1999). | 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.<br>Digital innovations<br>Social innovation and awareness | Willingness of consumers to accept new technology. Policy and political volatility can deter investment. | Subsidies for wind power California, the German feed-in tariff for PV, quotas for electric vehicles in China (Wang et al. 2017a) and Norway (Pereirinha et al. 2018)<br>Biofuels (Brazil); Social innovation with Wind Energy (Denmark, Germany) |

Early empirical studies examined the size of learning-by-doing effect. This was usually done by estimating learning rates using estimates of negative correlation between costs and 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 and Sewerin 2017) and for energy demand and energy supply technologies (Weiss et al. 2010). Meta-analyses find learning rates vary across technologies, within technologies and over time (Rubin et al. 2015);Wei et al. 2017; Nemet 2009a), but  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 from these early studies are not sufficiently precise to disentangle the causal effect of increase in deployment due to cost reduction from the causal effects of research and development and other factors (Nemet 2006). Numerous subsequent studies attempted to, amongst others, separate the effect of learning-by-doing and research and development (Klaassen et al. 2005; Mayer et al. 2012; Bettencourt et al. 2013), economies of scale (Arce 2014), and knowledge spill-overs (Nemet 2012b). Once those other factors are accounted for, some empirical studies find that the role of learning-by-doing in driving down the costs becomes minor (Kavlak et al. 2018; Nemet 2006). In addition the relation could reflect reverse causality: increase in deployment could be an effect (and not a cause) of a drop in price (Witajewski-Baltvilks et al. 2015; Nordhaus 2014). Nevertheless, in some applications, learning curves can be a useful proxy and heuristic (Nagy et al. 2013).

The negative relation between costs and experience is the reason to invest in a narrow set of technologies; the uncertainty regarding the parameters of this relation is the reason to invest in wider ranges of technologies (Way et al. 2019; Fleming and Sorenson 2001). Concentrating investment in narrow sets of technologies (specialisation) enables fast accumulation of experience for these technologies and large cost reductions. However, it also includes the risk that the optimal technology will be excluded from supported technologies, and hence will not benefit from learning-by-doing. Widening the set of supported technologies would reduce this risk (Way et al. 2019). Prediction is subject to uncertainty because noise in historical data hides the true value of learning rates as well as because of unanticipated future shocks to technology costs (Lafond et al. 2018). Ignoring uncertainty in the model implies that the model results are biased towards supporting narrow set of technologies neglecting the benefits of decreasing risk trough diversification (Sawulski and Witajewski-Baltvilks 2020).

#### *16.3.2.2 Knowledge spill-overs and general purpose technologies*

Knowledge spill-overs drive continuous technological progress (Rivera-Batiz and Romer 1991; Romer 1990) and are for that reason relevant to climate technologies as well as incumbent, carbon-intensive technologies. Every innovation and every addition to the knowledge stock gives an opportunity for others to create new innovations and increase the knowledge stock even further. The constant growth of knowledge stock through spill-overs translates into constant growth of productivity.

Spill-overs related to energy and low-emission technologies show path dependency, and can have both positive and negative impacts on climate change mitigation *(high confidence)*, according to a number of empirical studies (e.g., Popp 2002; Aghion et al. 2013; Witajewski-Baltvilks et al. 2017; Verdolini and Galeotti 2011; Conti et al. 2018). Aghion et al (Aghion et al. 2013) find that spill-overs result in path-dependency in the automobile industry: companies that patented more in combustion engines are more likely to patent in the same technology in the future. The spill-over effect associated with innovation in carbon-intensive technologies may lead to lock-in of fossil-fuel technologies. Continuous technological progress of carbon-intensive industry raises the bar for clean technologies: a larger drop in clean technologies' cost is necessary to become competitive (Acemoglu et al. 2012; Aghion et al. 2013). The implication is that delaying climate policy increases its cost (Aghion 2019).

The spill-over effect associated with innovation in low-emission technologies implies that temporary policy can lead economies to become locked-in to low-emission technologies in the long-run (Aghion 2019). A policy that encourages clean innovation leads to accumulation of knowledge in clean industry. This decreases the cost of clean technologies and 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 (Acemoglu et al. 2012).

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

By allowing for experimenting with existing knowledge and combining different technologies, knowledge spill-overs can result in the emergence of novel technological solutions, which has been referred to as recombinant innovation (Weitzman 1998; Olsson and Frey 2002; Tsur and Zemel 2007; Fleming and Sorenson 2001; Arthur 2009). Recombinant innovations speed up technological progress by combining different technological solutions, and make things happen that would be impossible with only incremental innovations (Safarzyńska and van den Bergh 2010; van den Bergh 2008; Frenken et al. 2012). It has been shown that 77% of all patents granted between 1790 and 2010 in the US are coded by a combination of at least two technology codes (Youn et al. 2015). Many technologies considered to be 'environmental' innovations combine distinct technological options: a hybrid car combines a conventional engine with an electric propulsion system; a combined cycle gas turbine (CCGT) integrates gas and steam turbine technologies; or Integrated Solar Combined Cycle Power Plants (ISCCs) produce electricity by combining gas-turbine with a photovoltaic system.

The opportunity for the development of new technologies is sometimes created by the arrival of new general purpose technologies (GPTs). GPTs provide solutions that could be applied across sectors and industries (Goldfarb 2011). Historical examples of GPTs include the steam engine, the electric dynamo and, more recently, information and communication technologies (ICTs). GPTs create technological platforms for a growing number of interrelated innovations. Each such innovation depends on the success of other innovations (Grubler et al. 2012). Examples of such dependencies include electric light and power (Du Boff 1984) and automobiles and complimentary services (Freeman and Perez 1988).

The IPCC SR1.5 has identified various GPTs relevant to reduction of greenhouse gas emissions (de Coninck et al. 2018). Table 16.4 identifies various GPTs relevant to climate change mitigation, sectors in which they might find application. It is highlighted that assessment of the environmental, social and economic implications of such technologies is challenging, and that rebound effects could occur (de Coninck et al. 2018) as well as increased emissions through energy use (see Cross-Chapter Box 8 in Chapter 16).

**Table 16.4 Cross-sectoral applications of general purpose technologies and their relevance to climate change mitigation**

| **GPT** | **Sector applicability** | **Examples of specific applications** |
|---|---|---|
| Additive manufacturing (3D printing) | Transport | Aircraft component manufacture to achieve more lightweight, cost-effective designs results in improved fuel consumption and lower primary resource inputs. Estimated life-cycle for the US aircraft fleet could achieve primary energy savings of 70-174 million GJ $yr^{-1}$ in 2050. Associated cumulative emission reduction potentials of $CO_2$-eq. were on the order of 100s of $MtCO_2$-eq over the next three decades (Huang et al. 2016) |
| Artificial Intelligence (AI) | Agriculture<br>Buildings | Applications in agriculture include irrigation management which can reduce power requirements for pumping and optimisation of energy for produce storage (Alfer'ev 2018) |
| Biotechnology | Agriculture<br>Transport | *[Text to be added in Final Draft.]* |
| Hydrogen | Energy<br>Industry<br>Transport | Hydrogen and fuel cell technology, which can be produced from a number of different fossil and renewable resources, may find applications in transport, industry and distributed generation (Hanley et al. 2018). |
| ICT | Buildings | ICT has been demonstrated to have potential to contribute to increased household energy efficiency. One estimate suggests ICT-based |

| | | |
|---|---|---|
| | Energy<br>Transport<br>Urban systems | interventions in household energy use could contribute between 0.23% and 3.3% of the EU $CO_2$-eq reduction target from the energy sector, corresponding to 4.5–64.7 million tonnes $CO_2$-eq abated per year (Bastida et al. 2019). (see also Cross-Chapter Box 8 in Chapter 16) |
| Internet of Things | Energy<br>Transport<br>Urban systems | [*Text to be added in Final Draft.]* |
| Nanotechnology | Energy<br>Transport | Nanotechnology has played a significant role in advancement of all the different types of renewable energy options (Hussein 2015) |
| Robots | Industry | *[Text to be added in Final Draft.]* |

## Cross-Chapter Box 8: Digitalisation: efficiency potentials and governance considerations

Felix Creutzig (Germany), Elena Verdolini (Italy), Paolo Bertoldi (Italy), Luisa F. Cabeza (Spain), María Josefina Figueroa Meza (Venezuela/Denmark), Kirsten Halsnæs (Denmark), Joni Jupesta (Indonesia), Şiir Kilkiş (Turkey), Michael Koenig (Germany), Eric Masanet (the United States of America), Joyashree Roy (India/Thailand), Ayyoob Sharifi (Iran/Japan)

Digitalisation is the adoption or increase in use of information and communication technologies (ICTs) by citizens, organisations, industries or countries as well as the restructuring of several domains of social life and of the economy around digital technologies and infrastructures (IEA 2017b; Brennen and Kreiss 2016). While digitalisation trends have been underway for decades, recent increases in digital data, their use to produce useful information and insights (i.e. analytics) and their exchange between humans, devices and machines (i.e. connectivity) have accelerated the pace at which the physical and digital worlds are converging, inter alia by combining finance with technology creating another transformation layer (see Chapter 15, Box 15.8 ), Digitalisation is a driver of disruptive change and will play a key role in societal transformations and in addressing sustainability challenges (European Commission 2020) (Chapter 4, Section 4.4.1). Digitalisation is underpinned by dynamic developments in key technologies, including the recent advent of 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). Countries differ widely in their adoption of digital technologies and in opportunities to gain access to digital technologies: the digital divide compounds and could amplify the already existing economic divides. As a result, developing countries could further lose out.

**In the next decades, all major energy-demand sectors will be deeply affected by the digital revolution** (European Commission 2014; IEA 2017). Digital technologies provide solutions to reduce the demand for traditional energy services, increase the role of demand-side management in the balancing of the electricity system and to shift away from asset redundancy (Chapter 6, Section 6.4.3.3). Home environments will be filled with smart devices (Serrenho and Bertoldi 2019) (Chapter 9, Sections 9.4 and 9.5). Smart mobility will change transport demand and efficiency; electric, automated vehicles will be fully integrated with the electricity system (Chapter 10, Section 10.2.3). Industrial sectors will be reshaped through increased robotisation, smart manufacturing (SM) systems, additive manufacturing, internet of things and artificial intelligence and digital technologies promoting energy management (Chapter 11, Section 11.3.4.2). Digital solutions are equally important on the supply side, for example by accelerating innovation with simulations and deep learning (Rolnick et al. 2019). Digital solutions are all closely related to energy-as-a-service concepts and particularly with Pay-As-You-Go, realising flexible and decentralised opportunities (Chapter 15, Box 15.8, Table 1).

**Digital technologies are relevant objects for climate change mitigation because they impact GHG emissions directly and indirectly. Closing the digital gap in developing countries and rural communities enables an opportunity for leapfrogging.** Direct impacts emerge because digital technologies affect energy demand as well as energy efficiency; indirect impacts materialise through induced demand for consumption goods, demand for skills and labour to sustain the digital economy, increased competitiveness, changes in trade patterns and impact inequality and access to services, and governance (*medium evidence, high agreement*) (Chapter 4 Section 4.4, Chapter 5 Sections 5.3 and 5.6). Communication technologies (such as mobile phones) are an integral component for enable participation of rural communities, especially in developing countries, and leapfrog technologies, e.g. by directly enabling adoption of decentral renewable energies and smart farming (Ugur and Mitra 2017; Foster and Azmeh 2020).

**Digital technologies, analytics and connectivity consume large amounts of energy** (Horner et al. 2016; Jones 2018) **implying higher direct energy demand and related carbon emissions.** The direct impact of digital technologies on energy demand due to servers running, streaming, clouds, etc., is perhaps best epitomised in the energy demand for cryptocurrencies. Global energy demand from digital appliances reached 7.14 EJ in 2018 (Chapter 9, Box 9.5). Furthermore, demand for data centre services increased by 550% between 2010 and 2018 and is now estimated at 1% of global electricity consumption (Masanet et al. 2020; Avgerinou et al. 2017; Stoll et al. 2019; Vranken 2017). Yet, the associated energy demand increased only modestly, by about 6% from 2000 to 2018. This is due to significant efficiency improvements over the same time period (Masanet et al. 2020). Renewable energy serves as low-carbon energy safety valve for the operation of data centres.

**Digital technologies have the potential to reduce energy demand in all end-use sectors through steep improvements in energy efficiency.** Digital technologies contribute to energy efficiency in economic and human systems through material input savings and increased coordination as they allow to use less inputs to perform a given task (Huang et al. 2016; IEA 2017b). For example, a small smart phone offers services previously requiring many different gadgets (Grubler et al. 2018). Clear savings are reported in building and industry sectors where smart appliances, energy consumption feedback devices and energy management effectively reduce energy demand and associated GHG emissions by 5 to 10%, with larger savings possible, while maintaining service levels equal. Mobility and building energy can become both much more efficient with digital technologies, especially in the context of systems integration that has importance for net-zero emissions (IEA 2020a), including demand response and smart charging (Cross-Chapter Box 8 Table 1). Data centres can also play a role in energy system management, e.g., by waste heat utilisation where district heat systems are close; temporal and spatial scheduling of electricity demand can provide about 10GW in demand response in the European electricity system in 2030, about 6% of the total potential demand response (Koronen et al. 2020; Wahlroos et al. 2017, 2018; Laine et al. 2020). Digitalisation will also reduce construction waste and the demand for construction material and their related embodied emissions.(Dixit 2019).

**System-wide effects may endanger energy and GHG emission savings**. Rising demand can diminish energy savings, and also produce run-away effects associated with additional consumption and GHG emissions, if left unregulated (Chapter 5 Section 5.3) (Table 1). Savings are varied in smart and shared mobility systems, as ride hailing increases GHG emissions due to deadheading, whereas shared pooled mobility and shared cycling reduce GHG emissions, as occupancy levels and/or weight per person km transported improve Chapter 5 Section 5.3). Energy savings in smart cities, characterised by the ubiquitous deployment of smart sensors and big data applications, are insufficiently assessed in the literature. Systemic effects have wider boundaries of analysis and are more difficult to quantify and investigate but are nonetheless very relevant. Systemic effects tend to have negative repercussions but policies and adequate infrastructures and choice architectures can help to manage and contain negative energy use effects (Chapter 6 Sections 5.4 and 5.6, Chapter 9 Section 9.9).

**Cross-Chapter Box 8, Table 1. 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 (+++). See also Chapters 5, 8, 9, and 11.**

| Sector | Approach | Quantitative evidence | Contribution of digitalisation | System's perspective | References |
|---|---|---|---|---|---|
| **Residential energy use** | Nudges (feedback, information, etc.) | 2-4% reduction in global household energy use possible | +<br>in combination with monetary incentives, non-digital information | New appliances increase consumption | (Buckley 2020)<br>(Zangheri et al. 2019)<br>(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 ecodriving | ++<br>Apps together with big data and machine learning algorithm key precondition for new shared mobility | Ride hailing increases marginal GHG emissions, especially due to deadheading | (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%, | ++<br>Big data analysis necessary for optimisation | Efficiency gains are often compensated by more driving and other rebound effects; danger of surveillance state | (Milojevic-Dupont and Creutzig 2021)<br>(Chapter 10, Box 10.2) |
| **Agriculture** | Using sensors and satellites provide information on soil moisture, temperature, crop growth and livestock feed levels | | ICTs provide information which enables farmers to increase yields, optimise crop management, reduce fertilisers and pesticides, feed and water; increases efficiency of | The digital divide is growing fast, especially between modern and subsistence farming; Privacy and data may erode trust in technologies | (Townsend et al. 2019)<br>(Deichmann et al. 2016) |

| | | | | | |
|---|---|---|---|---|---|
| | | | labour-intensive tasks | | |
| **Industry** | Industrial Internet of Things (IIoT), | Process, activity & functional optimisation increases energy and carbon efficiency | ++ increased efficiency<br>++ 1.3 $GtCO_2$-eq estimated abatement potential in manufacturing<br>+ promote sustainable business models | | (GeSI 2012; Parida et al. 2019; Rolnick et al. 2019) |
| **Demand response management** | Big data analysis for optimising demand management and using flexible load of appliances with batteries | Reduces capacity intended for peak demand | ++<br>Big data analysis necessary for optimisation | (small) system wide rebound effect possible | (Chapter 6, Section 6.4) |

**Digitalisation pathways can have potentially disruptive effects because digital technologies change the framework conditions in which decarbonisation will be pursued.** Digital technologies have major implications on global labour markets: robots displace labour, and suppress wages (Acemoglu and Restrepo 2019). Digitalisation changes the demand for skills, driving upward demand for high skills and depressing demand for low-skills. These patterns are different depending on the sector considered and its exposure to digitalisation. Digitalisation affects firms' competitiveness because it expands production possibilities. Increased used of robotics, smart manufacturing, and 3D printing can change production patterns and trade, and bring production back to some countries which have lost it to countries with lower labour costs and largely lower environmental quality. Digital technologies can lead to additional concentration in economic power (e.g., (Rikap 2020)). For instance, current form of digitisation favours platform solutions that oligopolises global digital markets, and suppresses competition. In the current form, profits and power concentration will continue to concentrate in OECD countries and China, leaving the rest of the world population as resource to extract data from and manipulate via communicative nudges and signals. Digital technologies affect access to services and information and play a role in mobilising citizens for climate action (and other actions). Through its impact on the labour market, as well as to access to services, digitalisation impacts inequality and raises fairness concerns. By displacing labour and suppressing wages in certain sectors (Acemoglu and Restrepo 2019), it can be a contributing driver to global inequality. This dynamic amplifies existing trends towards more inequity created by high saving rates of the most affluent household, and low saving rates and increasing debts of households with low income. Digitalisation may also put further pressure on workers' salaries. The reduced liquidity of the majority of consumers depresses future consumption and leads to economic stagnation (Mian et al. 2020).

**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 more in general.** Forecasts suggest that disruptive change will happen fast, and experts recognise this transition will create several challenges. The understanding of the disruptive potential of digital technologies, which is a function of both technical characteristics and non-technical aspect, is still limited (Aghion et al. 2018). This is partly due to their ground-breaking and disruptive nature, which makes it hard to extrapolate from previous history/experience. Indeed, digital technologies are still highly concentrated, with 80% of all industrial robots deployed in OECD countries in 2014, and China leading in adoption of robots (OECD 2017). The digital transformation will have profound distributional effects: it will affect competitiveness (Varian 2018), trade (Goldfarb and Trefler 2018), and employment (Trajtenberg 2018; Acemoglu and Restrepo 2019), thus becoming a driving force of social transformation (Chapter 4). Digital technologies have sector-specific potentials and barriers, and may benefit certain regions/areas/socioeconomic groups more than others, as in the case of integrated mobility services, which benefit cities more than rural and peripheral areas (OECD 2017). Digital technologies may also make it easier and cheaper (or harder and costlier) to implement stringent climate policies across sectors and countries (i.e., enhancing policy enforcement). (Chapter 17 Section 17.3)

**An important area of action relates to the governance using digital technologies for the purpose of mitigation.** Municipal and national entities can make use of digital technologies to manage and govern energy use and GHG emissions in their jurisdiction. They can break down solution strategies to specific infrastructures, building, and places, relying on remote sensing and mapping data, and contextual (machine-) learning about their use. Insights can translate into agile urban planning. Mobility apps can provide mobility-as-a-service access to cities providing due preference to active and healthy modes (see Chapter 9 Section 9.9 for the example of the Finnish city of Lahti). Trusted data governance can also enable citizen users to suggest, promote and eventually implement their own local climate solutions, supported by available big data on infrastructures and environmental quality. Governance decisions, such as taxing data, or prohibiting surveillance technologies, can change digitalisation pathways, and thus also modify underlying GHG emission trajectories. Data control by citizens, communities and local administrations can be key to source locally adapted mitigation solutions. This can all be realised without turning to big behavioural data and further intensification of surveillance capitalism (see below).

**In addition, appropriate mechanisms need to be designed govern digitalisation as megatrend.** Digitalisation is becoming a key driving force of social transformation (Chapter 4 Section 4.4), *inter alia* involving increasingly faster communication (5G, 6G) and new financial markets (cryptocurrencies). Power question is at the core: who controls and manages data created by everyday operations (calls, shopping, weather data, service use, etc.). While it is expected to be a fast process, this transformation takes place against entrenched individual behaviours, existing infrastructure, the legacy of time frames, vested interest and slow institutional processes. It also requires trust from consumers, producers and institutions. The power and economic concentration or de-concentration will decide about global inequality and induced consumption patterns and their GHG emissions. Digitisation realises a surveillance capitalism that enables algorithmic control over behaviour, and possibly authoritarian control over citizens. Digitalisation could also be used for more benign decentral decision making and support of democracy, but until now trends are dominated by global data aggregation. Regulations that limit or ban the expropriation and exploitation of behavioural data, sourced via smart phones, will be decisive about digitalisation pathways, and also about the possibility to create climate movements and political pressure from the civil society. Artificial intelligence may soon take over not only operational choices (how to navigate in an unknown city) but also ethical choices (how to react in unavoidable traffic accidents with other people involved) (Craglia et al. 2018). Digitalisation pathways can head towards increased overconsumption of for realising efficiency potentials in service provisioning. Overall governance will be decisive in optimising the effect of digitalisation for the public good.

**In summary, through appropriate governance, digitalisation can effectively work in tandem with established mitigation technologies and choice architectures and thus can marginally decrease GHG emissions. Consideration of system-wide effects and overall management is essential to avoid run-away effects. Overall governance of digitalisation remains a key challenge, and will have large-scale repercussions on energy demand and GHG emissions.**

#### *16.3.2.3 Disentangling the effect of various drivers of technology cost changes*

Researchers and policymakers alike are interested in using observed empirical patterns of learning to project future reductions in 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), 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). Looking to future costs in 2030, expert forecasts generally result in higher cost forecasts compared to model-based forecasts for more modular technologies, while in the past model forecasts were closer to the realise costs (Meng et al.).

Over time there has been a growing amount of work trying 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 include both cumulative deployment (as proxy for experience) and R&D investment as explanatory factors for cost reduction (see the "two factor" learning curve (Mayer et al. 2012; Bettencourt et al. 2013). However, reliable information on public energy R&D investments is hard to obtain, even in OECD countries (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 costs (see for example (Qiu and Anadon 2012) accounting for steel costs for wind turbines, (Kavlak et al. 2018; Nemet 2006) accounting for silicon costs, and (McNerney et al. 2011) including coal costs over time.

Changes in average unit costs of technologies could be also explained by the scale of production. When scaling-up the plant size leads to cost reduction, the plant experiences 'increasing returns to scale' or 'economies of scale'. This could be due to spreading the costs of shared infrastructure (or fixed capital) across greater output (Isoard and Soria 2001; Kavlak et al. 2018). When scaling up leads to cost increase, e.g. due difficulty in management, the plant experiences decreasing returns to scale (Yu et al. 2011). Gambhir et al. (2016) emphasised the substantial potential for economies of scale in the case of organic PV technologies, and Yu et al. (2011) and Kavlak et al. (2018) found that economies of scale played a significant role in the reduction of PV since the early 2000s.

In some cases, increase in deployment over time coincides with an increase in technology costs, at least in some countries (e.g., nuclear power in OECD countries due to stricter safety regulation (Lovering et al. 2016) and solar water heaters in the US (Nemet 2012a) ), however these cases are rare. It has been common to find that cost decreases are preceded by a short-term increases during the formative phase of the technologies (Dowlatabadi 1998; Rubin et al. 2015).

### 16.3.3 Determinants of direction of technological change trajectory

#### *16.3.3.1 Green direction of technological change*

Technological progress 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, such as Solow (1957) or 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 progress to alter the otherwise fixed relation between economic growth and the use of resources.

The direction of technological change can change if it saves relatively more of one input to production than another (Sue Wing 2006). In particular technological progress that is biased against carbon-intensive production could decouple growth and the use of fossil fuels (Acemoglu et al. 2014; Hémous 2016; Greaker et al. 2018; Acemoglu et al. 2012). For instance, since energy is complementary to other factors of production, energy efficiency improvement induced by an increase in energy price leads to drop in demand for energy (Hassler et al. 2012; Witajewski-Baltvilks et al. 2017).

#### *16.3.3.2 Determinants of direction of technological change: prices, market size and government*

Firms change their choice of technology upon change in prices: when one input (e.g., energy) becomes relatively expensive, firms pick technologies which allow them to economise on that input, according to price-induced technological change theory (Reder and Hicks 1965; Samuelson 1965). For example, an increase in oil price will lead to a choice of fuel-saving technologies. Such strong response of technological change was evident during the oil-price shocks in the 1970s (Hassler et al. 2012).

The dependence of the trajectory of technological change on prices is supported by the theory on directed technological change, which examines the incentives and dynamics as a result of redirection of R&D. An increase in the price of one input incentivises research that reduces relative demand for that input. However, absolute (as opposed to relative) reduction of an input use could be achieved only if the polluting and the clean inputs are sufficiently substitutable (Acemoglu et al. 2012).

The impact of energy prices on the size of low-carbon technological change is supported by large number of empirical studies (Popp 2019; Grubb and Wieners 2020). Studies document that higher energy prices are associated with higher number of low-carbon energy or energy efficiency patents (Noailly and Smeets 2015; Ley et al. 2016; Lin and Chen 2019; Newell et al. 1999; Verdolini and Galeotti 2011; Popp 2002; Witajewski-Baltvilks et al. 2017). Sue Wing (2008) finds that innovation induced by energy prices had a minor impact on the decline in U.S. energy intensity in the last decades of 20th century and that autonomous technological progress played a more important role. Several studies explore the impact of a carbon tax on green innovation (see Section 16.5). However, disentangling the effect of policy tools is complex because presence of some policies could distort the functioning of other policies (Böhringer and Rosendahl 2010; Fischer et al. 2017).

The direction of technological change depends also on the market size for dirty technologies relative to the size of other markets. Even a unilateral climate policy of one region will shift the direction of technological change towards clean goods (Maria and van der Werf 2008). And if technologies cannot be traded, but the output of the carbon-intensive sectors (e.g., chemicals or cement) can be traded, an introduction of carbon tax in one region leads to the expansion of carbon-intensive sector in the other region (carbon leakage). This increases the size of the market for dirty innovations and speeds up development of dirty technologies in the region with no climate policy (van den Bijgaart 2017; Hémous 2016). On the contrary, an introduction of carbon tax together with clean R&D subsidies and trade policies discouraging import of the carbon-intensive good decreases the size of the market for dirty innovation in the other region in the long-run (Hémous 2016). Global reduction of emissions is possible if one region could push the comparative advantage of the other regions to clean or carbon-neutral sectors and meanwhile develop technologies that could substitute the carbon-intensive goods (van den Bijgaart 2017; Hémous 2016).

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

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

#### *16.3.3.3 Determinants of direction of technological change: financial market*

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

The preference for particular types of investments in renewable energy technologies depends on investors attitude to risk (Mazzucato and Semieniuk 2018). Some investors invest in only one technology, others may spread their investments, or invest predominantly in high-risk technologies. The distribution of different types of investors will affect whether finance goes to support deployment of new high-risk technologies, or diffusion of more mature, less-risky technologies characterised by incremental innovations. The role of finance in directing investment and technological change is further discussed in Chapter 15, Section 15.6.

#### *16.3.3.4 Market failures in directing technological change*

Market forces alone cannot deliver Pareto optimal (i.e., socially efficient) outcome because first welfare theorem (Mas-Colell et al. 1995) fails due to two types of externalities: GHG emissions that cause climate damage and knowledge spill-overs that benefit firms other than the inventor. Nordhaus (2011) argues that these two problems should be tackled separately: once the intellectual property rights are in place, a price on carbon that corrects the emission externality is sufficient to induce optimal level of green technological change. Acemoglu et al.(Acemoglu et al. 2012) demonstrates that subsidising clean technologies (and not dirty ones) is also necessary to break the lock-in of dirty technological progress. van den Bijgaart (2017) and Hémous (2016) show that clean innovation subsidies in the coalition of environmentally concerned regions are necessary to induce global emission reduction if other regions are not willing to collaborate in setting climate policies.

### 16.3.4 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). Technological innovation plays a key role in the modelling of integrated pathways: one of the drivers of emissions reductions in model-based scenarios is the diffusion of cost-competitive climate mitigation technologies. Innovation activities modelled in climate-energy-economy models include the development of low-, zero- and negative-carbon energy options, but also investments to increase energy efficiency.

#### *16.3.4.1 Technology cost development*

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

In these models, technology costs may evolve exogenously or endogenously (Krey et al. 2019; Mercure et al. 2016). In the first case, technology costs are assumed to vary over time at some predefined rate. In this case, 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. One factor in this 'learning-by-researching' is applied to a wide range of technologies but also to model improvements in the efficiency of energy use (Goulder and Schneider 1999; Popp 2004).

More complex formulations include two-factor learning processes (see Section 16.3.2.3) (Criqui et al. 2015; Emmerling et al. 2016; Paroussos et al. 2020), or other drivers of cost reductions such as economies of scale and markets (Elia et al. 2020). The application of two-factor learning curves to model 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 technology costs reductions varies across technologies, even within the same model, depending on the availability of data and/or maturity level of the technology. Less mature technologies generally depend highly on learning-by-research, whereas learning-by-doing dominates in more mature technologies (Jamasb 2007).

Learning curves are not the only approach available to model induced technical change. Knowledge spill-over effects are also integrated in climate-energy-economy models to reflect the fact that innovation in a given country depends also on knowledge generated elsewhere (Fragkiadakis et al. 2020; Emmerling et al. 2016). Models with a more detailed representation of sectors (Paroussos et al. 2020) can use spill-over matrices to include bilateral spill-overs and compute learning rates that depend on the human capital stock and the regional and/or sectoral absorption rates (Fragkiadakis et al. 2020).

#### *16.3.4.2 Technology deployment and diffusion*

To forecast technology diffusion, models take into account a given technology cost relative to the costs of other technologies and its ability to supply the energy demand under the relevant energy system and physical constraints. This requires taking into consideration, for example, 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 other key factors other than technology costs and performance (Knobloch and Mercure 2016), such as non-cost, non-technological barriers or enablers regarding behaviours, society and institutions. 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 (Iyer et al. 2015; Baker et al. 2015; Marangoni and Tavoni 2014; van Sluisveld et al. 2020; Napp et al. 2017). These types of barriers to technology diffusion are currently not explicitly detailed in most of the climate-energy-economy models. Rather, they are accounted for in models through scenario narratives, such as the ones in the Shared Socioeconomic Pathways (Riahi et al. 2017), in which assumptions about technology adoption are spanned over a plausible range of values. Complementary methods are increasingly used to explore their importance in future scenarios (Turnheim et al. 2015; Gambhir et al. 2019; Trutnevyte et al. 2019; Doukas et al. 2018; Geels et al. 2016). It takes a very complex modelling framework to include all aspects affecting technology cost reductions and technology diffusion, such as heterogeneous agents (Lamperti et al. 2020), regional labour costs (Skelton et al. 2020), materials cost and trade and perfect foresight multi-objective optimisation (Aleluia Reis et al. 2020). 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 (Doukas and Nikas 2020; van Vliet et al. 2010; Nikas et al. 2017, 2018).

#### *16.3.4.3 Implications for the modelling of technical change in decarbonisation pathways*

The fact that climate-energy-economy models cannot mimic all the dynamics and factors influencing technology costs and diffusion at once has two potential implications. On the one hand, as demonstrated by the case of solar in the past decade, scenarios emerging from cost-optimal climate-energy-economy models may be too pessimistic. On the other hand, they may be too optimistic regarding the timing of action, or the availability of a given technology and its speed of diffusion. The IPCC SR1.5 concluded that integrated assessment models tend to underestimate innovation on energy supply but overestimate the contributions by energy efficiency (IPCC 2018a). This debate has yet to be settled, but if this were to be factored into the analysis, the resulting decarbonisation pathways may display significantly different patterns of low-carbon technology innovation and diffusion (Clarke et al. 2009; Edmonds et al. 2008; Stocker 2013).

There is a range of projected energy technology supply costs included in the AR6 Scenario (Box 16.1). Variations of costs over time and across scenarios are within ranges comparable to those observed in recent years. Conversely, limiting warming to 2°C or 1.5°C will require faster diffusion of installed capacity of renewable 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 low carbon pathways**

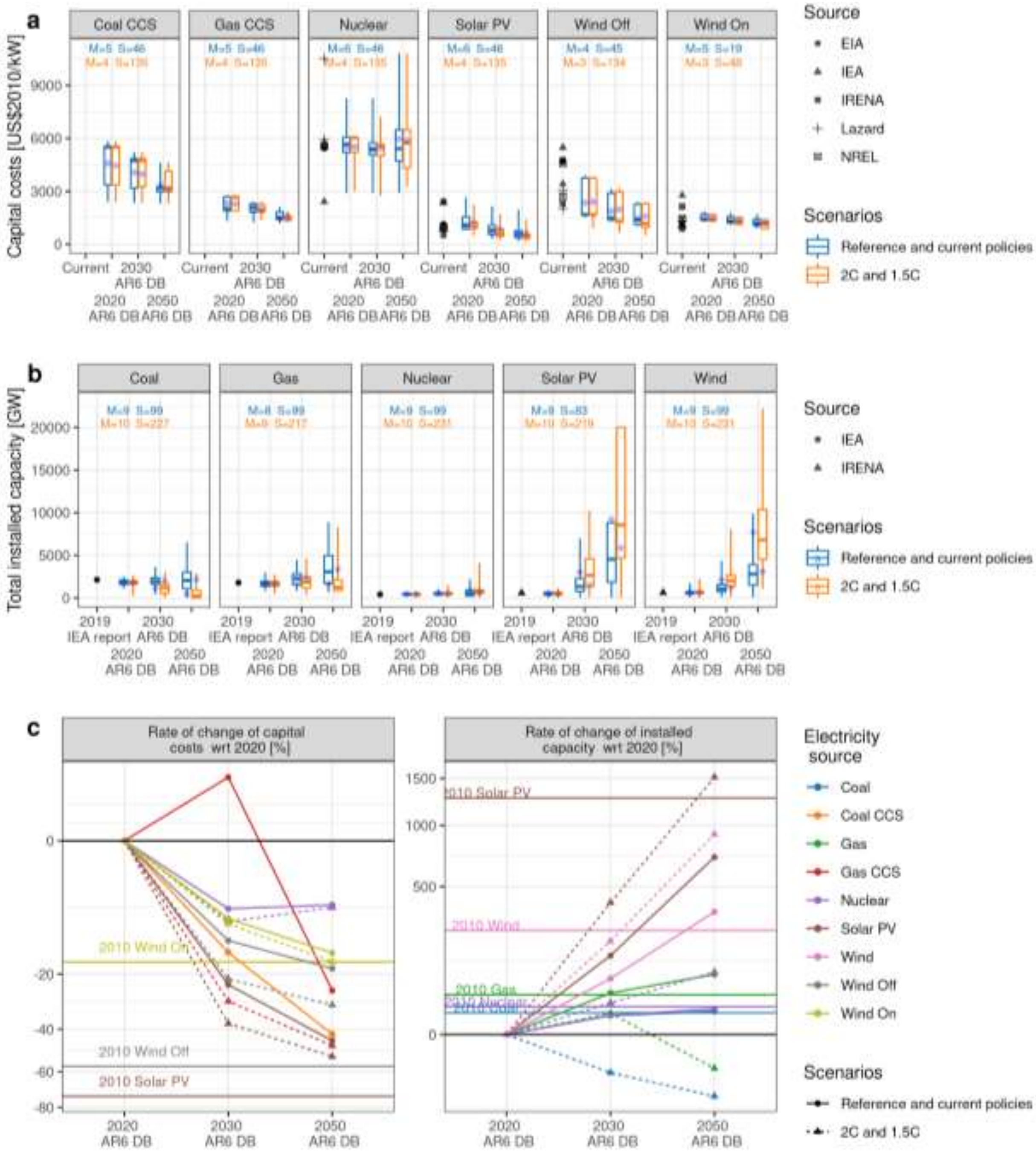
Currently observed costs and deployment for selected energy supply technologies are compared with projections from two different sets of scenarios: 1) reference and current policies including NDCs and 2) 2°C and well-below 2°C (AR6 model database). Technologies include Coal with CCS, Gas with CCS, Nuclear, Solar PV, Onshore and Offshore Wind. Global aggregates are shown, but regional differences exist (IRENA 2019).

The decrease in forecasted capital costs is not large compared to current capital costs for most technologies, and does not differ much between the two scenarios (Box 16.1, Figure 1a). For Wind offshore some of the models are more optimistic than the current reality (Timilsina 2020). Several sources of current solar PV costs report values that are at the low end of the AR6 model scenario database. Nuclear current and future costs reflect the high uncertainty regarding this technology. By

2050, the median technology cost forecasts decrease by between 5% for nuclear and 45-52% for solar (Box 16.1, Figure 1c).

Median values of renewables installed capacity increase with respect to 2020 capacity in "*current policies"* scenarios (Box 16.1, Figure 1b), where energy and climate policies are implemented in line with the current NDCs, as many renewable technologies are currently cost-competitive with traditional generation in many places. Furthermore, additional technological improvements are assumed, including in complementary technologies (e.g. energy storage). Achieving more stringent targets (2°C) requires further increasing the deployment of renewable technologies: by 2050 solar (wind) capacity would need to increase by a factor of 15 (10) (Box 16.1, Figure 1c). This is accompanied by an almost complete phase out of coal (-87%). The percentage of median changes in installed capacity in the current policies scenarios is within comparable ranges of that observed in the last decade. In the case of the 2°C and well-below 2°C scenarios, they are higher for renewable technologies and nuclear, and lower for fossil-based technologies (Box 16.1, Figure 1c).

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



**Box 16.1, Figure 1: Global Technology cost and deployment in two groups of AR6 scenarios: (1) reference and current policies including NDCs and (2) 2°C and well-below 2°C.**

Panel a) Current capital costs (Timilsina 2020); distribution of capital costs in 2030 and 2050 (AR6 database). Blue symbols represent the mean. 'Current' capital costs for coal and gas plants with CCS are not available; Panel b) Total installed capacity in 2019 (IEA and IRENA); distribution of total installed capacity in 2030 and 2050 (AR6 database). Blue symbols represent the mean; Panel c) Percentage of change in capital costs and installed capacity between (2010-2020) and percentage of median change (2020-2030 and 2020-2050) (Median$_{year}$-Median$_{2020}$)/Median$_{2020}$*100. "M" indicates the number of models, "S" the number of scenarios for which this data is available. Each model may have submitted data for more than one model version.

## 16.4 A systemic view of technological innovation process

While the innovation process is often stylised as a linear process (Section 16.3.1), 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 (e.g. Kline and Rosenberg 1986). Furthermore, it is not just invention that leads to technological change but the cumulative contribution of incremental innovations over time can be very significant (Kline and Rosenberg 1986). Innovations can come not just from formal R&D but also sources such as production engineers and the shop floor (Freeman 1995a; Kline and Rosenberg 1986).

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.

### 16.4.1 Frameworks for analysing technological innovation processes

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

The most common application of this framework is that of *national innovation systems (NIS),* which highlights the importance of national and regional relationships for determining the technological and industrial capabilities and development of a country (Nelson 1993; Lundvall 1992; Freeman 1995a). Nelson (Nelson 1993) and Freeman (Freeman 1995a) highlight the role of institutions that determine the innovative performance of national firms as way to understand differences across countries, while Lundvall (Lundvall 1992) focuses on the “elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge”, i.e., notions of interactive learning, in which user-producer relationships are particularly important (Lundvall 1988). In a similar vein, Jensen, et al. (2007) have identified two broad modes of innovation: a “science, technology and innovation (STI) mode” that relies on the production and use of codified scientific and technical knowledge, with formal R&D playing a central role; and a “doing, using and interacting (DUI) mode” that draws on informal processes of learning and experience-based know-how, where learning-by-doing, learning-by-interacting, and learning-by-using play key roles.

Building on this, other applications of the “innovation systems” framework include:

*Technology Innovation systems (TIS),* with technology or set of technologies (more narrowly or broadly defined in different cases) as the unit of analysis and focus on explaining what accelerates or hinders their development and diffusion. Carlsson and Stankiewicz (1991) define a technological system as “a dynamic network of agents interacting in a specific economic/ industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology.” More recent work explains how some of the sectoral, geographical and political dimensions intersect with technology innovation systems (Bergek et al. 2015; Quitzow 2015).

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

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

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

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

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

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

| **Functions** | **Description** |
|---|---|
| Entrepreneurial activities and experimentation | Entrepreneurial activities and experimentation for translating new knowledge and/or market opportunities into real-world application |
| Knowledge development | Knowledge development includes both "learning-by-searching" and "learning-by-doing" |
| Knowledge diffusion | Knowledge diffusion through networks, both among members of a community (e.g., scientific researchers) and across communities (e.g., universities, business, policy, and users). |
| Guidance of search | Guidance of search directs the investments in innovation in consonance with signals from the market, firms or government |
| Market formation | Market formation through customers or government policy is necessary to allow new technologies to compete with incumbent technologies |
| Resource mobilisation | Resource mobilisation pertains to the basic inputs – human and financial capital – to the innovation process |
| Creation of legitimacy/counteract resistance to change | Creation of legitimacy or counteracting resistance to change, through activities that allow a new technology to become accepted by users, often despite opposition by incumbent interests |
| Development of external economies | Development of external economies, or the degree to which other interests benefit from the new technology |

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

An important, complementary systemic framework is multilevel perspective (MLP) (Geels 2002), which focuses mainly on the diffusion of technologies in relation to incumbent technologies in the sector and the overall economy. 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 are selected and supported at the micro-level by niche markets, often through a directed process that has been termed "strategic niche management" (Kemp et al. 1998). As at the macro landscape level pressures on incumbent regimes mount, the niche technologies get a chance to get established in a new socio-technical regime allows these technologies to grow and stabilise, shaping a changed or sometimes radically renewed socio-technical regime. Over time, such new regimes could also lead to the reconfiguration of the socio-technical landscape at the macro level. This perspective takes a systematic and comprehensive view about how to nurture and shape technological transitions by understanding them as evolutionary, multi-directional and cumulative socio-technical process playing out at multiple levels over time with a concomitant expansion in the scale and scope of the transition (Elzen et al. 2004; Geels 2005).

There have been a number of studies that draw on the MLP (e.g. van Bree et al. 2010; Geels et al. 2017; Geels 2012) to understand different aspects of climate technology innovation and diffusion.

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

### 16.4.2 Identifying systemic failures to innovation in climate-related technologies

Traditional perspectives on innovation policy were mostly science-driven, and focused on strengthening invention and its translation into application in a narrow sense, and a second main traditional perspective on innovation policy was focused on correcting for 'market failures' (covered in Section 16.3) (Weber and Truffer 2017). The more recent understanding of, and shift of focus to, the systemic nature on the innovation and diffusion of technologies has implications for innovation policy since innovation outcomes depend not just on inputs such as R&D but much more on the functioning of the overall innovation system (see Section 16.5). Policies can therefore be directed at innovation systems components and processes that need the greatest attention or support. This may include, for example, strengthening the capabilities of weak actors and improving interactions between actors (Jacobsson et al. 2017; Weber and Truffer 2017). At the same time, a systemic perspective also brings into sharp relief the notion of 'system failures' (Weber and Truffer 2017).

Systemic failures include infrastructural failures; hard (e.g., laws, regulation) and soft (e.g., culture, social norms) institutional failures; interaction failures (strong and weak network failures); capability failures relating to firms and other actors; lock-in; and directional, reflexivity, and coordination failures (Klein Woolthuis et al. 2005; Chaminade and Esquist 2010; Weber and Rohracher 2012; Wieczorek and Hekkert 2012; Negro et al. 2012). By far most of the literature is on energy-related innovation policy. For example, Negro et al. (2012) in a meta-study 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 16.4.1. A summary of that work is in Table 16.6.

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

| Systemic problems | Empirical sub-categories | No. of cases |
|---|---|---|
| Hard institutions | ‘Stop and go policy’: lack of continuity and long-term regulations; inconsistent policy and existing laws and regulations<br>‘Attention shift’: policy makers only support technologies if they contribute to the solving of a current problem<br>‘Misalignment’ between policies on sector level such as agriculture, waste, and on governmental levels, i.e. EU, national, regional level, etc.<br>“Valley of Death”: lack of subsidies, feed-in tariffs, tax exemption, laws, emission regulations, venture capital to move technology from experimental phase towards commercialisation phase | 51 |
| Market structures | Large-scale criteria<br>Incremental/near-to-market innovation<br>Incumbent’s dominance | 30 |
| Soft institutions | Lack of legitimacy<br>Different actors opposing change | 28 |
| Capabilities/capacities | Lack of technological knowledge of policy makers and engineers<br>Lack of ability of entrepreneurs to pack together, to formulate clear message, to lobby to the government<br>Lack of users to formulate demand<br>Lack of skilled staff | 19 |
| Knowledge infrastructure | - Wrong focus or not specific courses at universities knowledge institutes<br>- Gap/Misalignment between knowledge produce at universities and what needed in practice | 16 |
| Too weak interactions | - Individualistic entrepreneurs<br>- No networks, no platforms<br>- Lack of knowledge diffusion between actors<br>- Lack of attention for learning-by-doing | 13 |
| Too strong interactions | - Strong dependence on government action or dominant partners (incumbents)<br>- Networks allows no access to new entrants | 8 |
| Physical infrastructure | - No access to existing electricity or gas grid for RETs<br>- No decentralised, small-scale grid<br>- No refill infrastructure for biofuels, ABG, H2, biogas | 2 |

Depending on the sector, specific technology characteristics, and national and regional context, the relevance of these systemic problems varies (Trianni et al. 2013; Bauer et al. 2017; Wesseling and Van der Vooren 2017), suggesting that innovation policy has to be a tailor-made mix to respond to the diversity of systemic failures (Rogge et al. 2017). The systemic and dynamic nature, spanning many decades and countries, of technological innovation is illustrated by a case study of solar PV in Box 16.2.

## BOX 16.2: Sources of cost reductions in solar photovoltaics

**No single country persisted in developing solar PV. Five countries each made a distinct contribution. Each leader relinquished its lead. The free flow of ideas, people, machines, finance,**

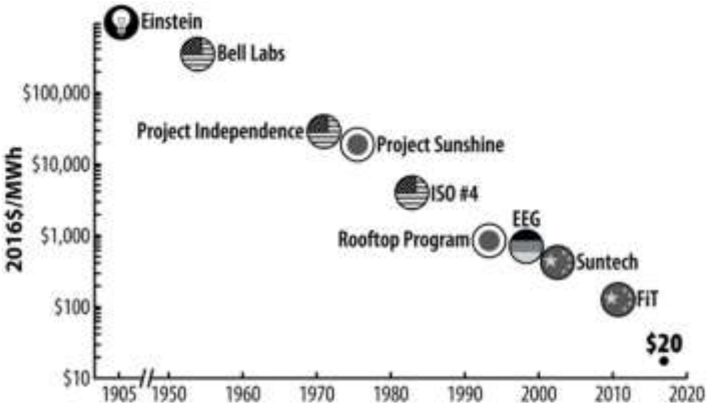
**and products across countries explains the success of solar photovoltaics (PV). Barriers to knowledge flow delay innovation.**

Solar PV has attracted interest for decades, and until recently was seen as an intriguing novelty, serving a niche, but widely dismissed as a serious answer to climate change and other social problems associated with energy use. Since AR5, PV has become a substantial global industry—a truly disruptive technology that has generated trade disputes among superpowers, threatened the solvency of large energy companies, and prompted reconsideration of electric utility regulation rooted in the 1930s. More favourably, its continually falling costs and rapid adoption are improving air quality and facilitating climate change mitigation. PV is now so inexpensive that it is not important only in those initiating countries. In 2020, 41 countries, in 6 continents, had installed at least 1GW of solar each (IRENA 2020).

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

The costs of solar PV modules have fallen by more than a factor of 10,000 since they were first commercialised in 1957. This four orders of magnitude cost reduction from the first commercial application in 1958 until 2018 can be summarised as the result of distinct contributions by the US, Japan, Germany, Australia, and China—in that sequence (Green 2019; Nemet 2019b). As shown in Box 16.2 Figure 1, PV improved as the result of:

1) Scientific contributions in the 1800s and early 1900s, in Europe and the US, that provided a fundamental understanding of the ways that light interacts with molecular structures, leading to the development of the p-n junction to separate electrons and holes (Einstein 1905; Perlin 1999);
2) A breakthrough at a corporate laboratory in the US in 1954 that made a commercially available PV device available and led to the first substantial orders, by the US Navy in 1957 (Gertner 2013; Ohl 1946);
3) A government R&D and public procurement effort in the 1970s in the US, that entrained skilled scientists and engineers into the effort and stimulated the first commercial production lines (Laird 2001; Christensen 1985; Blieden 1999);
4) Japanese electronic conglomerates serving niche markets in the 1980s and in 1994 launching the world's first major rooftop subsidy program, with a declining rebate schedule and demonstrating there was substantial consumer demand for PV (Kimura and Suzuki 2006);
5) Germany passing a feed-in tariff in 2000 that quadrupled the market for PV catalysing development of PV-specific production equipment that automated and scaled PV manufacturing (RESA 2001; Lauber and Jacobsson 2016);
6) Chinese entrepreneurs, almost all trained in Australia, building supply chains and factories of gigawatt scale in the 2000s. China became the world's installer of PV from 2013 onward (Helveston and Nahm 2019; Quitzow 2015).
7) A cohort of adopters with high willingness to pay, accessing information from neighbours, and installer firms that learned from their installation experience, as well as that of their competitors to lower soft costs (Gillingham et al. 2016a; Ardani and Margolis 2015).



**Box 16.2, Figure 1. Milestones in the development of low-cost solar photovoltaics** (Nemet 2019b)

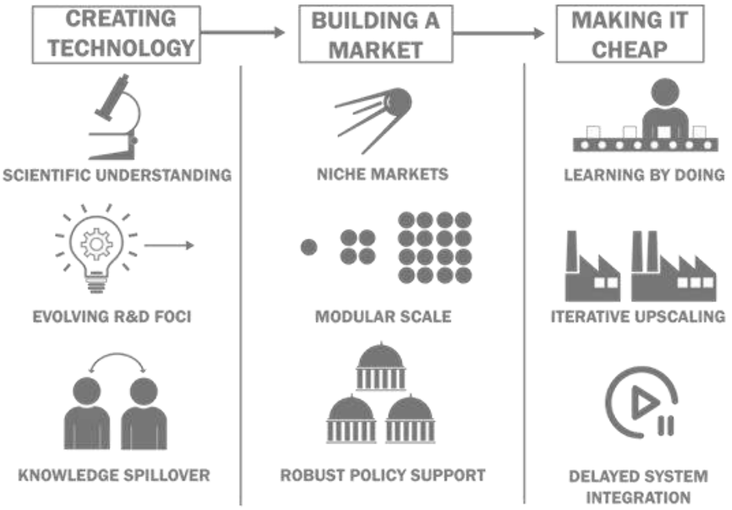
As this evolution makes clear, no individual country persisted in leading the technology and every world leading firm lost its lead within a few years (Green 2019). More generally, solar followed an overlapping but sequential process of technology creation, market creation, and cost reductions (Box 16.2, Figure 2).

**Creating a technology**. Key processes involved: scientific understanding, e.g., Einstein's work on activation energy; public support for and shifting focus of R&D investment; and flows of knowledge from one person to another, between firms, and between countries. US and Japanese R&D funding in the 1970s and early 1980s was central.

**Building a market**. PVs modular scale allowed it to serve a variety of niche markets from satellites in the 1950s to toys in the 1980s. Germany transformed the industry from niche to mass market with its subsidy program that began in 2000 but became important for PV in 2004. The dramatic increase in size combined with its 20-year guaranteed contracts reduced risk for investors and created confidence in PVs long term growth leading to investments in installations developing equipment and scaling up manufacturing. Crucial to forming these expectations was that supportive policies emerged outside Germany: in Spain, Italy, California, and China. This made the demand pull effect robust to elections and changes in national priorities, so that global demand consistently grew even as national policy support was more volatile.

**Making it cheap**. Awareness that the market for PV was growing rapidly and expectations that it would continue to do so catalysed a variety of investment that lowered costs. This included: 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 that could spread fixed costs through economies of scale and economically justify automation; as well as incremental improvements in the PV devices themselves, such as passivated emitter rear contact cells and bifacial modules, which reduced electricity costs by increasing PV efficiency.

Central to PV development has been its modularity, which provided two distinct advantages: access to niche markets, and iterative improvement. Solar has been deployed as a commercial technology across 9 orders of magnitude: from a 1W cell in a calculator to a 1GW plant in the Egyptian desert, and almost every scale in between. This modular scale enabled PV to serve a sequence of policy-independent niche markets (such as satellites and telecom applications), which generally increased in size and decreased in willingness to pay, in line with the technology's progress in cost reductions. This modular scale also enabled a massive number of iterations, such that in 2020 over three billion solar panels have been produced. Compare this to the approximately 1000 nuclear reactors ever constructed. This provides PV with a million times more opportunities for learning-by-doing: to make incremental improvements, to introduce new manufacturing equipment, to optimise that equipment, and to learn from failures. We see these same benefits of iterations in the progress in lithium-ion batteries today, as well their corresponding ability serve high-value niches such as phones and laptops before competing with gasoline engines in electronic vehicles as well as in electric grid applications. More generally, recent work has point to the benefits of modularity in the speed of adoption (Wilson et al. 2020) and learning rates (Sweerts et al. 2020).



**Box 16.2, Figure 2. Factor influencing the development of solar photovoltaics**

Solar PV is exciting not just because of its massive solar resource and low prices (Chapter 6), but how far solar has come. The payoff from understanding the reasons for solar's success includes learning how to support other low-carbon technologies with analogous properties. While many technologies do not fit into the solar model, some including small nuclear reactors and direct air capture, have characteristics that make them suitable for following solar's path. They can benefit from solar's drivers.

This sequence and the factors behind them can provide a model for similar technologies to follow. But PV took solar 60 years to become cheap. That is far too slow for nascent technologies to be useful for climate change. A key challenge in applying the solar model is to how to use public policy speed up innovation, perhaps by a factor of 4.

### 16.4.3 Low-emission innovation activity in the private sector

*[This is a placeholder text that will be further enhanced based on comments.]*

Overall, evidence shows that some of the industrial sectors that are important for meeting climate goals (electricity, agriculture and forestry, mining, oil and gas, and other energy intensive industrial sectors) (European Commission 2015; National Science Board 2018; American Energy Innovation Council 2017; Jasmab and Pollitt 2005; Sanyal and Cohen 2009; Jamasb and Pollitt 2008; Gaddy et al. 2017) are investing relatively small fractions of sales on R&D (*medium evidence, high agreement*).

The venture capital financing model, which has been used to overcome the "valley of death" in the biotech and IT space (Frank et al. 1996), has not been as suitable for hardware start-ups in the energy space: for example, the percentage of exit outcomes in clean-tech start-ups was almost half of that in medical start-ups and less than a third of software investments (Gaddy et al. 2017). Complementary research documents the 'valley of death' in hardware energy technologies indicating that the current VC model and other private finance does not sufficiently cover the need to demonstrate technologies at scale (Anadón 2012; Mazzucato 2013; Nemet et al. 2018). Similarly, data on venture capital and private equity finance for renewable energy technologies, which typically aims at relatively innovative technologies (generally before large scale deployment) (UN Environment et al. 2020) shown in Figure 16.1, indicates that this greater difficulty in growing in the market compared to other sectors may have contributed to a reduction in private equity and venture capital finance for renewable energy technologies after the boom of the late 2000s.

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

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

**Figure 16.1 Evolution of global venture capital and private equity investment in renewable energy by stage 2004-2019 in billions of US$. Source: (UN Environment et al. 2020)**

### 16.4.4 Emerging policy perspectives on systemic transformations

Because of the multiple market, government, system, and other failures that are associated with the energy system, a range of policy interventions are usually required to enable the development and introduction of new technologies in the market (Twomey 2012; Jaffe et al. 2005; Bürer and Wüstenhagen 2009; Veugelers 2012; Negro et al. 2012; Weber and Rohracher 2012) and used in what is termed as policy mixes (Rogge and Reichardt 2016). Empirical research shows that when in the energy and environment space new technologies were developed and introduced in the market, it was usually at least partly as a result of a range of policies that shaped the socio-technical system (Nemet 2019a; Bunn et al. 2014; Bergek et al. 2015; Rogge and Reichardt 2016) (*robust evidence, high agreement*).

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

Learning from the innovation systems literature, some of the recent policy focus is not only directed on innovation policies that can optimise the innovation system to improve economic competitiveness and growth but also policies that can induce strategic directionality and guide processes of transformative changes towards desired societal objectives (Mitcham 2003; Steneck 2006). Therefore, the aim is to connect innovation policy with societal challenges and transformative changes through engagement with a variety of actors and ideas and incorporating equity, nowadays often referred to as a just transition (Newell and Mulvaney 2013; Swilling et al. 2016; Heffron and McCauley 2018). This new policy paradigm is opening up a new discursive space and shape policy outcomes, and is also giving rise to the emerging paradigm of transformative innovative policy (Diercks et al. 2019; Fagerberg 2018).

Transformative innovative policy has a broader coverage of the innovation process with a much wider participation of actors, activities and modes of innovation. It is often expressed as social-technical transitions (Edquist 2019; Elzen et al. 2004) or societal transformations (Scoones 2015; Roberts et al. 2018). The transformation innovation policy encompasses different ideas and concepts that aim to address the societal challenges involving a variety of discussions including social innovation (Mulgan 2012), complex adaptive systems (Lance H. Gunderson 2002), eco-innovation (Kemp 2011) and framework for responsible innovation (Stilgoe et al. 2013), value-sensitive design (Friedman and Hendry 2019) and social-technical integration (Fisher et al. 2006). An example of transformative innovation policy that makes use of the public and private sector dynamics is the Standards and Labelling policies in India, explained in Box 16.3.

**BOX: 16.3: Standards and Labelling (S&L) for energy efficient refrigerators and air conditioners in India[1]**

Energy efficiency is often characterised as a "low-hanging fruit" for reducing energy use and hence mitigating carbon emissions. Indeed, efforts for climate change mitigation through energy efficiency measures can often result in cost savings (Sorrell 2015; Duan et al. 2017), even though there are concerns about the rebound effect (Gillingham et al. 2016b) and crowding out investments and political space for low-carbon energy sources (Patt et al. 2019). However, barriers such as lack of access to capital, hidden costs of implementation, and imperfect information can often result in low investments into adoption and innovation in energy efficiency measures (Sorrell et al. 2004). To address such barriers, India's Bureau of Energy Efficiency (BEE) introduced the Standards and Labelling (S&L) program for promotion of innovation in energy efficient appliances in 2006 (Sundaramoorthy and Walia 2017).

*Program design and addressal of early systemic barriers*

To design the S&L program, BEE drew on the international experiences and technical expertise of the Collaborative Labelling and Appliance Standards Program (CLASP) – a non-profit organisation that provides technical and policy support to governments in implementing S&L programs. For example,

---

FOOTNOTE [1] 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. under review) since there was no data on the efficiency of appliances in the Indian market, CLASP assisted with early data collection efforts, based on which refrigerators and air conditioners (ACs) became an important focus of the program (McNeil et al. 2008).

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

To ensure the buy-in of the manufacturers, BEE employed three strategies to set the standards at an ambitious yet acceptable level. First, BEE enlisted IIT Delhi (a public technical university) to engage with manufacturers and to demonstrate cost-effective designs of energy efficient appliances. Second, BEE agreed to make the standards voluntary from 2006 to 2010. In return, the manufacturers agreed to mandatory and progressively more stringent standards starting in 2010. Third, BEE established a multi-stakeholder committee with representation from BEE, the Bureau of Indian Standards, appliance manufacturers, test laboratories, independent experts, and consumer groups (Jairaj et al. 2016) to ensure that adequately stringent standards are negotiated after 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 IIT Delhi and IIT Bombay. In the meantime, the Australian standards for testing frost-free refrigerators were adopted until local standards were developed. Thus, once the testing laboratories, protocols and benchmark prices for testing were in place, the appliance manufacturers could employ their services.

Finally, a customer outreach program was conducted from 2006 to 2008 to inform customers regarding energy efficient appliances, to enable them to interpret the labels correctly, and to understand their purchase decisions and information sources (Joshi et al. 2019; Jain et al. 2018). Retailers were learnt to be an important information source for costumers. Thus, BEE initiated a capacity building program for retailers. 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, resulting in one of the most stringent refrigerator efficiency standards globally.

AC testing protocols also had to be adapted because of the emergence of inverter-based ACs. Existing testing done only at a single temperature did not value inverter-based ACs’ better average performance as compared to fixed-speed ACs over a range of temperatures. Thus, the Indian Seasonal Energy Efficiency Ratio (ISEER) was developed for Indian temperature conditions in 2015 by studying ISO standards and through consultations with manufacturers (Mukherjee et al. 2020). It was defined as the weighted average of the energy efficiency ratio at each temperature from 24 to 43°C, weighed by the number of hours at each temperature in an average meteorological year.

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

*Scaling up policies for market transformation*

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

Besides issuing labels, the enforcement of standards also needed to be scaled up efficiently. Thus, 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. Thus, besides ensuring that all the actors and resources necessary for the innovation system to function were present, and that the standards were well-designed, ensuring effective administration and enforcement of standards was just as important.

### 16.4.5 Systemic indicators for technological innovation

Assessing the state of technological innovation takes on significant importance in terms of, both, understanding how current efforts and policies are doing in relation to stated objectives and how we might design policies in order to do better.

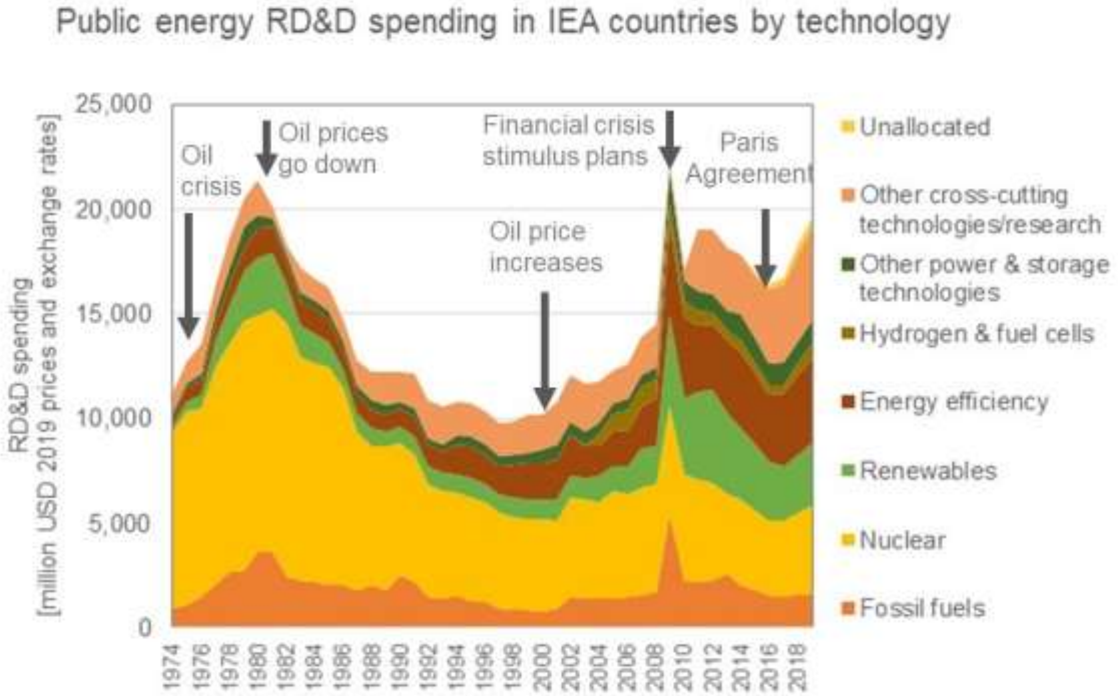
Traditionally, input measures such as RD&D investments and output measures such as scientific publication and patents were used to characterise innovation activities (Freeman and Soete 2009), partly because of the successes of specialised R&D efforts (Freeman 1995a), the predominant linear model of innovation, and because such measures can (relatively) easily obtained and compared. However these indicators are far from complete, and they often only provide a partial view into innovation activities. For instance, using energy-related patents as indicator of innovative activities is complicated by several issues (Haščič and Migotto 2015;Jaffe and de Rassenfosse 2017; De Rassenfosse et al. 2013), including the fact that the scope of what are to be considered climate mitigation inventions is not always clear or straightforward.

The European Patent Office (EPO) developed a special patent classification scheme for patents related to adaptation and mitigation technologies, known as Y02 class, which however include also improvements in the energy efficiency of fossil-based technologies (Veefkind et al. 2012; Angelucci et al. 2018). For this reason, researchers often rely on other methods, including keyword search and manual inspection, to select patents because the Y02 classes (for instance Persoon et al. (2020), Nemet (2012b) and Surana et al. (2020a)). Alone, quantitative indicators such as RD&D investments and patent counts are insufficient to assessment of innovation systems (David and Foray 1995), and potentially misleading (Freeman and Soete 2009). Despite this, in the realm of energy-related innovation, RD&D investments remains the single-most used indicator measure inputs and patent counts a widely used indicator of outputs. In Box 16.4 the development of energy RD&D in OECD countries is illustrated.

**BOX 16.4: National public spending in energy RD&D**

While many factors contribute to energy technology innovation (Section 16.4.1), public investment in energy RD&D is a crucial driver (Anadón et al. 2017; Kammen and Nemet 2007; Chan and Diaz Anadon 2016). Box 16.4, Figure 1 shows the time profile of energy-related RD&D budgets in OECD countries. Such data on other countries, in particular developing countries, are not available, although recent evidence suggests that such expenditures are increasing in several countries, particularly in China (IEA 2020b). The figure illustrates two key points. First, in the last 20 years energy-related RD&D has risen slowly, 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 R&D

spending was on low-emission technologies – energy efficiency, CCUS, renewables, nuclear, hydrogen, energy storage and cross-cutting issues such as smart grids. Box 16.4, Figure 1 also shows how events have coincided with developments of energy RD&D spending.



**Box 16.4, Figure 1 Fraction of public energy RD&D spending by technology over time for IEA (largely OECD) countries between 1974 and 2018. Sources: IEA RD&D Database, 2019 (IEA 2019). (extracted on November 11, 2020**).

The figures only include the public energy RD&D budgets for 30 individual countries plus the European Union. The countries are Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Luxembourg, Mexico (starting with 2013 data), the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. Data for other regions (notably, South America, Africa, South and East Asia and other regions) is not available because there is no source of uniform data. Although IEA has collected some data from China and India in the context of Mission Innovation, this was only available starting in 2014 and is thus not included in the trend.

Qualitative indicators measuring the more intangible aspects of the innovation process and system, are crucial to fully understanding the innovation dynamics in a climate or energy technologies or sectors (Gallagher et al. 2006), including in relation to adopting an adaptive strategies and supporting learning demonstration projects (Chan et al. 2017).

Since innovation is a systemic process, it is important to assess of 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). More relevant and comprehensive approaches of assessing innovation have been called for, but are yet to be developed (Freeman and Soete 2009). Importantly, 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). This is illustrated by the development of agrifood systems in Latin America, see Box 16.5.

**BOX 16.5: Agrifood systems, Agroecology and Climate Change: Technology and innovation solutions based in Nature**

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

The trend shows that, considering world land demands, the largest amounts of land will continue to contribute from South America, e.g. The Amazon forest (Lambin and Meyfroidt 2011; TEEB 2018) or Chaco forest (Grau et al. 2015). In developing countries, land use change for satisfying international demand is promoting a strong process of deforestation. In Brazil, the amount of GHG emitted only by the beef cattle sector represents 65% of the emissions of the agricultural sector and 15% of the overall emissions of the country. Emissions from agriculture and livestock have grown 163% since 1970 (May 2019).

The development and effective diffusion of new agricultural practices and technologies will shape how mitigate and adapt to climate change (Vermeulen et al. 2012). However, agricultural and food systems are complex and diverse; this includes traditional food systems, mixed food systems and modern food systems (Pengue et al. 2018).

An emerging feature of global food systems is the existence of multiple forms of visible and invisible flows of natural resources (Pascual et al. 2017; IPBES 2019; TEEB 2018). Although the underlying problem of the economic invisibility of environmental damages is similar to the problem of economic invisibility of loss of biodiversity or climate change, the solutions differ significantly (TEEB 2018).

Technological practices, management and changes in the food chain could help to reduce emissions and absorb carbon in the soils, thus contributing to carbon dioxide removal. Different technologies can be implemented, from high technologies such as transgenic crops resistant to drought (e.g., wheat resistance) (González et al. 2019), salt or pesticides resistance (OECD 2011a; Kim and Kwak 2020), smart and 4.0 agriculture (Klerkx et al. 2019) to low cost technologies such as agroecological models adapted locally (Francis et al. 2003; FAO 2018b).

For developing countries, agroecological approach could tackle both climate change challenges and food security. In SIDS countries, supports the resilience of livelihoods through a special agro-ecological approach (FAO 2019) can promote climate change adaptation and the sustainable management of natural resources, help build resilience, preserve biodiversity and improve response to climate change impacts and natural disasters to develop more efficient local food value chains (FAO 2019).

Agricultural intensification provides ways on how to use land, as well as water or energy requirements, to ensure adequate food supply while also addressing concerns about climate change and biodiversity (Cassman and Grassini 2020). The term ecological intensification, promoted by Tittonell (2014), focuses on biological and ecological processes and functions in agroecosystems. In line with the development of the concept of agroecology, the goal of agroecological intensification has a focus on the integration of social and cultural perspectives (Wezel et al. 2015). Agroecological intensification (Mockshell and Villarino 2019) for sub-Saharan Africa confronts the challenge of employment and food security (Pretty et al. 2011; Altieri et al. 2015). Agroecology is a dynamic concept that has gained prominence in scientific, agricultural and political discourse in recent years (Wezel et al. 2020; Anderson et al. 2021).

Agroecological practices seem to be well adapted to different social, economic and ecological environments (Altieri and Nicholls 2017). They are less intensive in physical and financial capital, and integrates better to the social and cultural capital of rural territories and local resources (knowledge, natural resources, etc.), without leading to technological dependencies (Côte et al. 2019).

Agroforestry provides many examples of positive agroecological feedbacks, such as ‘the regreening of the Sahel’ in Niger. The practice is based on the assisted natural regeneration of trees in cultivated fields, an old method which was slowly dying out but which innovative public policies (the transfer from the state to farmers of property rights over trees) helped revive (Sendzimir et al. 2011). Afforestation is another alternative to sequester carbon but also to bend the trend of rapid biodiversity loss (Carton 2020).

Rice paddy fields have been recognised as a major source of atmospheric GHG emissions, mainly in the form of methane. Climate change impact and its adaptation strategies can positively or negatively affect rice production and net income of rice farmers. Biochar use in rice systems has been advocated as a potential strategy to reduce GHG emissions from soils, enhance soil carbon (C) stocks and nitrogen (N) retention, and improve soil function and crop productivity (Mohammadi et al. 2020).

Contributions of indigenous people (Díaz et al. 2019), heritage agriculture (Koohafkan and Altieri 2010) and peasants agroecological knowledge (Holt-Giménez 2002) offer a wide array of management of land, soils, biodiversity and enhance food security without depending on modern agricultural technologies (Denevan 1995). In farming agriculture and food systems, innovation and technology based in nature could help to reduce climate change impacts (Griscom et al. 2017).

Traditional technologies or low-tech green solutions in the form of eco-remediations are also useful to prevent soil degradation and ensure wastewater treatment (Davidovic and Bujehi 2020). Studies show the benefits of integrating tradition with green technologies in order to design new approaches to farming tailored to local circumstances (Nicholls and Altieri 2018).

In Table 16.7, a number of 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-outcome-outcome classification and its variations (Hu et al. 2018; Freeman and Soete 1997; Sagar and Holdren 2002), combined with the functions of innovation systems approach (Miremadi et al. 2018), while also being cognizant of the specific role of key actors and institutions (Gallagher et al. 2012). Note that a specific assessment of innovation may focus on only some part of such a list of indicators, depending on what aspect of innovation is being studied, whether the analysis takes a more or less systemic perspective, and the specific technology and geography considered. Similarly, innovation policies may be designed to specifically boost only some of these aspects, depending whether a given country/region is committed to strengthen a given technology or phase.

An important knowledge gap is that many of these indicators are not easily or globally available and/or comparable. There has been significant work developing a set of quantitative metrics that, collectively, can help get a picture of innovation in a particular energy technology or set of energy technologies. Data availability is larger for OECD and developed countries (OECD 2005), and scarcer for BRIICS and developing countries. Furthermore, the understanding of how to systematically use a set of qualitative indicators to characterise the more intangible aspects of the energy innovation system is still poor.

## 16.5 Innovation policies and institutions

Building on the frameworks for identifying market failures (Section 16.3) and systemic failures (Section 16.4) in the innovation system for climate-related technologies, Section 16.5 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 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 instruments and institutions which are implemented at the national level. Whenever relevant, this section highlights examples of policies or initiatives that delve more deeply into the main high-level sectors: power, transport, industry, buildings, and AFOLU. Whenever possible, this section also discusses issues in policy selection, design, and implementation that have been identified as more relevant in developing countries and emerging economies.

Overall, this section shows that national and subnational policies and institutions are one of the main factors determining the redirection and acceleration of technological innovation and low-emission technological change (Åhman et al. 2017; Rogge and Reichardt 2016; Anadon et al. 2016b; Anadón et al. 2017; Roberts et al. 2018) *(robust evidence, high agreement).* Both technology push (e.g., scientific training, R&D) and demand pull (e.g., economic and fiscal support and regulatory policy instruments), as well as instruments promoting knowledge flows and especially technology transfer, can be part of the mix *(robust evidence, medium agreement)* (see also Sections 16.3 and 16.4).

Public R&D investments in energy and climate-related technologies have a positive impact on innovation outcomes (*medium evidence, high agreement*). The evidence on procurement is generally positive but limited. The record of the economic policy instruments with a more indirect focus on innovation when it comes to the competitiveness outcome (at least in the short term) is more mixed. Results show that indirect 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*). For several of them, carbon taxes or feed-in tariffs for example, the evidence of a positive impact on innovation is more consistent than the others. Evidence suggests that complementary policies or improved policy design can mitigate such negative distributional impacts.

### 16.5.1 Overview of policy instruments for climate technology innovation

Government policies can influence changes in technologies, as well as changes to the systems they support (Somanathan et al. 2014) (see Chapter 13 and Sections 16.3 and 16.4).

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 indirectly through demand-pull instruments which support market creation or expansion and thus promoting learning by doing, economies of scale, and automation (Section 16.3). Demand-pull policy instruments include regulation, carbon prices, subsidies that reduce the cost of adoption, public procurement, and intellectual property regulation. Typically, technology push is especially important for early-stage technologies, characterised by higher uncertainty and lower appropriability (see Section16.3); demand-pull become more relevant in the later stages (Section 16.3) (Mowery and Rosenberg 1979; Anadon and Holdren 2009; Nemet 2009b)

Table 16.7 summarises the set of policies shaping broader climate outcomes over the past few decades in many countries outlined in Chapter 13 Section 13.6, which groups them into economic and financial, regulatory, and soft instruments. Other policies, such as monetary, banking and trade policies, for instance, can also shape innovation but most government action to shape energy has not focussed on them. As Table 1 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. Not all policy instruments discussed in Chapter 13 are treated here. Section 16.5 specifically gives insights on the impact of the subset of policy instruments on competitiveness (a subcomponent of the economic effectiveness evaluation criterion) and on distributional effectiveness. Many of the policy instrument types listed in Table 16.7 may be considered to address different types of market or systemic failures or bottlenecks described in Section 16.4 (OECD 2011b).

**Table 16.7 Overview of policy instrument types covered in Chapter 13 and their correspondence to the subset of policy instrument types reviewed in Chapter 16**

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

Section 16.4 has clarified that technological innovation is a systemic and dynamic process. Figure 16.2 below connects the innovation process stages presented in Section 16.3 with mechanisms in the

technological innovation system and with some of the decarbonisation policy instruments assessed in Section 16.5.4.

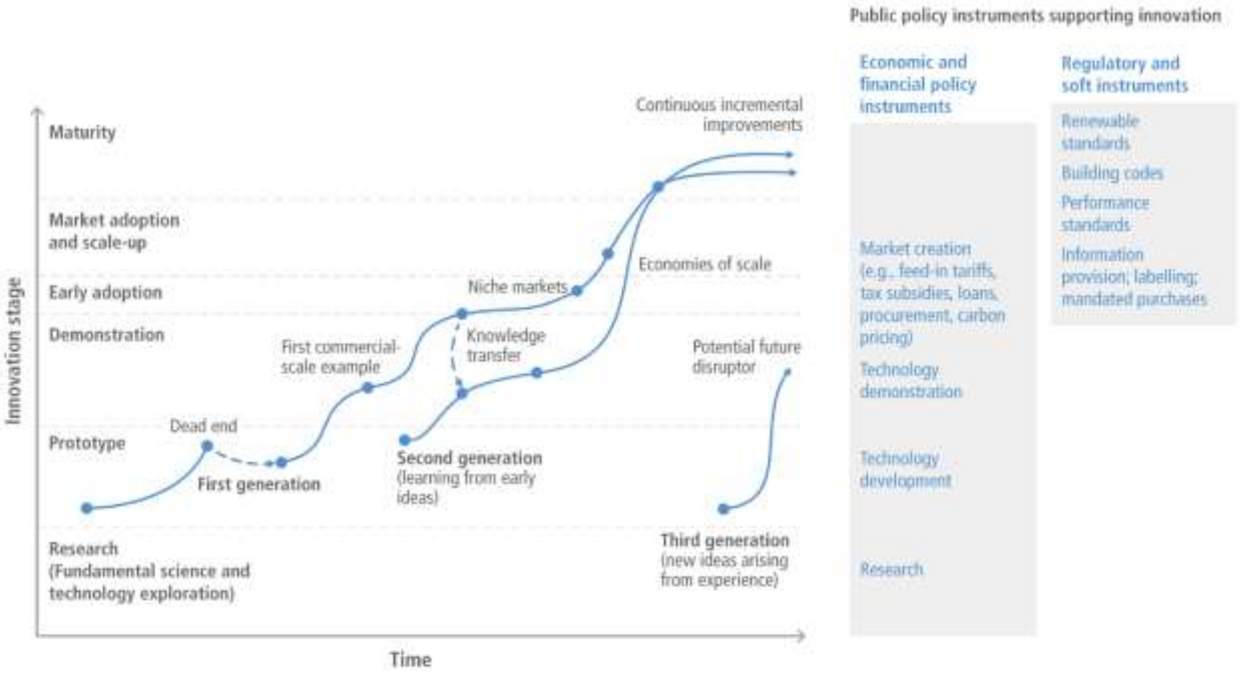


**Figure 16.2 Technology innovation process and the (illustrative) roles of different public policy instruments (on the right-hand side). Adapted from** (IEA 2020a)**.**

### 16.5.2 Drivers of national policies for climate change mitigation and adaptation

Governments around the world implement innovation policies in the energy and climate space with the aim of simultaneously advancing environmental, industrial policy (or competitiveness), and security goals (Surana and Anadon 2015; Meckling et al. 2017; Matsuo and Schmidt 2019; Penasco et al. 2020; Anadón 2012) (*medium evidence, medium agreement*). Co-benefits of policies shaping technological innovation in climate-related technologies, including competitiveness, health, and improved distributional impacts can be drivers of climate mitigation policy in the innovation sphere (Deng et al. 2017; Stokes and Warshaw 2017; Probst et al. 2020a). This was the case for climate and air pollution policies with local content requirements for different types of renewable energy projects in places including China (Lewis 2014; Qiu and Anadon 2012), India (Behuria 2020), South Africa (Kuntze and Moerenhout 2012), and Canada (Vanier 2014) (*robust evidence, medium agreement*).

The emergence of industries and support groups can lead to more sustained support for innovation policies (Schmid et al. 2020; Stokes and Breetz 2018; Meckling 2019; Meckling and Nahm 2019; Meckling et al. 2015; Schmidt and Sewerin 2017). Conversely, policies shaping technology innovation contribute to the creation and evolution of different stakeholder groups *(robust evidence, high agreement*). Most of the literature focuses on renewable energy technologies. The extent to which some of the existing research in renewable energy is relevant for building efficiency or technologies to reduce emissions from agriculture is an area that has not been explored.

As novel technologies are becoming 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 16.4 above, and Geels (2002)). In the first phase of 'niche market diffusion', the politics of more sustained support for a technology or set of technologies become possible after a group of economic winners and 'clean energy constituencies' are created (Meckling et al. 2015). When technologies grow out of the niche (second phase), they pose a more serious competition to incumbents who may become more vocal opponents of additional support for innovation in the competing technologies (Stokes 2016; Geels 2014). In a third phase, path-dependence in policymaking and lock-in in institutions need to change to accommodate new infrastructure, the integration of technologies, the emergence of complementary technologies and of new regulatory regimes (Aklin and Urpelainen 2013; Levin et al. 2012).

### 16.5.3 Innovation, competitiveness and distributional outcomes

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; Penasco et al. 2020). Given this and the current policy focus on green recovery and green industrial policy, although we primarily focus on innovation outcomes, we assess also impacts on competitiveness and the equity. Table 16.8 lists the selected set of indicators used to assess the impact of the policy instrument types covered in right hand side column in Table 16.7. The table does not include technology diffusion or deployment because these are covered in the technological effectiveness evaluation criterion in Chapter 13.

**Table 16.8 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), Penasco et al (2020) and Grubb et al (2021); the indicators under the competitiveness and distributional effects criteria are sourced from Penasco et al (2020).

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

### 16.5.4 Assessment of innovation and other impacts of innovation policy instruments

While it is very difficult to attribute a causal relationship between a particular policy instrument implementation and different innovation indicators, given the complexity of the innovation system (see Section 16.4) there is a large quantitative and qualitative literature aiming to identify such impact.

#### 16.5.4.1 Assessment of the impact on innovation of policy instruments with a direct focus on fostering innovation: public RD&D investments, and public procurement

Economic and direct investment policy instrument types are typically associated with a direct focus on technological innovation: R&D grants, R&D tax credits, prizes, national laboratories, technology incubators (including support for business development, plans), novel direct funding instruments (e.g., ARPA-E), and innovation procurement.

Public RD&D investments have been found to have a positive impact on innovation in energy and climate related technologies (*robust evidence, high agreement*), but the assessment relies almost entirely on evidence from industrialised countries. Out of 17 publications focussing on this assessment, only three found no relationship between R&D funding and innovation metrics (Penasco et al. 2020;Goldstein et al. 2020; Doblinger et al. 2019). Sixteen out of them *used ex post* quantitative methods and one relied on theoretical *ex ante* assessment; only two of them included some non-industrialised countries, with one being the theoretical analysis. Thus, 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.

Overall, public procurement has high potential to incentivise innovation in climate technologies, but the evidence is mixed, particularly in developing countries (*limited evidence, medium agreement*). Public procurement accounted for 13 % of gross domestic products in OECD in 2013 and much more in some emerging and developing economies (Baron 2016). Its main objective is to determine and purchase products or services for the betterment of public services, infrastructures and facilities. 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. The literature on assessing the innovation impact of public procurement programs is very limited, and suggests either a positive impact or no impact (Penasco et al 2020; Alvarez and Rubio 2015; Fernández-Sastre and Montalvo-Quizhpi 2019; Baron 2016). The majority of cases where the impact is positive are analyses of industrialised countries, while no impact emerges in the case of a developing country (Ecuador). More empirical research is needed to understand the impact of public procurement, which has the potential to support the achievement of other societal challenges (Edler and Georghiou 2007; Henderson and Newell 2011; ICLEI 2018; Baron 2016) in both developing and developed countries.

**BOX 16.6: Green Public Procurement in The Netherlands**

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

The Green Public Procurement (GPP) policy is targeted at minimising the negative impacts of production and consumption on the nature environment (Melissen and Reinders 2012; Cerutti et al. 2016). It includes a wide range of environmental criteria for different product groups that public organisations frequently procure such as office equipment, uniforms, road works and catering. There are 6 product clusters and 45 product groups that are under the government’s purchasing in terms of sustainability. The six product clusters are: i) Automation & telecommunications, ii) Energy, iii)

Ground, road & hydraulic engineering, iv) Office facilities and services, v) Office buildings, and vi) Transport (Grandia and Voncken 2019).

The GPP 2020 Tender Implementation Plan spells out the terms and conditions for making their green public procurement. Some of these are confidential documents and are not shared online. Others are available for download. The tender implementation plan for the Netherlands is available on https://gpp2020.eu/low-carbon-tenders/open-tenders/. One of the important scenarios is that the public procurers need the details of LCA analysis carried out in a tool called DuboCalc which calculates the environmental impacts of the materials and methods of an infrastructural projects. GPP 2020 has reported that three million tonnes of $CO_2$ would be saved in the Netherlands alone if all Dutch public authorities applied the national Sustainable Public Procurement Criteria.

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

#### *16.5.4.2 Assessment of the impact on competitiveness of policy instruments with a direct focus on fostering innovation: public RD&D investments, and public procurement*

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

There is limited and mixed evidence regarding the (positive or negative) impact of public procurement for low-carbon or climate technologies and it emerges from developed countries (*limited evidence, low agreement*). All of the four evaluations identified in the Penasco et al (2020) 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*). Penasco et al (2020) 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).

#### *16.5.4.3 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*). Most of these assessments use a limited number of indicators (e.g., patents and publications and follow-on private financing, firm growth and survival, respectively), focusses on the energy sector and on the US and other industrialised countries. Extrapolating to emerging economies and low-income countries is difficult. There is no evidence on the impact of different ways of allocating public energy R&D investments in the context of developing countries.

Block funding, which tends to be more flexible, can lead to research that is more productive or novel, but this can be mediated by various factors (*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. In the case of the US Department of Energy, block funding can be quickly deployed for high-risk projects and this can, on the margin, help improve research productivity measured by patents (Anadon et al. 2016a). Research on Japan, but not specific to energy or climate technologies, indicates that R&D funds allocated competitively result in more novel research or researchers of a 'high status' competitive, while block funding was associated with research of higher novelty lower status researchers (Wang et al. 2018).

**BOX 16.7: ARPA-E a novel R&D funding allocation mechanism focussed on an energy mission**

Another approach for allocating public R&D funds in energy involves relying on active program managers and having clear technology development missions that focus on high-risk high-reward areas and projects. This approach can be exemplified by a relatively new energy R&D funding agency in the US, the Advanced Research Projects Agency for Energy (ARPA-E). This agency as created in 2009 and it was modelled on the experience of DARPA (a US government agency funding high risk high reward research in defence-related areas (Bonvillian and Van Atta 2011; Bonvillian 2018; U.S. National Academies of Sciences Engineering and Medicine 2017). DARPA program managers had a lot of discretion for making decisions about funding projects, but since energy is usually more politically vulnerable, the ARPA-E novel involved program managers requesting external review as an informational input (Azoulay et al. 2019). ARPA-E program managers did not just follow the advice of peer reviewers and in many cases they reported using information from review comments (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 results in a portfolio of projects with a higher level of uncertainty, as defined by disagreement among reviewers. Moreover, under the premise that uncertainty is a corollary to novelty, individual discretion is an antidote to novelty bias in peer review. While innovation is notoriously hard to track and, particularly for emerging technologies, it can take a lot time to assess, early analysis has shown that this mission-orientation and more 'actively managed' R&D funding program may yield greater innovation outcomes patenting outcomes than other US energy R&D funding programs and a greater or similar rate of academic publications when compared to other public funding agencies in energy in the US, ranging from the Office of Science, the more applied Office of Energy Efficiency and Renewable Energy or the small grants office (Goldstein and Narayanamurti 2018; U.S. National Academies of Sciences Engineering and Medicine 2017). In addition research analysing the first cohort of cleantech start-ups has found that start-ups supported by ARPA-E had more innovative outcomes when compared to those that had applied but nor received funding, with others that had not received any government support, and with others that had received other types of government R&D support (Goldstein et al. 2020). Overall, the mission-oriented ARPA approach has shown early promise in the United States when it comes to innovation outcomes, but the extent to which it can be applied elsewhere remains unknown. (*limited evidence, medium 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 (Pless 2019; Howell 2017). US cleantech start-ups which partner with government partners for joint technology development or licensing partnerships accrue more patents and follow on financing (Doblinger et al. 2019).

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

Without carefully designed public funding for demonstration efforts, often in a cost shared manner with industry, the experimentation at larger scales needed for more novel technologies needed for climate change mitigation may not take place. (*medium evidence, high agreement*). Government funding specifically for technology demonstration projects, for RD&D (research, development and demonstration) in energy technologies plays a crucial supporting role (Section 16.3.1). Governments can facilitate knowledge spill-overs between firms, between countries, and between technologies (see Section 16.3, Cohen et al. (2002) and Baudry and Bonnet (2019)).

#### *16.5.4.4 Assessment of the impact on innovation and on competitiveness and distributional outcomes of policy instruments with a more indirect direct focus on fostering innovation*

Demand pull policies such as such as tradeable green certificates, taxes, or auctions, are essential to support efforts and pace of scale up (Remer and Mattos 2003; Nahm and Steinfeld 2014; Wilson 2012). Just like for R&D investments, research has indicated that effective demand pull depends are credible, durable, and aligned with other policies (Nemet et al. 2017). Historical analyses of the relative importance of demand pull and technology push are clear; both are needed to provide robust incentives for investment in innovation. Interactions between them are central as their combination enables innovators to connect a technical opportunity with a market opportunity (Grubler and Wilson 2014; Freeman 1995b; Jacobsson et al. 2004).

**Emission Trading Schemes**

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

Penasco et al (2020) review 20 evaluations: eight identified a positive impact (although in at least two cases the paper indicated the impact was small or negligible), 11 no impact and one was associated with a negative impact on innovation indicators. The studies that found no impact and the studies that found some impact covered all three methods covered (quantitative *ex post*, qualitative and theoretical and *ex ante* analysis). Another review focussed only on empirical studies (mainly quantitative but also qualitative), covered a slightly longer period and identified 19 studies (15 using quantitative methods) (Lilliestam et al. 2020). With a narrower set of indicators of innovation, they concluded there was very little empirical evidence linking the emissions trading schemes studied to date and innovation (Lilliestam et al. 2020). There are a total of 27 individual studies, some of them providing mixed evidence of impact, and 23 of them suggest there was no impact or (in a couple of cases) it was very small.

**Carbon and environmental taxes**

The impact of carbon taxes on innovation outcomes is more positive than that for ETS schemes but the evidence is more limited (*limited evidence, medium agreement*). Assessments of their impact on innovation metrics have been very limited, with only four studies (three quantitative and one *ex ante*).

Three of the studies found a positive impact of carbon taxes on innovation outcomes and one found no impact (Penasco et al. 2020).

Depending on the design, carbon taxes can either have positive, negative or null impact on competitiveness and distributional outcomes (*medium evidence, medium agreement*). The evidence on the impact of carbon taxes on competitiveness is significant (a total of 27 evaluations) and mixed, with six of them reporting some positive impacts, ten reporting no impact, and 11 reporting negative impacts (so 59% were not associated with negative impacts). Most of the evaluations reporting negative impacts were theoretical assessments, and only three *ex post* quantitative analysis (Penasco et al. 2020). 24 evaluations covered distributional impacts of carbon taxes and other environmental taxes and the majority (15) found the existence of some distributional impacts, six found positive impacts and three no distributional impacts. Differences in the result of the assessments stems from the design of the taxes (Penasco et al. 2020).

**Feed-in-Tariffs**

Feed-in tariffs in renewable energy have been found to be generally associated with positive innovation outcomes *(medium evidence, medium agreement*) and in at least some negative competitiveness impacts *(low evidence, medium agreement*) and distributional impacts *(medium evidence, high agreement*).

Out of the 14 studies identified in a recent review, ten of them found a positive impact of FITs on innovation and four no impact, with eight of the studies being quantitative (Penasco et al. 2020). Out of ten assessments of the impact of FITs on competitiveness, five were associated with some positive outcomes, three assessments identified no impacts, and two identified some negative impacts on at least some players. This means that 20% of the evaluations identified some negative impacts. The results on distributional impacts for feed in tariffs are more negative, with 8% (one of 13) finding no impact and 91% finding at least some negative distributional impacts.

Many factors affect the impacts of feed in tariffs on outcomes other than innovation (*robust evidence, high agreement*). While FITs have been generally associated with positive innovation outcomes, they may favour existing PV (e.g., polysilicon) among alternative PVs including more novel solar power technologies such as thin-film PV, amorphous PV, perovskites (Sivaram 2019), which may hinder innovation of competing alternatives in infancy (Meckling et al. 2017). Contradictory evidence on the impact of the same may arise from differences in the evaluation method (Penasco et al. 2020) 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. 2016), and the geographical and temporal context of where the policy was put in place (Section 16.4). The design of feed-in-tariffs should thus account for the specificities of the country, the technology and the policy could result in negative distributional and (to a lesser extent) competitiveness impacts.

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 16.4) Prioritising low cost renewable energy generation in the design of FIT schemes can result in a lower focus of innovation efforts on more novel technologies (Hoppmann et al. 2013). Similarly, focusing on low cost renewable energy generation only can result in a greater reliance on existing foreign value chains and capital, and thus in lower or negative impacts on domestic competitiveness—in other words, some approaches can hinder the development of the local capabilities that could result in greater long-term benefits domestically (Hoppmann et al. 2013; Matsuo and Schmidt 2019). Evidence for developing countries indicates that local and absorptive capacity also play an important role in particular on the ability of policies to contribute to competitiveness or industrial policy goals (e.g., Binz and Anadon 2018). Research comparing China's and India's policies and outcomes on wind also suggest that policy durability and systemic approaches can affect industrial outcomes (Surana and Anadon 2015).

**Renewable auctions**

The evidence of the impact of renewable energy auctions on innovation outcomes is very small and provides mixed results *(limited evidence, low agreement*). Out of six evaluations, three of 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 (Penasco et al. 2020) . 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 innovation, and broader work on auctions covering OECD countries as well as Brazil, South Africa and China not finding a significant impact on innovation (Wigand et al. 2016), and work comparing renewable energy auctions in different countries in South America finding generally a positive impact on innovation outcomes (Mastropietro et al. 2014). The body of evidence on the impact of auctions on competitiveness is also limited (six evaluations) and indicates negative outcomes of renewable auctions of competitiveness (*limited evidence, low agreement*). Only two studies investigated distributional outcomes and both were negative, with one study being theoretical and the other qualitative.

**Other financial instruments**

There is no explicit literature on the ability of green public banks, and targeted loans, and loan guarantees to lead to upstream innovation investments and activities, although there is evidence on their role in deployment (see e.g. (Geddes et al. 2018)). This notwithstanding the key role of these institutions in the innovation system (Sections 16.3.1 and 16.4) (OECD 2015b; Geddes et al. 2018) and the belief that they can de-risk scale-up and the testing of business models (Probst et al. 2020b; Geddes et al. 2018) (see Chapter 17).

**Renewable obligations with tradeable green certificates**

There is mixed evidence of the impact of tradeable green certificates (TGCs) on innovation (*limited evidence, low agreement),* competitiveness (*limited evidence, low agreement)*. Out of the seven evaluations in Penasco et al (2020), six found no impact, two a positive impact, and three a negative impact. All of them used a qualitative research approach. Of the six studies focusing on competitiveness outcomes, three conclude TGCs have had no impact on competitiveness, while two indicate negative impact and one a positive impact. Only one of the studies was quantitative and did not identify an impact on competitiveness.

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

**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 (Penasco et al. 2020). Impact on competitiveness is found to be negligible or positive (*limited evidence, medium agreement*). Out of eight evaluations, five report positive impact and three negligible impact; only two are quantitative studies (Penasco et al. 2020). 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.

**Efficiency obligations with tradeable credits**

The impact of tradeable white certificates in innovation is largely positive, but the evidence is limited (*limited evidence, medium/high agreement*). Out of four evaluations, only one of which was quantitative, three report positive impact and one no impact (Penasco et al. 2020). The impact of white certificates on competitiveness is positive (*limited evidence, high agreement*) while that on distributional outcomes is very mixed (*limited evidence, low agreement*). Two theoretical studies report positive competitiveness impacts. Out of 11 evaluations of distributional outcomes, eight rely on theoretical *ex ante* approaches. Seven evaluations reported positive impacts (four of them using theoretical methods), three of them (using theoretical methods) indicated negative impacts and one of them no impact.

**Building codes**

There is evidence of the impact of building codes on innovation outcomes (Penasco et al. 2020). Only two studies assessed competitiveness impacts (one identifying positive impacts and one negligible ones) and three studies identifying distributional impacts, all positive.

Overall, the evidence of the impact on competitiveness of the policy instruments covered in Section 16.5.4.4 with a more indirect focus on innovation 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). Penasco et al (2020) 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.

#### *16.5.4.5 Assessment of the impact on innovation and on competitiveness and distributional outcomes of regulatory policy instruments targeting efficiency improvements*

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

**Relationship between automotive efficiency regulations and innovation**

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

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

**Relationship between appliance efficiency standards and innovation**

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

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

**Distributional and competitiveness impacts associated with vehicles and appliance performance standards**

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

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

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

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

##### *16.5.4.6 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 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, n.d.). Although there are many studies on energy efficiency more broadly and for both standards and labels, only eight studies specifically focus on labels. Furthermore, seven of them report positive outcomes and one negative outcomes. Six of the studies used qualitative methods mentioning the impacts of labelling on the development of new products (Wiel et al. 2006). Research specifically comparing voluntary labels with other mechanisms found a significant and positive relationship between labels and the number of energy-efficient inventions (Girod et al. 2017). More research is needed especially in developing countries that have extensive labelling programs in place, and also with quantitative methods, to develop evidence on the impacts of labelling on innovation.

**BOX 16.8: China Energy Labelling Policies, combined with sale bans and financial subsidies**

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

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

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

Before 2008, the market share of grade 1 and grade 2 air conditioners was about 5%, and about 70% of all air conditioners were grade 5 (the most inefficient). Driven by the financial subsidies, the selling price of the highly efficient air conditioners became competitive with that of the general air conditioners. Hence, the sales of energy efficient air conditioners increased substantially, making the market share of air conditioners at grade 1 and 2 to be about 80% in 2010 (Wang et al. 2017b).

According to the information from energy efficiency labelling management centre of China National Institute of Standardisation, under the energy label system implemented 5 years ago, more than 1.5 hundred billion kWh power was saved by March 2010, equivalent to more than 60 million tons of standard coal, 1.4 billion tons of carbon dioxide emissions, and 60 tons of sulphur dioxide emissions (Zhan et al. 2011), which significantly contributed to energy saving goals of the 11th Five-Year Plan.

**Voluntary approaches and innovation**

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

**Competitiveness and distributional outcomes of soft instruments**

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

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

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

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

#### *16.5.4.7 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 16.3 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 16.8 above. For example, it indicates the extent to which there has been a greater focus of evaluations of the impact of R&D investments, emissions trading schemes and voluntary approaches on innovation. It also shows a limited amount of evidence on procurement, efficiency obligations with tradeable green certificates (TGCs), or building codes.

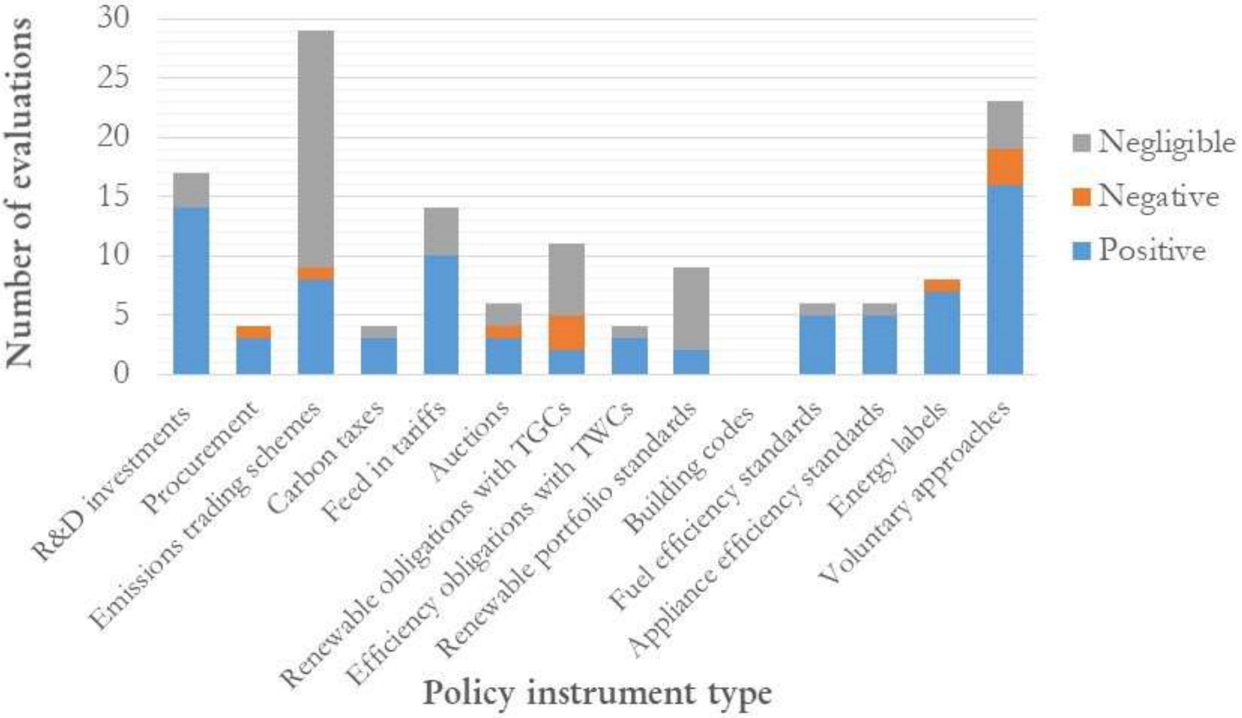


**Figure 16.3 Number of evaluations available for each policy instrument type covered and direction of the assessment**

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 16.8. The colour indicates whether each evaluation identified a positive impact on the innovation outcome (blue), the existence of a negative impact (in blue), and no impact (in grey). It builds on Penasco et al (2020), Grubb et al (2021),. Lilliestam et al (2020) and additional studies identified as part of these review studies. TGC stands for tradeable green certificates. TWC stands for tradeable white certificates.

### 16.5.5 Trade instruments and their impact on innovation

There has been a long interest on the impact of Foreign Direct Investment (FDI) on domestic capacity on innovation and on environmental outcomes. This section does not cover the much larger body of evidence on the relationship between FDI and economic development and growth.

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

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

### 16.5.6 Intellectual property rights, legal framework and the impact on innovation

Virtually all countries around the world have instituted systems for the protection of creations and inventions, known as Intellectual Property (IP) rights systems (WIPO 2020). While several types of intellectual property exist – patents, copyright, design rights, trademarks, and more –, this section will focus on patents, as the most relevant property right for technological innovations (World Intellectual Property Organization 2008), and hence the most relevant for policy instruments in this context.

Patent systems aim to promote innovation and economic growth, by stimulating both the creation of new knowledge and diffusion of that knowledge (*high evidence, strong agreement*). National patent systems, as institutions, play a central role in theories on national innovation systems (*high evidence, strong agreement).* Patent systems are usually instituted to promote innovation and economic growth (Nelson and Mazzoleni 1996; Machlup and Penrose 1950; Encaoua et al. 2006). Some countries explicitly refer to this purpose in their law or legislation – for instance, the US Constitution states the purpose of the US IP rights system to "promote the progress of science and useful arts". Patent systems aim to reach their goals by trying to strike a balance between the creation of new knowledge and diffusion of that knowledge (Scotchmer and Green 1990; Devlin 2010; Anadon et al. 2016b), some of the stages of innovation outlined in section 16.3. They promote the creation of new knowledge (e.g. technological inventions) by providing a temporary, exclusive right to the holder of the patent, thus providing incentives to develop such new knowledge and helping parties to justify investments in research and development. They promote the diffusion of this new knowledge via the detailed disclosure of the invention in the patent publication, and by enabling a 'market for knowledge' via the trading of patents and the issuance of licenses (Arora et al. 2004). Although IP protections provide incentives to invest in innovation, they have the double effect of restricting the use of new knowledge by raising prices or blocking follow-on innovation (Stiglitz 2008; Wallerstein et al. 1993). National patent systems, as institutions, feature prominently in models and theories of National Innovation Systems (Edquist 1997; Klein Woolthuis et al. 2005).

The degree to which patent systems actually promote innovation is subject to debate. While patents seem to promote innovation in selected areas like pharmaceuticals, there is an increasing body of theoretical and empirical literature that suggests that the proliferation of patents also discourages innovation (*medium evidence, medium agreement)*. Theoretical contributions note that a too stringent appropriability regime may greatly limit the diffusion of advanced technological knowledge and eventually block the development of differentiated technological capabilities within an industry, in what is called an ‘appropriability trap’ (Edquist 1997; Klein Woolthuis et al. 2005). There has been a long-standing debate on the impact of patents and other IP rights on innovation and economic development (Hall and Helmers 2019; Machlup 1958). Jaffe and Lerner (2006) and Bessen and Meurer (2008) highlight how IP rights also hamper innovation in a variety of ways. Other more specific contributions in the literature focus on specific factors. For example, Shapiro (2001) discusses patent thickets, where overlapping sets of patent rights mean that those seeking to commercialise new technology, need to obtain licenses from multiple patentees. Heller and Eisenberg (1998) argue that a ‘tragedy of the anticommons’ is likely to emerge when too many parties obtain the right to exclude others from using fragmented and overlapping pieces of knowledge, with ultimately no one having the effective privilege of use using the example of biomedical research. Reitzig et al. (2007) describe the damaging effects of extreme business strategies employing patents, such as patent trolling.

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

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

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

For a discussion on the impact of IPR on international technology diffusion, see Section 16.6.

### 16.5.7 Sub-national innovation policies and industrial clusters

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

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

Sub-national policies also directly support innovation and competitiveness through green incubators and direct grants or R&D funding for local companies working on clean energy, intending to promote local economic development *(limited evidence, medium agreemen*t). The literature on the impacts of such policies on innovation and competitiveness is sparse. Some case studies and program evaluation reports, primarily in the United States, have identified the impacts of sub-national policies on competitiveness — for example, job creation from direct R&D funding in North Carolina (Hall and

Link 2015), perceptions for local industry development and support for follow-on financing for companies receiving state-funded grants in Colorado (Surana et al. 2020c), and return on investments for the state in research and innovation spending from the New York state's energy agency (Nyserda 2020). There is a general paucity of metrics on innovation and competitiveness for systematic assessments of such programs in developed countries, and even more so in India and other developing countries where such programs have been increasing (Surana et al. 2020b).

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

### 16.5.8 System-oriented policies and instruments

Although previous sections summarised the research disentangling the role of individual policies in advancing or hindering innovation (as well as impacts on other objectives), other research has tried to characterise the impact of a policy mix on a particular outcome. Although the outcome studied was not innovation, but diffusion (technology effectiveness is in the set of criteria outlined above), it seems relevant to discuss overall findings. Using renewable energy policies in nine OECD countries, research concludes that over time they have a significantly broad set of policies in renewable energy, a similar balance of policies (defined as dispersion of policy instruments across different instrument types). This research also identifies a significant negative association between the balance of policies in renewable energy and the diffusion of total renewable energy capacity but no significant effect of the overall intensity (coded as the 46 weighted average of six indicators) on renewable capacity (Schmidt and Sewerin 2019), indicating that a neural conception of balance across all possible policies may not be desirable and that policy mix intensity by itself does not explain technology diffusion.

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

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

## 16.6 International technology cooperation for transformative change

This section covers international cooperation in relation to climate-related technology, "the flows of know-how, experience and equipment for mitigating and adapting to climate change amongst different stakeholders" (IPCC 2000) as well as innovation to support transformative change compared to the AR5 (IPCC 2014) and the SR1.5 (IPCC 2018b). Technology transfer has essentially two strands of literature: one focussed on the transfer of technologies from firms' or universities' R&D departments to the market (e.g., (Pagani et al. 2016)), and the other, in the context of climate change, which is the focus of this section. This section complements the discussion on international cooperation on science and technology in Chapter 14.

This section first reviews the current state of global innovation processes, and objectives and functions of international cooperation on technology development and transfer. It then describes how this cooperation on technology happens, and assesses the activities reported in the literature on the policy assessment criteria also applied in Chapters 13 and 14. Finally, it discusses emerging ideas on international cooperation on technology, and any possible modifications to accommodate climate change and sustainable development goals.

### 16.6.1 Current state and recent developments in global innovation processes

The growing complexity of technologies and global competition have made the development of a technology into an international process, that involves the flow of knowledge across borders (Koengkan et al. 2020; Lehoux et al. 2014). For instance, in production of electronics, Asian economies have captured co-location synergies and dominate production and assembly of product components, whereas American firms have adopted "design-only" strategies (Tassey 2014). In the context of renewable energy technologies, "green global division of labour" has been observed, with countries specialising in investments in R&D, manufacturing or deployment of renewables (Lachapelle et al. 2017).

At the same time, not all countries benefit equally from the globalisation of innovation, as barriers remain related to finance, environmental performance, human capabilities and cost (Egli et al. 2018; Weiss and Bonvillian 2013). Yan et al (2017) indicate that between 1990 and 2012, the gap in low-carbon technology innovation between countries has possibly only been reducing amongst OECD countries, and recommend continued promotion of technology transfer to countries with low levels of technological development. Both in literature and in UNFCCC deliberations, South-South technology transfer is highlighted (Khosla et al. 2017), linked to the level of innovation capabilities in China (Urban 2018), although Wu (2016) argues that China agreed to commitments in part because it relies on developed countries for technology transfer.

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

### 16.6.2 Objectives and functions of international technology transfer and cooperation

Earlier assessments have made it clear that international technology transfer and cooperation could play a role in climate policy at both the international and the domestic policy level (IPCC 2018a; Stavins et al. 2014; Somanathan et al. 2014) and for low-carbon development at the regional level (Agrawala et al. 2014).

International efforts for technology transfer can have different motives, determinants and modes. Motives for technology transfer and cooperation in climate change include access to financial instruments as well as promotion of domestic industry on the part of the developed country (Huh and Kim 2018). Based on an econometric analysis international technology transfer factors and characteristics of CDM projects, Gandenberger et al (2016) find that complexity and novelty of technologies explain whether the CDM project includes hardware technology transfer, and that factors like project size and absorptive capacity of the host country do not seem to be drivers. Halleck Vega and Mandel (2018) argue that 'long-term economic relations', for instance being part of a customs union, affects technological diffusion between countries for the case of wind energy, and indicate that for this, low-income countries have been 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 for climate change mitigation and compliance. A handful of papers conducted game-theoretic analysis on technology cooperation, sometimes as an alternative for cooperation on emission reductions, and found partially positive effects (Rubio 2017; Narita and Wagner 2017; Bosetti et al. 2017; Verdolini and Bosetti 2017). However, Sarr and Swanson (2017) model that, due to the rebound effect, technology development and transfer of resource-saving technologies may not lead to envisioned emission reductions.

There are three main areas in the literature that could be objectives for technology transfer in relation to mitigation of climate change. First, technology cooperation could help enhancing climate technology deployment in developing countries, second, it could help building capabilities, and third, it could lead to enhanced RD&D through cooperation and knowledge spill-overs.

#### *16.6.2.1 Enhancing deployment in developing countries*

Literature suggests that low-carbon technology deployment in developing countries could be enhanced by (1) technology development and transfer collaboration and a 'need-driven' approach, (2) development of the specific types of capacity required across the entire innovation chain and (3) domestic strengthening of the coordination and agendas across and between governance level (Upadhyaya et al. 2020; Zhou 2019a; Khosla et al. 2017). However, there are also other views. Glachant and Dechezleprêtre (2017) indicate that low-carbon technology deployment in emerging economies deployment through technology transfer has been strong but that least-developed countries are lagging behind. They indicate that this due to their lack of participation in economic globalisation and that the role of the climate negotiations for technology transfer to those countries should be the creation of demand for low-carbon technologies through stronger emission targets.

Ramos-Mejía et al (2018) indicate that the governance of low-emission technology transfer and deployment in developing countries is frequently negatively affected by a mixture of well- and ill-functioning institutions, in a context of for instance market imperfection, clientelist and social exclusive communities and patrimonial and/or marketised states. Boyd (2012) indicates, based on a case study of biogas in South Africa, that both national and international engagement is needed to address the needs for technology transfer to developing countries as well as deployment. Surana et al (2020b) emphasise the need for entrepreneurial capabilities in "science, technology, and innovation-based start-ups to meet social goals". In general, there is robust evidence and medium agreement that enhancing deployment and diffusion of climate technologies in developing countries would require a variety of actors with sufficient capabilities (Ockwell et al. 2018; Kumar et al. 1999; Sagar et al. 2009), sometimes summarised as "national systems of innovation" (Ockwell and Byrne 2016), a terms also embraced by the UNFCCC Technology Executive Committee (Technology Executive Committee 2015).

#### *16.6.2.2 Capabilities for innovation, integrated planning and implementation*

Early work has indicated 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), and government involvement (including institutional capacity) (Kumar et al. 1999), and that knowledge and capacity are part of the 'intangible assets' or the 'software' of a firm or a country (Corsi et al. 2020; da Silva et al. 2019; Ockwell et al. 2015). For sustainable development, capacity to plan in an integrated way and implement the SDGs (Elder et al. 2016; Khalili et al. 2015), including using participatory approaches (Disterheft et al. 2015), are conditional means of implementation.

It is argued in various studies that human capital should be at the focus of international climate negotiations as well as national climate policy, as it could change the political economy in favour of climate mitigation and the transformation needs to happen so fast that developing such capabilities in advance would be required (Hsu 2017; Upadhyaya et al. 2020; Ockwell et al. 2015; IPCC 2018a). An econometric analysis lends quantitative credibility to the often-stated conclusion that a technology skill base is a key determinant of technological diffusion in wind energy globally (Halleck-Vega et al. 2018). Activities to enhance capabilities include informational contacts, research activities, consulting, education & training and activities related to technical facilities (Huh and Kim 2018).

There are multiple studies reporting examples that come to this conclusion. For South-South technology transfer between India and Kenya, not just technical characteristics, but also mutual learning on how to address common problems of electricity access and poverty, was suggested as an important condition for success (Ulsrud et al. 2018). Specifically for Africa, Olawuyi (2018) discusses the capability gap in Africa, despite decades of technology transfer efforts under various mechanisms and programmes of the UNFCCC. The study suggests that barriers need to be resolved by African countries themselves, in particular inadequate access to information about imported climate technologies, lack of domestic capacities to deploy and maintain imported technologies, the weak regulatory environment to stimulate clean technology entrepreneurship, the absence of inadequacy of climate change laws, and weak legal protection for imported technologies. Moreover, (Ziervogel et al., under review) indicate that for transformative adaptation, transdisciplinary approaches and capacity building shifting "the co-creation of contextual understandings" instead of top-down transferal of existing knowledge would deliver better results.

#### *16.6.2.3 Enhancing RD&D and knowledge spill-overs*

Various international initiatives aim to cooperate on technology in order to create knowledge spill-overs and develop capacity. For example, the UNFCCC Technology Mechanism, amongst other things, aims to facilitate finance for RD&D of climate technologies by helping with readiness activities for developing country actors. In particular preparing early-stage technologies for a smoother transition to deployment and commercialisation has been emphasised in the context of the Technology Executive Committee (Technology Executive Committee 2017). There are numerous programmes, multilateral, bilateral and private, that have facilitated RD&D, although they show a bias towards mitigation (as opposed to adaptation) activities, and many programmes that seemed to be about RD&D were in reality dialogues about research coordination (Ockwell et al. 2015). An update by the Technology Executive Committee reviewed good practices in international cooperation of technology (Technology Executive Committee 2021) confirmed the conclusions of Ockwell et al (2015), and moreover highlighted that the 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.

### 16.6.3 Assessment of international technology transfer and cooperation

In the sections below, the literature on various categories of international technology cooperation and transfer is discussed against the policy evaluation criteria identified in Section 13.6.2: environmental effectiveness, economic effectiveness, distributional effects, transformative potential, co-benefits/side-effects and institutional requirements.

#### *16.6.3.1 UNFCCC technology and capacity building institutions*

Technology development and transfer are a part of the UNFCCC since its agreement in 1992 and has undergone discussions and developments in the context of the international climate negotiations ever since (Stavins et al. 2014). The implementation of "Technology Needs Assessments" was the first mechanism used by the UNFCCC, and has underwent different cycles of learning (Nygaard and Hansen 2015; Hofman and van der Gaast 2019). Since 2009, the UNFCCC discussions on technology development and transfer have focussed on the technology mechanism under the Cancun Agreements of 2010, which can be seen as the global climate governance answer to redistributive claims by developing countries (McGee and Wenta 2014). The technology mechanism consists of a Technology Executive Committee (TEC) and a Climate Technology Centre and Network (CTCN). The latter organisation can been evaluated positively on environmental effectiveness, distributional effects, co-benefits and transformational potential, but has challenges in terms of institutional requirements, as evidenced by the modest funding (Oh 2020).

The ‘technology’ discussion has been further strengthened by the Paris Agreement, in which Article 10 is fully devoted to technology (UNFCCC 2015). The contribution of the UNFCCC Technology Mechanism and the subsequent Paris Agreement technology framework to climate change mitigation and adaptation have been assessed as predominantly focussed on hardware for adaptation (Olhoff 2015), and relatively limited in scope (de Coninck and Sagar 2017).

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

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

From the broader assessment above, despite limitations of available information, it is clear that the number of initiatives and activities on international cooperation and technology transfer and capacity building seem to have been enhanced since both the Cancun Agreements and the Paris Agreement. However, a gap remains, in the coverage of activities, the amount of committed funding, and the effectiveness. Specifically, the UNFCCC mechanisms for technology are insufficiently fulfilling the needs of low-emission technologies (Brook et al. 2016). An assessment of UNFCCC instruments specifically for technology transfer to developing countries indicates that knowledge development, market formation and legitimacy are functions that are currently poorly addressed in developing countries’ low-emission technological innovation systems (de Coninck and Puig 2015; Ockwell et al. 2015).

#### *16.6.3.2 International RD&D cooperation and capacity building initiatives*

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

For instance, "Mission Innovation" (MI) is a global initiative consisting of members of 23 countries and the European Commission working together to reinvigorate and accelerate global clean energy innovation with the objective to make clean energy widely affordable with improved reliability and secured supply of energy. The goal is to accelerate clean energy innovation in order to limit the rise in the global temperature to well below 2°C. These 24 members are committed to seek and increase public investments in clean energy R&D with the engagement of private sectors. MI also seeks to foster international collaboration amongst its members. A recent assessment shows that, although expenditures are rising, the aims are not met by 2020 (Myslikova and Gallagher 2020). Gross et al (2018) caution against too much focus on R&D efforts for energy technologies to address climate change, including Mission Innovation. They argue that given the timescales of commercialisation, developing new technologies now would mean they would be commercial too late for addressing climate change. Huh and Kim (2018) discuss two 'knowledge and technology transfer' projects that were eventually not pursued through beyond study due to cooperation and commitment problems between national and local governments and highlight the need for ownership and engagement of local residents and recipient governments.

An example of how innovative technologies combined with capacity development and institutional innovation is combined in the context of adaptation to extreme weather in SIDS can be found in Box 16.9.

**Box 16.9 Capacity building and innovation for early warning systems in Small Island Developing States**

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

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

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

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

#### *16.6.3.3 Patent regimes and trade*

The role of intellectual property rights in international technology transfer of climate mitigation technologies has been described as particularly controversial (Abdel-Latif 2015). While there is evidence of non-availability (Zhou 2019b; Zhuang 2017), there is also evidence from modelling or empirical studies that patents hinder the technology transfer of climate mitigation technologies (Dechezleprêtre et al. 2011; Ing and Nicolaï 2020; Li et al. 2020). The literature on this is robust, but has a low level of agreement.

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

Several studies argue that, particularly in developing nations, IP rights have resulted in delayed access, reduced competition and higher prices (Littleton 2008; Zhuang 2017). Such studies also state that many climate-change-related technologies are unavailable in developing countries at reasonable prices, meaning that these technologies cannot be employed in parts of the world where they may be needed most, and conclude that climate-change-related technology transfer is insufficiently stimulated under the current IP rights regime. Compulsory licensing (as already used in medicine) is one of the routes proposed to repair this (Littleton 2008; Abdel-Latif 2015).

In contrast, other studies find the opposite. All studies indicate that the relationships between IP rights, innovation, international technology transfer and local mitigation and adaptation are complex (Maskus 2010; Abdel-Latif 2015; Li et al. 2020). There is some anecdotal evidence that patent holders have refused to license important climate-related technologies in the past, but systematic evidence that patents and other IP rights restrict access to environmentally sound technologies is lacking and largely exists 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. Likewise, Li et al (2020) and Dechezleprêtre et al (2011) report that case studies suggest that IP rights do not eliminate competition in markets for environmental technologies, referring to earlier case studies in the field of solar PV, wind power, and biofuel technologies in emerging economies, and in the field of integrated gasification technology in India.

This strand of literature stresses the potential merits of effective patent protection as a means to promote technology transfer toward developing countries when foreign technology providers face the threat of imitation by local competitors, and that stronger patent protection encourages the use of FDI and licenses, which induces technology transfer that goes beyond the mere export of equipment or goods (Li et al. 2020; Maskus 2010). Also, patents may support market transactions in technology, including international technology transfer especially to "middle-income" countries and larger emerging economies (Maskus 2010; Hall and Helmers 2019). Concerning least-developed countries, the patent system as it exists today may not be the most appropriate vehicle for encouraging innovation international access, and capacity for technology R&D to diffusion may be more important (Sanni et al. 2016; Hall and Helmers 2010; Maskus 2010; Glachant and Dechezleprêtre 2017). Also Zhuang (2017) argues that the developed/developing country difference may not be relevant for IPR anymore, rather distinctions based on levels of technological and economic development would need to be made, where least-developed countries are one group and the other developing and developed countries constitute the other group (Abbott 2018).

In terms of ways forward to meet the challenge of climate change, different suggestions are made in the context of IPRs that can help to further improve international technology transfer of climate mitigation technologies, including through the TRIPS agreement, by making decisions on IPR to developing countries on a case-by-case basis, or by developing countries experimenting more with policies on IPR protection (Littleton 2009; Dussaux et al. 2018; Maskus and Reichman 2017).

### 16.6.4 Emerging ideas for international technology transfer and cooperation

The literature proposes several ideas to enable greater activity in line with the needs of the development of national systems of innovation (Technology Executive Committee 2017), which are reviewed here. All publications have in common an emphasis on participative social innovation, local grounding and policy learning as a replacement of the expert-led technological change (Kowarsch et al. 2016; Chaudhary et al. 2012; Disterheft et al. 2015), and a move to international cooperation based on equity rather than technology transfer which implies a hierarchy (Pandey et al., under review). A broad transformative agenda therefore proposes that contemporary societal challenges are wider in the scope and are often more difficult to be clearly defined and will require the actions of a broader and more diverse set of actors to both formulate and address the policy, implying social, institutional and behavioural changes next to technological innovations are the possible solutions (Geels 2004).

Several authors have proposed new mechanisms for international cooperation on technology. Ockwell and Byrne (2016) argue that a role for the UNFCCC could be to support climate relevant innovation-system builders in developing countries, institutions locally that develop capabilities that "form the bedrock of transformative, climate-compatible, technological change and development". 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, and that developing countries outline more clearly in their NDCs what capacity building needs they have.

Building on an earlier discussion of technology-oriented and sectoral agreements (Meckling and Chung 2009) and the potential for international cooperation in energy-intensive industry (Åhman et al. 2017), where deep emission reduction measures require transformative changes (see also Chapter 11), Oberthür et al. (2020) propose that the potential of global governance for energy-intensive industry is underexploited. They conclude that relatively low-cost, viable international sectoral cooperation in energy-intensive industry could comprise knowledge and learning, and the explicit inclusion of industry in the UNFCCC means of implementation, including the Green Climate Fund and the World Bank funds. They conclude that "goal-setting" and "signalling" are more challenging, especially in existing multilateral institutions. Organisation in sub-sector 'clubs' including governmental, private and societal actors could be effective (Oberthür et al. 2020).

Examples of emerging ideas for international cooperation on climate technology, as well as their relation to the objectives and existing efforts, and in relation to the level of development of the innovation system around a technology (Bergek et al. 2008; Hekkert et al. 2007) or in nations (Lundvall et al. 2009) are summarised in Figure 16.4.

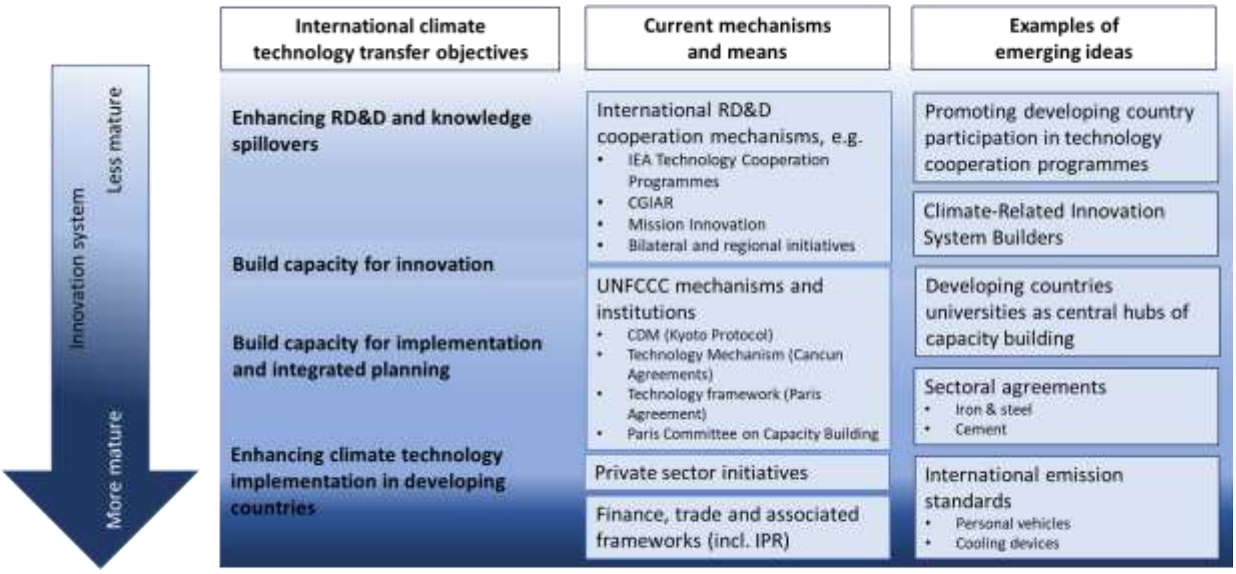


**Figure 16.4 Examples of emerging ideas (right column) in relation to level of maturity of the national or technological innovation system, objectives of international climate technology transfer efforts and current mechanisms and means. Sources: (Oberthür et al. 2020; Khan et al. 2020; Ockwell and Byrne 2016)**

## 16.7 Knowledge gaps

Filling the gaps in literature availability, data collection, modelling, application of frameworks and further analysis will improve knowledge in innovation and technology development and transfer to support policy making in climate change mitigation as well as adaptation.

The first and most glaring gap in knowledge 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. It goes both for studies about 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 SIDSs is limited. For instance, research on innovation, competitiveness or distributional outcomes in sub-Saharan Africa beyond South Africa, and South Asia beyond India is non-existent or scant. Expanding the knowledge base with studies with a focus on developing countries would not only allow for testing whether the theories (developed by predominantly by developed-country researchers for industrialised countries) hold in developing country contexts, but also yield policy insights that could help both domestic and international policymakers working on climate-related technology cooperation.

Besides the strong bias of literature to studies originating from and based in developed countries, innovation and technology literature is also skewed to mitigation, and within that to energy. This chapter is on mitigation, but in places, adaptation is also covered, but a literature base on innovation systems for adaptation is largely missing. Within mitigation, the energy sector is strongly overrepresented, and, within energy, supply-side, renewable energy (especially solar PV) is better documented and has a stronger literature base than, for instance, agriculture and food systems, the materials industry, or transport. In the latter sectors, more research applying innovation systems concepts could strengthen the fundament of innovation studies and yield more widely applicable policy insights, though context dependence will remain a dominant consideration.

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 and strength of institutions.

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

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

The understanding of the role of digitisation in decarbonisation pathways is lacking. Given the implications of the digital revolution for sustainability, a better characterisation of governance aspects would increase understanding of the implications and possibilities of digitalisation and other GPTs for policymakers. Relatedly, research (both theoretical and empirical) on the impacts of imitation, or adaptation of new green technological solutions invented in one region and used in other regions, could fill knowledge gaps, in order to accelerate the diffusion of climate-related technologies, while taking care not to reduce the incentive for inventors to invest in the search for new solutions.

Lastly, an independent assessment of whether the Paris Agreement is complied with in regard to the means of implementation of technology and capacity building is missing, in part because a methodology of monitoring, reporting and verification has not been developed, and data are also largely missing. For instance, it is difficult to assess the extent of the "technology gap" because the need for RD&D in energy, industry, agriculture and other key mitigation sectors is unclear, and the data of what is currently happening are not consistently updated.

# 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, business-as-usual innovation and even fast technological change will not be enough to achieve Paris agreement objectives.

Besides technological changes, policy and behavioural changes, changes in the financial system and in development of human capacity and resources will be needed for the systems transitions that are needed to achieve the Paris Agreement objectives.

Trends in some sectors, such as energy, show that technological innovation and the spread of new technologies can reduce greenhouse gas emissions and enable low-emission development. However, such 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.

The implication is that if the speed, spread and direction of technological change is to be accelerated, holistic approaches are needed. 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 technology needs of all actors, including private and societal ones. Such policies could also help prevent unintended and undesirable consequences of technological change. Such consequences could include unequal access to new technologies across countries and between income groups, environmental degradation and negative effects on employment.

In summary, innovation and technological change are necessary but insufficient conditions for achieving the Paris Agreement objectives. Only with the help of policy interventions and other factors can the appropriate implementation of new technology can be enabled.

### 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 innovation process includes basic research, applied research, demonstration, deployment, diffusion and eventually obsolescence. Whether a technology successfully passes each stage is based on different factors including financing needs, policy support and actors involved.

Recent years have shown the widespread diffusion of several new technologies needed to address climate change, such as solar energy, batteries for electric vehicles and energy-efficient lighting. For their adoption, policies by some governments have played an important role, and have led to almost global adoption, although this took multiple decades.

The increasing complexity of technologies and global competition means that technology development is a truly international process, and the necessary knowledge flow transcends borders. Research and development could generate new knowledge, skills, ideas and practices.

The speed of innovation processes could be greater if policies could be enhanced with involvement of a wider range of global industry, research and financial actors as well as consumers, in partnerships at the regional and international level. This would help strengthening another necessary enabling condition: of institutional and human capacities as well as domestic and international financing in developing countries.

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

To address climate change, new technologies are needed. Also, sustainable technologies that are currently known but not yet widely used, need to be spread around the world, and adapted to local preferences and conditions. To do that, it is not only research and development that is needed, although that is part of the story. It is also about education systems that teach new students how to use, improve and innovate on those new technologies. It is also about governmental institutions that might make policies to promote those new technologies. Businesses need to be able to use and sell new technologies, and banks need to be able to estimate the financial risks.

Different countries can learn from each other's experiences and insights. If every country would figure out everything by itself, the climate response would get much more expensive and slower. This is one reason why international cooperation is needed.

The other reason for international cooperation on technology is that poor countries are able to be active players in this global process. More even than developed countries, that have better education systems, modern infrastructure, and the financial resources to invest, developing countries need to build the capacities to be able to participate fully in the development, implementation and spread of new climate-friendly technologies.

The United Nations, including the 2015 Paris Agreement, therefore requires all parties to cooperate in the development, application and spread of climate-friendly technologies. Although technology transfer is mainly done by the private sector, through foreign direct investment and international trade, the UN also requires developed countries to help transfer technologies and knowledge to developing countries.

Many initiatives exist both regionally and internationally to help countries in achieving technology development and transfer, such as through partnerships and research collaboration, with a key role for universities. Enhancing current activities would help an effective, long-term global response to climate change, while promoting sustainable development.

# References

Abbott, F. M., 2018: Intellectual Property Rights and Climate Change: Interpreting the TRIPS Agreement for Environmentally Sound Technologies. By WEI ZHUANG. *J. Int. Econ. Law*, **21**, 233–236, https://doi.org/10.1093/jiel/jgy011.

Abdel-Latif, A., 2015: Intellectual property rights and the transfer of climate change technologies: issues, challenges, and way forward. *Clim. Policy*, **15**, 103–126, https://doi.org/10.1080/14693062.2014.951919.

Acemoglu, D., and P. Restrepo, 2019: Automation and New Tasks: How Technology Displaces and Reinstates Labor. *J. Econ. Perspect.*, **33**, 3–30, https://doi.org/10.1257/jep.33.2.3.

——, P. Aghion, L. Bursztyn, and D. Hemous, 2012: The Environment and Directed Technical Change. *Am. Econ. Rev.*, **102**, 131–166, https://doi.org/10.1257/aer.102.1.131.

——, U. Akcigit, D. Hanley, and W. R. Kerr, 2014: Transition to Clean Technology. *SSRN Electron. J.*, https://doi.org/10.2139/ssrn.2534407.

Adami, V. S., J. A. V. Antunes Júnior, and M. A. Sellitto, 2017: Regional industrial policy in the wind energy sector: The case of the State of Rio Grande do Sul, Brazil. *Energy Policy*, **111**, 18–27, https://doi.org/10.1016/j.enpol.2017.08.050.

Aghion, P., 2019: Path dependence, innovation and the economics of climate change. *Handbook on Green Growth*, Edward Elgar Publishing, 67–83.

——, A. Dechezleprêtre, D. Hemous, R. Martin, and J. M. Van Reenen, 2013: Carbon Taxes, Path Dependency and Directed Technical Change: Evidence from the Auto Industry. *SSRN Electron. J.*, **124**, 1–51, https://doi.org/10.2139/ssrn.2202047.

——, B. F. Jones, and S. Gsb, 2018: Artificial Intelligence and Economic Growth Charles I. Jones. *The Economics of Artificial Intelligence: An Agenda*.

Agrawala, S., and Coauthors, 2014: Regional Development and Cooperation. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, O. Edenhofer et al., Eds., Cambridge University Press, 1083–1140.

Åhman, M., L. J. Nilsson, and B. Johansson, 2017: Global climate policy and deep decarbonization of energy-intensive industries. *Clim. Policy*, **17**, 634–649, https://doi.org/10.1080/14693062.2016.1167009.

Aklin, M., and J. Urpelainen, 2013: Political competition, path dependence, and the strategy of sustainable energy transitions. *Am. J. Pol. Sci.*, **57**, 643–658.

Aleluia Reis, L., L. Drouet, and M. Tavoni, 2020: Economically Integrated Climate and Air Pollution Policies Save Lives. *under Revis. Lancet Planet. Heal.*,.

Alfer'ev, D., 2018: Artificial intelligence in agriculture. *Agric. Lifestock Technol.*, **7**, https://doi.org/10.15838/alt.2018.1.4.5.

Alkemade, F., and R. A. A. Suurs, 2012: Patterns of expectations for emerging sustainable technologies. *Technol. Forecast. Soc. Change*, **79**, 448–456, https://doi.org/10.1016/j.techfore.2011.08.014.

Altenburg, T., 2009: Building inclusive innovation systems in developing countries: Challenges for IS research. *Handbook of Innovation Systems and Developing Countries: Building Domestic Capabilities in a Global Setting*.

Altieri, M. A., and C. I. Nicholls, 2017: The adaptation and mitigation potential of traditional agriculture in a changing climate. *Clim. Change*, **140**, 33–45, https://doi.org/10.1007/s10584-013-0909-y.

——, ——, A. Henao, and M. A. Lana, 2015: Agroecology and the design of climate change-resilient farming systems. *Agron. Sustain. Dev.*, **35**, 869–890, https://doi.org/10.1007/s13593-015-0285-2.

Alvarez, S., and A. Rubio, 2015: Carbon footprint in Green Public Procurement: a case study in the services sector. *J. Clean. Prod.*, **93**, 159–166, https://doi.org/10.1016/j.jclepro.2015.01.048.

Ambec, S., M. A. Cohen, S. Elgie, and P. Lanoie, 2013: The Porter Hypothesis at 20: Can Environmental Regulation Enhance Innovation and Competitiveness? *Rev. Environ. Econ. Policy*, **7**, 2–22, https://doi.org/10.1093/reep/res016.

American Energy Innovation Council, 2017: *The power of innovation: inventing the Future*. 52 pp.

Anadon, L. D., and J. P. Holdren, 2009: Policy for Energy-Technology Innovation. *Acting in Time on Energy Policy*, K.S. Gallagher, Ed., Brookings Press.

——, M. Bunn, and V. Narayanamurti, 2014: *Transforming U.S. Energy Innovation*. Cambridge University Press,.

——, G. Chan, A. Y. Bin-Nun, and V. Narayanamurti, 2016a: The pressing energy innovation challenge of the US National Laboratories. *Nat. Energy*, **1**, 16117, https://doi.org/10.1038/nenergy.2016.117.

——, ——, A. G. Harley, K. Matus, S. Moon, S. L. Murthy, and W. C. Clark, 2016b: Making technological innovation work for sustainable development. *Proc. Natl. Acad. Sci.*, **113**, 9682–9690, https://doi.org/10.1073/pnas.1525004113.

Anadón, L. D., 2012: Missions-oriented RD&amp;D institutions in energy between 2000 and 2010: A comparative analysis of China, the United Kingdom, and the United States. *Res. Policy*, **41**, 1742–1756, https://doi.org/10.1016/j.respol.2012.02.015.

——, G. F. Nemet, A. Grübler, and C. Wilson, 2011: The U.S. Synthetic Fuels Corporation: Policy Consistency, Flexibility, and the Long-Term Consequences of Perceived Failures. *Energy Technology Innovation*, Cambridge University Press, 257–272.

——, E. Baker, and V. Bosetti, 2017: Integrating uncertainty into public energy research and development decisions. *Nat. Energy*, **2**, 17071, https://doi.org/10.1038/nenergy.2017.71.

Anderson, K., J. Bruil, J. Chappell, C. Kiss, and M. P. Pimbert, 2021: *Agroecology Now!. Transformations towards More Just and Sustainable Food Systems*.

André, F. J., and S. Smulders, 2014: Fueling growth when oil peaks: Directed technological change and the limits to efficiency. *Eur. Econ. Rev.*, **69**, 18–39, https://doi.org/10.1016/j.euroecorev.2013.10.007.

Angelucci, S., F. J. Hurtado-Albir, and A. Volpe, 2018: Supporting global initiatives on climate change: The EPO's "Y02-Y04S" tagging scheme. *World Pat. Inf.*, **54**, S85–S92, https://doi.org/10.1016/j.wpi.2017.04.006.

Arce, D., 2014: Experience, Learning and Returns to Scale. *South. Econ. J.*, **80**, 938–947.

Ardani, K., and R. Margolis, 2015: *Decreasing Soft Costs for Solar Photovoltaics by Improving the Interconnection Process: A Case Study of Pacific Gas and Electric*. National Renewable Energy Laboratory (NREL),.

Arocena, R., and J. Sutz, 2020: The need for new theoretical conceptualizations on National Systems of Innovation, based on the experience of Latin America. *Econ. Innov. New Technol.*, **29**, 814–829, https://doi.org/10.1080/10438599.2020.1719640.

——, B. Göransson, and J. Sutz, 2015: Knowledge policies and universities in developing countries: Inclusive development and the "developmental university." *Technol. Soc.*, **41**, 10–20, https://doi.org/10.1016/j.techsoc.2014.10.004.

Arora, A., A. Fosfuri, and A. Gambardella, 2004: *Markets for Technology: The Economics of Innovation and Corporate Strategy*. MIT Press,.

Arrow, K. J., 1962a: *Economic welfare and the allocation of resources for invention*. National Bureau of Economic Research, Ed. Princeton University Press, 609–626 pp.

——, 1962b: The Economic Implications of Learning by Doing. *Rev. Econ. Stud.*, **29**, 155, https://doi.org/10.2307/2295952.

Arthur, W., 2009: *The Nature of Technology*. First. Free Press, 246 pp.

Auerswald, P. E., and L. M. Branscomb, 2003: Valleys of Death and Darwinian Seas: Financing the Invention to Innovation Transition in the United States. *J. Technol. Transf.*, **28**, 227–239, https://doi.org/https://doi.org/10.1023/A:1024980525678.

Avelino, F., and Coauthors, 2019: Transformative social innovation and (dis)empowerment. *Technol. Forecast. Soc. Change*, **145**, 195–206, https://doi.org/10.1016/j.techfore.2017.05.002.

Avgerinou, M., P. Bertoldi, and L. Castellazzi, 2017: Trends in Data Centre Energy Consumption under the European Code of Conduct for Data Centre Energy Efficiency. *Energies*, **10**, 1470, https://doi.org/10.3390/en10101470.

Azoulay, P., E. Fuchs, A. P. Goldstein, and M. Kearney, 2019: Funding Breakthrough Research: Promises and Challenges of the “ARPA Model.” *Innov. Policy Econ.*, **19**, 69–96, https://doi.org/10.1086/699933.

Baker, E., O. Olaleye, and L. Aleluia Reis, 2015: Decision frameworks and the investment in R&D. *Energy Policy*, **80**, 275–285, https://doi.org/10.1016/j.enpol.2015.01.027.

Barbieri, N., 2015: Investigating the impacts of technological position and European environmental regulation on green automotive patent activity. *Ecol. Econ.*, **117**, 140–152, https://doi.org/10.1016/j.ecolecon.2015.06.017.

Baron, R., 2016: *The Role of Public Procurement in Low-carbon Innovation*.

Barron-Gafford, G. A., and Coauthors, 2019: Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nat. Sustain.*, **2**, 848–855, https://doi.org/10.1038/s41893-019-0364-5.

Basel, B., G. Goby, and J. Johnson, 2020: Community-based adaptation to climate change in villages of Western Province, Solomon Islands. *Mar. Pollut. Bull.*, **156**, 111266, https://doi.org/10.1016/j.marpolbul.2020.111266.

Bastida, L., J. J. Cohen, A. Kollmann, A. Moya, and J. Reichl, 2019: Exploring the role of ICT on household behavioural energy efficiency to mitigate global warming. *Renew. Sustain. Energy Rev.*, **103**, 455–462, https://doi.org/10.1016/j.rser.2019.01.004.

Baudry, M., and C. Bonnet, 2019: Demand-Pull Instruments and the Development of Wind Power in Europe: A Counterfactual Analysis. *Environ. Resour. Econ.*, **73**, 385–429, https://doi.org/10.1007/s10640-018-0267-3.

Bauer, F., L. Coenen, T. Hansen, K. McCormick, and Y. V. Palgan, 2017: Technological innovation systems for biorefineries: a review of the literature. *BIOFUELS Bioprod. BIOREFINING-BIOFPR*, **11**, 534–548, https://doi.org/10.1002/bbb.1767.

Bayer, P., J. Urpelainen, and A. Xu, 2016: Explaining differences in sub-national patterns of clean technology transfer to China and India. *Int. Environ. Agreements Polit. Law Econ.*, **16**, 261–283, https://doi.org/10.1007/s10784-014-9257-2.

Bazilian, M., and Coauthors, 2011: Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy*, **39**, 7896–7906, https://doi.org/10.1016/j.enpol.2011.09.039.

BEE, 2020: *Impact of Energy Efficiency Measures for the Year 2018-19.*

Behuria, P., 2020: The politics of late late development in renewable energy sectors: Dependency and contradictory tensions in India’s National Solar Mission. *World Dev.*, **126**, 104726, https://doi.org/10.1016/j.worlddev.2019.104726.

Bekkers, R., 2017: Where patents and standards come together. *Handbook of Standards and Innovation*, Edward Elgar.

Bellesi, F., D. Lehrer, and A. Tal, 2005: Comparative Advantage: The Impact of ISO 14001 Environmental Certification on Exports. *Environ. Sci. Technol.*, **39**, 1943–1953, https://doi.org/10.1021/es0497983.

Bento, N., and C. Wilson, 2016: Measuring the duration of formative phases for energy technologies. *Environ. Innov. Soc. Transitions*, **21**, 95–112, https://doi.org/10.1016/j.eist.2016.04.004.

——, ——, and L. D. Anadon, 2018: Time to get ready: Conceptualizing the temporal and spatial dynamics of formative phases for energy technologies. *Energy Policy*, **119**, 282–293, https://doi.org/10.1016/j.enpol.2018.04.015.

Bergek, A., S. Jacobsson, B. Carlsson, S. Lindmark, and A. Rickne, 2008: Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Res. Policy*, **37**, 407–429, https://doi.org/10.1016/j.respol.2007.12.003.

——, ——, M. Hekkert, and K. Smith, 2010: Functionality of innovation systems as a rationale for and guide to innovation policy. *The Theory and Practice of Innovation Policy: An International Research Handbook*.

——, M. Hekkert, S. Jacobsson, J. Markard, B. Sandén, and B. Truffer, 2015: Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. *Environ. Innov. Soc. Transitions*, **16**, 51–64, https://doi.org/10.1016/j.eist.2015.07.003.

Bernauer, T., and L. F. McGrath, 2016: Simple reframing unlikely to boost public support for climate policy. *Nat. Clim. Chang.*, **6**, 680–683, https://doi.org/10.1038/nclimate2948.

Bessen, J., and M. J. Meurer, 2008: *Patent failure: how judges, bureaucrats, and lawyers put innovators at risk*. Princeton University Press,.

Bettencourt, L. M. A., J. E. Trancik, and J. Kaur, 2013: Determinants of the Pace of Global Innovation in Energy Technologies. *PLoS One*, **8**, e67864, https://doi.org/10.1371/journal.pone.0067864.

Bhattacharya, G., 1984: Learning and the Behavior of Potential Entrants. *RAND J. Econ.*, **15**, 281, https://doi.org/10.2307/2555681.

Biadgleng, E. T., 2009: *Compulsory Licenses & Government Use*. UNCTAD,.

van den Bijgaart, I., 2017: The unilateral implementation of a sustainable growth path with directed technical change. *Eur. Econ. Rev.*, **91**, 305–327, https://doi.org/10.1016/j.euroecorev.2016.10.005.

Binz, C., and B. Truffer, 2017: Global Innovation Systems—A conceptual framework for innovation dynamics in transnational contexts. *Res. Policy*, **46**, 1284–1298, https://doi.org/10.1016/j.respol.2017.05.012.

——, and L. D. Anadon, 2018: Unrelated diversification in latecomer contexts: Emergence of the Chinese solar photovoltaics industry. *Environ. Innov. Soc. Transitions*, **28**, 14–34, https://doi.org/10.1016/j.eist.2018.03.005.

Black, G., D. Holley, D. Solan, and M. Bergloff, 2014: Fiscal and economic impacts of state incentives for wind energy development in the Western United States. *Renew. Sustain. Energy Rev.*, **34**, 136–144, https://doi.org/10.1016/j.rser.2014.03.015.

Blieden, R., 1999: Cherry hill revisited—a retrospective on the creation of a national plan for photovoltaic conversion of solar energy for terrestrial applications. *AIP Conference Proceedings*, AIP, 796–799.

Du Boff, R. B., 1984: Networks of Power: Electrification in Western Society, 1880–1930. By Thomas P. Hughes (Baltimore: Johns Hopkins University Press, 1983. xi + 474 pp. $38.50.) - Engineers, Managers, and Politicians: The First Fifteen Years of Nationalised Electricity Suppl. *Bus. Hist. Rev.*, **58**, 282–284, https://doi.org/10.2307/3115059.

Böhringer, C., and K. E. Rosendahl, 2010: Green promotes the dirtiest: on the interaction between black and green quotas in energy markets. *J. Regul. Econ.*, **37**, 316–325, https://doi.org/10.1007/s11149-010-9116-1.

Boiral, O., L. Guillaumie, I. Heras-Saizarbitoria, and C. V. Tayo Tene, 2018: Adoption and Outcomes of ISO 14001: A Systematic Review. *Int. J. Manag. Rev.*, **20**, 411–432, https://doi.org/10.1111/ijmr.12139.

Bolisetty, S., M. Peydayesh, and R. Mezzenga, 2019: Sustainable technologies for water purification from heavy metals: review and analysis. *Chem. Soc. Rev.*, **48**, 463–487, https://doi.org/10.1039/C8CS00493E.

Bonvillian, W. B., 2018: DARPA and its ARPA-E and IARPA clones: a unique innovation organization model. *Ind. Corp. Chang.*, **27**, 897–914, https://doi.org/10.1093/icc/dty026.

Bonvillian, W. B., and R. Van Atta, 2011: ARPA-E and DARPA: Applying the DARPA model to energy innovation. *J. Technol. Transf.*, **36**, 469–513, https://doi.org/10.1007/s10961-011-9223-x.

Boodoo, Z., F. Mersmann, and K. H. Olsen, 2018: The implications of how climate funds conceptualize transformational change in developing countries. *Clim. Dev.*, **10**, 673–686, https://doi.org/10.1080/17565529.2018.1442788.

Bosetti, V., M. Heugues, and A. Tavoni, 2017: Luring others into climate action: coalition formation games with threshold and spillover effects. *Oxf. Econ. Pap.*, **69**, 410–431, https://doi.org/10.1093/oep/gpx017.

Bowen, W. M., S. Park, and J. A. Elvery, 2013: Empirical Estimates of the Influence of Renewable Energy Portfolio Standards on the Green Economies of States. *Econ. Dev. Q.*, **27**, 338–351, https://doi.org/10.1177/0891242413491316.

Boyd, A., 2012: Informing international UNFCCC technology mechanisms from the ground up: Using biogas technology in South Africa as a case study to evaluate the usefulness of potential elements of an international technology agreement in the UNFCCC negotiations process. *Energy Policy*, **51**, 301–311, https://doi.org/10.1016/j.enpol.2012.08.020.

Boyd, P., and L. Schweber, 2018: Unintended consequences: institutional artefacts, closure mechanisms and the performance gap. *Build. Res. Inf.*, **46**, 10–22, https://doi.org/10.1080/09613218.2017.1331096.

van Bree, B., G. P. J. Verbong, and G. J. Kramer, 2010: A multi-level perspective on the introduction of hydrogen and battery-electric vehicles. *Technol. Forecast. Soc. Change*, **77**, 529–540, https://doi.org/10.1016/j.techfore.2009.12.005.

Breetz, H., M. Mildenberger, and L. Stokes, 2018: The political logics of clean energy transitions. *Bus. Polit.*, **20**, 492–522, https://doi.org/10.1017/bap.2018.14.

Brennen, J. S., and D. Kreiss, 2016: Digitalization. *The International Encyclopedia of Communication Theory and Philosophy*, Wiley, 1–11.

Breschi, S., and F. Malerba, 1997: Sectoral Innovation Systems: Technological Regimes, Schumpeterian Dynamics, and Spatial Boundaries. *Systems of Innovation Technologies, Institutions and Organisations*.

Bringezu, S., 2019: Toward Science-Based and Knowledge-Based Targets for Global Sustainable Resource Use. *Resources*, **8**, 140, https://doi.org/10.3390/resources8030140.

Brook, B. W., K. Edney, R. Hillerbrand, R. Karlsson, and J. Symons, 2016: Energy research within the UNFCCC: a proposal to guard against ongoing climate-deadlock. *Clim. Policy*, **16**, 803–813, https://doi.org/10.1080/14693062.2015.1037820.

Brooks, H., 1980: Technology, Evolution and Purpose. *Daedalus*, **109**, 65–81.

Brooks, S., and M. Loevinsohn, 2011: Shaping agricultural innovation systems responsive to food insecurity and climate change. *Nat. Resour. Forum*, **35**, 185–200, https://doi.org/10.1111/j.1477-

8947.2011.01396.x.

Brown, J., and C. Hendry, 2009: Public demonstration projects and field trials: Accelerating commercialisation of sustainable technology in solar photovoltaics. *Energy Policy*, **37**, 2560–2573, https://doi.org/10.1016/j.enpol.2009.01.040.

Brown, M. B., W. Canzler, F. Fischer, and A. Knie, 1995: Technological Innovation through Environmental Policy: California's Zero-Emission Vehicle Regulation. *Public Product. Manag. Rev.*, **19**, 77, https://doi.org/10.2307/3380822.

Bryden, J., and S. S. Gezelius, 2017: Innovation as if people mattered: the ethics of innovation for sustainable development. *Innov. Dev.*, **7**, 101–118, https://doi.org/10.1080/2157930X.2017.1281208.

Buckley, P., 2020: Prices, information and nudges for residential electricity conservation: A meta-analysis. *Ecol. Econ.*, **172**, 106635, https://doi.org/10.1016/j.ecolecon.2020.106635.

Bukkens, S., T. Dunlop, L. J. Di Felice, Z. Kovacic, I. W. Nilsen, R. Strand, T. Völker, and L. Zamarioli, 2020: *The Nexus Times*. S. Bukkens, T. Dunlop, L.J. Di Felice, Z. Kovacic, I.W. Nilsen, R. Strand, T. Völker, and L. Zamarioli, Eds. Megaloceros Press,.

Bumpus, A., and S. Comello, 2017: Emerging clean energy technology investment trends. *Nat. Clim. Chang.*, **7**, 382–385, https://doi.org/10.1038/nclimate3306.

Bunn, M., L. D. Anadon, and V. Narayanamurti, 2014: The need to transform U.S. energy innovation. *Transforming U.S. Energy Innovation*, L.D. Anadon, M. Bunn, and V. Narayanamurti, Eds., Cambridge University Press, 14–16.

Bürer, M. J., and R. Wüstenhagen, 2009: Which renewable energy policy is a venture capitalist's best friend? Empirical evidence from a survey of international cleantech investors. *Energy Policy*, **37**, 4997–5006, https://doi.org/10.1016/j.enpol.2009.06.071.

Van Buskirk, R. D., C. L. S. Kantner, B. F. Gerke, and S. Chu, 2014: A retrospective investigation of energy efficiency standards: policies may have accelerated long term declines in appliance costs. *Environ. Res. Lett.*, **9**, 114010, https://doi.org/10.1088/1748-9326/9/11/114010.

Carlsson, B., and R. Stankiewicz, 1991: On the nature, function and composition of technological systems. *J. Evol. Econ.*, **1**, 93–118, https://doi.org/10.1007/BF01224915.

Carton, W., 2020: Carbon unicorns and fossil futures. Whose emission reduction pathways is the IPCC performing? *Has it Come to This? The Promises and Perils of Geoengineering on the BrinkThe Promises and Perils of Geoengineering on the Brink*, J. Sapinsk, H. Buck, and A. Malm, Eds., Rutgers University Press.

Cassman, K. G., and P. Grassini, 2020: A global perspective on sustainable intensification research. *Nat. Sustain.*, **3**, 262–268, https://doi.org/10.1038/s41893-020-0507-8.

Cerutti, A. K., S. Contu, F. Ardente, D. Donno, and G. L. Beccaro, 2016: Carbon footprint in green public procurement: Policy evaluation from a case study in the food sector. *Food Policy*, **58**, 82–93, https://doi.org/10.1016/j.foodpol.2015.12.001.

Chaffin, B. C., and Coauthors, 2016: Transformative Environmental Governance. *Annu. Rev. Environ. Resour.*, **41**, 399–423, https://doi.org/10.1146/annurev-environ-110615-085817.

Chaminade, C., and C. Esquist, 2010: Rationales for Public Policy Intervention in the Innovation Process: Systems of Innovation Approach. *The Theory and Practice of Innovation Policy*, Edward Elgar Publishing.

Chan, G., and L. Diaz Anadon, 2016: *Improving Decision Making for Public R&D Investment in Energy: Utilizing Expert Elicitation in Parametric Models Improving Decision Making for Public R&D Investment in Energy: Utilizing Expert Elicitation in Parametric Models 1*.

——, A. P. Goldstein, A. Bin-Nun, L. Diaz Anadon, and V. Narayanamurti, 2017: Six principles for energy innovation. *Nature*, **552**, 25–27, https://doi.org/10.1038/d41586-017-07761-0.

Chaudhary, A., A. D. Sagar, and A. Mathur, 2012: Innovating for energy efficiency: a perspective from India. *Innov. Dev.*, **2**, 45–66, https://doi.org/10.1080/2157930X.2012.667212.

Chen, Y.-S., H.-S. Lei, and W.-C. Hsu, 2019: A study on the sustainable development strategy of firms: Niche and social network theory. *Sustain.*, **11**, https://doi.org/10.3390/su11092593.

Chitnis, M., S. Sorrell, A. Druckman, S. K. Firth, and T. Jackson, 2014: Who rebounds most? Estimating direct and indirect rebound effects for different UK socioeconomic groups. *Ecol. Econ.*, **106**, 12–32, https://doi.org/10.1016/j.ecolecon.2014.07.003.

Choi, H., and H. Zo, 2019: Assessing the efficiency of national innovation systems in developing countries. *Sci. Public Policy*, **46**, 530–540, https://doi.org/10.1093/scipol/scz005.

Christensen, E., 1985: Electricity from photovoltaic solar cells. Flat-Plate Solar Array Project of the US Department of Energy's National Photovoltaics Program: 10 years of progress. *NASA STI/Recon Tech. Rep. N*,.

Cinner, J. E., and Coauthors, 2018: Building adaptive capacity to climate change in tropical coastal communities. *Nat. Clim. Chang.*, **8**, 117–123, https://doi.org/10.1038/s41558-017-0065-x.

Clark, W. C., L. van Kerkhoff, L. Lebel, and G. C. Gallopin, 2016: Crafting usable knowledge for sustainable development. *Proc. Natl. Acad. Sci.*, **113**, 4570–4578, https://doi.org/10.1073/pnas.1601266113.

Clarke, L., J. Edmonds, V. Krey, R. Richels, S. Rose, and M. Tavoni, 2009: International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Econ.*, **31**, S64–S81, https://doi.org/10.1016/j.eneco.2009.10.013.

Cohen, M. A., and A. Tubb, 2018: The Impact of Environmental Regulation on Firm and Country Competitiveness: A Meta-analysis of the Porter Hypothesis. *J. Assoc. Environ. Resour. Econ.*, **5**, 371–399, https://doi.org/10.1086/695613.

Cohen, W., R. Nelson, and J. Walsh, 2000: *Protecting Their Intellectual Assets: Appropriability Conditions and Why U.S. Manufacturing Firms Patent (or Not)*.

Cohen, W. M., A. Goto, A. Nagata, R. R. Nelson, and J. P. Walsh, 2002: R&D spillovers, patents and the incentives to innovate in Japan and the United States. *Res. Policy*, **31**, 1349–1367, https://doi.org/10.1016/S0048-7333(02)00068-9.

Coiera, E., J. Ash, and M. Berg, 2016: The Unintended Consequences of Health Information Technology Revisited. *Yearb. Med. Inform.*, **25**, 163–169, https://doi.org/10.15265/IY-2016-014.

Colicchio, T. K., J. J. Cimino, and G. Del Fiol, 2019: Unintended Consequences of Nationwide Electronic Health Record Adoption: Challenges and Opportunities in the Post-Meaningful Use Era. *J. Med. Internet Res.*, **21**, e13313, https://doi.org/10.2196/13313.

Collste, D., M. Pedercini, and S. E. Cornell, 2017: Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies. *Sustain. Sci.*, **12**, 921–931, https://doi.org/10.1007/s11625-017-0457-x.

de Coninck, H., and D. Puig, 2015: Assessing climate change mitigation technology interventions by international institutions. *Clim. Change*, **131**, 417–433, https://doi.org/10.1007/s10584-015-1344-z.

——, and A. Sagar, 2017: Technology Development and Transfer (Article 10). *The Paris Agreement on Climate Change: Analysis and Commentary*, D. Klein, M. Pía Carazo, M. Doelle, J. Bulmer, and A. Higham, Eds., Oxford University Press.

de Coninck, H., and Coauthors, 2018: Strengthening and implementing the global response. *Global Warming of 1.5C: an IPCC special report on the impacts of global warming of 1.5C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*.

Conti, C., M. L. Mancusi, F. Sanna-Randaccio, R. Sestini, and E. Verdolini, 2018: Transition towards a green economy in Europe: Innovation and knowledge integration in the renewable energy sector. *Res. Policy*, **47**, 1996–2009, https://doi.org/10.1016/j.respol.2018.07.007.

Contreras, J. L., 2015: A brief history of frand: Analyzing current debates in standard setting and antitrust through a historical lens. *Antitrust Law J.*, **80**, 82, https://doi.org/10.2139/ssrn.2374983.

Cooke, P., M. Gomez Uranga, and G. Etxebarria, 1997: Regional innovation systems: Institutional and organisational dimensions. *Res. Policy*, **26**, 475–491, https://doi.org/10.1016/S0048-7333(97)00025-5.

Corey, A., 2014: Diffusion of Green Technology: A Survey. *Int. Rev. Environ. Resour. Econ.*, **7**, 1–33, https://doi.org/10.1561/101.00000055.

Correa, C. M., J. I. Correa, and B. De Jonge, 2020: The status of patenting plants in the Global South. *J. World Intellect. Prop.*, **23**, 121–146, https://doi.org/10.1111/jwip.12143.

Corsatea, T. D., 2016: Localised knowledge, local policies and regional innovation activity for renewable energy technologies: Evidence from Italy. *Pap. Reg. Sci.*, **95**, 443–466, https://doi.org/10.1111/pirs.12136.

Corsi, A., R. N. Pagani, J. L. Kovaleski, and V. Luiz da Silva, 2020: Technology transfer for sustainable development: Social impacts depicted and some other answers to a few questions. *J. Clean. Prod.*, **245**, 118522, https://doi.org/10.1016/j.jclepro.2019.118522.

Côte, F.-X., E. Poirier-Magona, S. Perret, B. Rapide, P. Roudier, and M.-C. Thirion, 2019: *The agroecological transition of agricultural systems in the Global South*. F.-X. Côte, E. Poirier-Magona, S. Perret, P. Roudier, B. Rapidel, and M.-C. Thirion, Eds. éditions Quae,.

Cottrell, R. S., A. Fleming, E. A. Fulton, K. L. Nash, R. A. Watson, and J. L. Blanchard, 2018: Considering land–sea interactions and trade-offs for food and biodiversity. *Glob. Chang. Biol.*, **24**, 580–596, https://doi.org/10.1111/gcb.13873.

Coughlan de Perez, E., B. van den Hurk, M. K. van Aalst, B. Jongman, T. Klose, and P. Suarez, 2015: Forecast-based financing: an approach for catalyzing humanitarian action based on extreme weather and climate forecasts. *Nat. Hazards Earth Syst. Sci.*, **15**, 895–904, https://doi.org/10.5194/nhess-15-895-2015.

Cowan, R., 1990: Nuclear Power Reactors: A Study in Technological Lock-in. *J. Econ. Hist.*, **50**, 541–567, https://doi.org/10.1017/S0022050700037153.

Crabb, J. M., and D. K. N. Johnson, 2010: Fueling Innovation: The Impact of Oil Prices and CAFE Standards on Energy-Efficient Automotive Technology. *Energy J.*, **31**, https://doi.org/10.5547/ISSN0195-6574-EJ-Vol31-No1-9.

Craglia, M., and Coauthors, 2018: *Artificial Intelligence: A European Perspective*. Publications Office of the European Union,.

CREWS, 2016: *CREWS Operational Procedures Note No1 Programming and Project Development*.

Criqui, P., S. Mima, P. Menanteau, and A. Kitous, 2015: Mitigation strategies and energy technology learning: An assessment with the POLES model. *Technol. Forecast. Soc. Change*, **90**, 119–136, https://doi.org/10.1016/j.techfore.2014.05.005.

Cui, J., X. Liu, Y. Sun, and H. Yu, 2020: Can CDM projects trigger host countries' innovation in renewable energy? Evidence of firm-level dataset from China. *Energy Policy*, **139**, 111349, https://doi.org/10.1016/j.enpol.2020.111349.

D´Auvergne, C., and M. Nummelin, 2017: Capacity-Building (Article 11). *The Paris Agreement on Climate Change: Analysis and Commentary*, D. Klein, M. Pia Carazo, M. Doelle, J. Bulmer, and A. Higham, Eds., Oxford University Press.

Dai, J., and Coauthors, 2018: Water-energy nexus: A review of methods and tools for macro-assessment. *Appl. Energy*, **210**, 393–408, https://doi.org/10.1016/j.apenergy.2017.08.243.

Darmani, A., N. Arvidsson, A. Hidalgo, and J. Albors, 2014: What drives the development of renewable energy technologies? Toward a typology for the systemic drivers. *Renew. Sustain. Energy Rev.*, **38**, 834–847, https://doi.org/10.1016/j.rser.2014.07.023.

David, P., and D. Foray, 1995: Accessing and expanding the science and technology knowledge base. *STI Rev.*, **16**.

Davidovic, D., and M. Bujehi, 2020: Sustainable Practices in Agroecology for Adapting to Climate Change. *Int. J. Inspir. Resil. Econ.*, **4**, 10–15, https://doi.org/10.5923.j.ijire.20200401.02.

Davis, L. W., and C. R. Knittel, 2019: Are Fuel Economy Standards Regressive? *J. Assoc. Environ. Resour. Econ.*, **6**, S37–S63, https://doi.org/10.1086/701187.

Dechezleprêtre, A., M. Glachant, I. Haščič, N. Johnstone, and Y. Ménière, 2011: Invention and Transfer of Climate Change–Mitigation Technologies: A Global Analysis. *Rev. Environ. Econ. Policy*, **5**, 109–130, https://doi.org/10.1093/reep/req023.

Deichmann, U., A. Goyal, and D. Mishra, 2016: *Will Digital Technologies Transform Agriculture in Developing Countries?* World Bank, Washington, DC,.

Denevan, W. M., 1995: 2 Prehistoric agricultural methods as models for sustainability. 21–43.

Deng, H.-M., Q.-M. Liang, L.-J. Liu, and L. D. Anadon, 2017: Co-benefits of greenhouse gas mitigation: a review and classification by type, mitigation sector, and geography. *Environ. Res. Lett.*, **12**, 123001, https://doi.org/10.1088/1748-9326/aa98d2.

Devine, A., and N. Kok, 2015: Green Certification and Building Performance: Implications for Tangibles and Intangibles. *J. Portf. Manag.*, **41**, 151–163, https://doi.org/10.3905/jpm.2015.41.6.151.

Devlin, A., 2010: The Misunderstood Function of Disclosure in Patent Law. *Harv. J.L. Tech.*,.

Díaz, S., and Coauthors, 2019: Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science (80-. ).*, **366**, eaax3100, https://doi.org/10.1126/science.aax3100.

Diercks, G., H. Larsen, and F. Steward, 2019: Transformative innovation policy: Addressing variety in an emerging policy paradigm. *Res. Policy*, **48**, 880–894, https://doi.org/10.1016/j.respol.2018.10.028.

Disterheft, A., S. Caeiro, U. M. Azeiteiro, and W. L. Filho, 2015: Sustainable universities – a study of critical success factors for participatory approaches. *J. Clean. Prod.*, **106**, 11–21, https://doi.org/10.1016/j.jclepro.2014.01.030.

Dixit, M. K., 2019: 3-D Printing in Building Construction: A Literature Review of Opportunities and Challenges of Reducing Life Cycle Energy and Carbon of Buildings. *IOP Conf. Ser. Earth Environ. Sci.*, **290**, 012012, https://doi.org/10.1088/1755-1315/290/1/012012.

Doblinger, C., K. Surana, and L. D. Anadon, 2019: Governments as partners: The role of alliances in U.S. cleantech startup innovation. *Res. Policy*, **48**, 1458–1475, https://doi.org/10.1016/j.respol.2019.02.006.

Doranova, A., I. Costa, and G. Duysters, 2010: Knowledge base determinants of technology sourcing in clean development mechanism projects. *Energy Policy*, **38**, 5550–5559, https://doi.org/10.1016/j.enpol.2010.04.055.

Doukas, H., and A. Nikas, 2020: Decision support models in climate policy. *Eur. J. Oper. Res.*, **280**, 1–24, https://doi.org/10.1016/j.ejor.2019.01.017.

——, ——, M. González-Eguino, I. Arto, and A. Anger-Kraavi, 2018: From Integrated to Integrative: Delivering on the Paris Agreement. *Sustainability*, **10**, 2299, https://doi.org/10.3390/su10072299.

Dowlatabadi, H., 1998: Sensitivity of climate change mitigation estimates to assumptions about technical change. *Energy Econ.*, **20**, 473–493, https://doi.org/10.1016/S0140-9883(98)00009-7.

Duan, H., G. Zhang, Y. Fan, and S. Wang, 2017: Role of endogenous energy efficiency improvement in global climate change mitigation. *Energy Effic.*, **10**, 459–473, https://doi.org/10.1007/s12053-016-9468-1.

Dussaux, D., A. Dechezleprêtre, and M. Glachant, 2018: *Intellectual property rights protection and the international transfer of low-carbon technologies*. 63 pp.

Echeverría, R. G., 1998: Agricultural research policy issues in Latin America: An Overview. *World Dev.*, **26**, 1103–1111, https://doi.org/10.1016/S0305-750X(98)00036-9.

Edler, J., and L. Georghiou, 2007: Public procurement and innovation—Resurrecting the demand side. *Res. Policy*, **36**, 949–963, https://doi.org/10.1016/j.respol.2007.03.003.

Edmonds, J., L. Clarke, J. Lurz, and M. Wise, 2008: Stabilizing CO2 concentrations with incomplete international cooperation. *Clim. Policy*, https://doi.org/10.3763/cpol.2007.0469.

Edquist, C., 1997: *Systems of Innovation: Technologies, Institutions and Organizations*.

——, 2019: Towards a holistic innovation policy: Can the Swedish National Innovation Council (NIC) be a role model? *Res. Policy*, **48**, 869–879, https://doi.org/10.1016/j.respol.2018.10.008.

Egli, F., B. Steffen, and T. S. Schmidt, 2018: A dynamic analysis of financing conditions for renewable energy technologies. *Nat. Energy*, **3**, 1084–1092, https://doi.org/10.1038/s41560-018-0277-y.

Einstein, A., 1905: Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt. *Ann. Phys.*, **322**, 132–148, https://doi.org/10.1002/andp.19053220607.

Elder, M., M. Bengtsson, and L. Akenji, 2016: An Optimistic Analysis of the Means of Implementation for Sustainable Development Goals: Thinking about Goals as Means. *Sustainability*, **8**, 962, https://doi.org/10.3390/su8090962.

Elia, A., M. Kamidelivand, F. Rogan, and B. Ó Gallachóir, 2020: Impacts of innovation on renewable energy technology cost reductions. *Renew. Sustain. Energy Rev.*, 110488, https://doi.org/10.1016/j.rser.2020.110488.

Elzen, B., F. Geels, and K. Green, 2004: *System Innovation and the Transition to Sustainability*. 0th ed. Edward Elgar Publishing,.

Emmerling, J., and Coauthors, 2016: *The WITCH 2016 Model - Documentation and Implementation of the Shared Socioeconomic Pathways*. 63 pp.

Encaoua, D., D. Guellec, and C. Martínez, 2006: Patent systems for encouraging innovation: Lessons from economic analysis. *Res. Policy*, **35**, 1423–1440, https://doi.org/10.1016/j.respol.2006.07.004.

EPO, 2017: *Unitary Patent Guide*. European Patent Office,.

Erickson, P., S. Kartha, M. Lazarus, and K. Tempest, 2015: Assessing carbon lock-in. *Environ. Res. Lett.*, **10**, 084023, https://doi.org/10.1088/1748-9326/10/8/084023.

European Association of Research Technology Organisations, 2014: *The TRL Scale as a Research & Innovation Policy Tool*.

European Commission, 2014: *“Advancing Manufacturing - Advancing Europe” - Report of the Task Force on Advanced Manufacturing for Clean Production*.

——, 2015: *EU R&amp;D Survey: The 2015 EU Survey on Industrial R&amp;D Investment Trends*. 54 pp.

——, 2018: *Ecodesign Impacts Accounting, Status October 2018*.

——, 2020: An SME Strategy for a sustainable and digital Europe. 19.

Fagerberg, J., 2018: Mobilizing innovation for sustainability transitions: A comment on transformative innovation policy. *Res. Policy*, **47**, 1568–1576, https://doi.org/10.1016/j.respol.2018.08.012.

Falvey, R., N. Foster, and D. Greenaway, 2006: Intellectual Property Rights and Economic Growth.

*Rev. Dev. Econ.*, **10**, 700–719, https://doi.org/10.1111/j.1467-9361.2006.00343.x.

FAO, 2018a: *Transforming Food and Agriculture to Achieve the SDGs: 20 interconnected actions to guide decision-makers*. 132 pp.

——, 2018b: *Los 10 Elementos De La Agroecología Guía para la Transición Hacia Sistemas Alimentarios y Agrícolas Sostenibles*.

——, 2019: FAO activities in SIDS.

Farmer, J. D., and Coauthors, 2019: Sensitive intervention points in the post-carbon transition. *Science (80-. ).*, **364**, 132–134, https://doi.org/10.1126/science.aaw7287.

Fernández-Sastre, J., and F. Montalvo-Quizhpi, 2019: The effect of developing countries' innovation policies on firms' decisions to invest in R&D. *Technol. Forecast. Soc. Change*, **143**, 214–223, https://doi.org/10.1016/j.techfore.2019.02.006.

Fischer, C., L. Preonas, and R. G. Newell, 2017: Environmental and Technology Policy Options in the Electricity Sector: Are We Deploying Too Many? *J. Assoc. Environ. Resour. Econ.*, **4**, 959–984, https://doi.org/10.1086/692507.

Fisher, E., R. L. Mahajan, and C. Mitcham, 2006: Midstream Modulation of Technology: Governance From Within. *Bull. Sci. Technol. Soc.*, **26**, 485–496, https://doi.org/10.1177/0270467606295402.

Fleming, L., and O. Sorenson, 2001: Technology as a complex adaptive system: evidence from patent data. *Res. Policy*, **30**, 1019–1039, https://doi.org/10.1016/S0048-7333(00)00135-9.

Foray, D., 2004: The patent system and the dynamics of innovation in Europe. *Sci. Public Policy*, **31**, 449–456, https://doi.org/10.3152/147154304781779732.

Foster, C., and S. Azmeh, 2020: Latecomer Economies and National Digital Policy: An Industrial Policy Perspective. *J. Dev. Stud.*, **56**, 1247–1262, https://doi.org/10.1080/00220388.2019.1677886.

Fragkiadakis, K., P. Fragkos, and L. Paroussos, 2020: Low-Carbon R&amp;D Can Boost EU Growth and Competitiveness. *Energies*, **13**, 5236, https://doi.org/10.3390/en13195236.

Francis, C., and Coauthors, 2003: Agroecology: The Ecology of Food Systems. *J. Sustain. Agric.*, **22**, 99–118, https://doi.org/10.1300/J064v22n03_10.

Frank, C., C. Sink, L. Mynatt, R. Rogers, and A. Rappazzo, 1996: Surviving the "valley of death": A comparative analysis. *J. Technol. Transf.*, **21**, 61–69, https://doi.org/10.1007/BF02220308.

Freeman, C., 1995a: The 'National System of Innovation' in historical perspective. *Cambridge J. Econ.*, **19**, 5–14, https://doi.org/10.1093/oxfordjournals.cje.a035309.

——, 1995b: The "national system of innovation" in historical perspective. *Cambridge J. Econ.*, **19**, 5–24, https://doi.org/10.1093/oxfordjournals.cje.a035309.

——, and C. Perez, 1988: Structural crises of adjustment, business cycles and investment behaviour. *Technical Change and Economic Theory*, G. Dosi, C. Freeman, R. Nelson, and G. Silverberg, Eds., Francis Printer, 38–66.

Freeman, C., and L. Soete, 1997: *The Economics of Industrial Innovation*. Routledge, Taylor & Francis Group,.

Freeman, C., and L. Soete, 2009: Developing science, technology and innovation indicators: What we can learn from the past. *Res. Policy*, https://doi.org/10.1016/j.respol.2009.01.018.

Frenken, K., L. R. Izquierdo, and P. Zeppini, 2012: Branching innovation, recombinant innovation, and endogenous technological transitions. *Environ. Innov. Soc. Transitions*, **4**, 25–35, https://doi.org/10.1016/j.eist.2012.06.001.

Friedman, B., and D. G. Hendry, 2019: Value Sensitive Design. *Value Sensitive Des.*, **3**, 17–23, https://doi.org/10.7551/mitpress/7585.001.0001.

Fu, B., S. Wang, J. Zhang, Z. Hou, and J. Li, 2019: Unravelling the complexity in achieving the 17 sustainable-development goals. *Natl. Sci. Rev.*, **6**, 386–388, https://doi.org/10.1093/nsr/nwz038.

Fu, W., C. Li, J. Ondrich, and D. Popp, 2018: *Technological spillover effects of state renewable energy policy: Evidence from patent counts*.

Fuerst, F., and P. McAllister, 2011: Eco-labeling in commercial office markets: Do LEED and Energy Star offices obtain multiple premiums? *Ecol. Econ.*, **70**, 1220–1230, https://doi.org/10.1016/j.ecolecon.2011.01.026.

Funtowicz, S., 2020: From risk calculations to narratives of danger. *Clim. Risk Manag.*, **27**, 100212, https://doi.org/10.1016/j.crm.2020.100212.

Gaddy, B. E., V. Sivaram, T. B. Jones, and L. Wayman, 2017: Venture Capital and Cleantech: The wrong model for energy innovation. *Energy Policy*, **102**, 385–395, https://doi.org/10.1016/j.enpol.2016.12.035.

Gallagher, K. S., J. P. Holdren, and A. D. Sagar, 2006: Energy-Technology Innovation. *Annu. Rev. Environ. Resour.*, **31**, 193–237, https://doi.org/10.1146/annurev.energy.30.050504.144321.

——, A. Grübler, L. Kuhl, G. Nemet, and C. Wilson, 2012: The Energy Technology Innovation System. *Annu. Rev. Environ. Resour.*, **37**, 137–162, https://doi.org/10.1146/annurev-environ-060311-133915.

Gambhir, A., P. Sandwell, and J. Nelson, 2016: The future costs of OPV – A bottom-up model of material and manufacturing costs with uncertainty analysis. *Sol. Energy Mater. Sol. Cells*, **156**, 49–58, https://doi.org/10.1016/j.solmat.2016.05.056.

——, I. Butnar, P.-H. Li, P. Smith, and N. Strachan, 2019: A Review of Criticisms of Integrated Assessment Models and Proposed Approaches to Address These, through the Lens of BECCS. *Energies*, **12**, 1747, https://doi.org/10.3390/en12091747.

Gandenberger, C., M. Bodenheimer, J. Schleich, R. Orzanna, and L. Macht, 2016: Factors driving international technology transfer: empirical insights from a CDM project survey. *Clim. Policy*, **16**, 1065–1084, https://doi.org/10.1080/14693062.2015.1069176.

Gann, D. M., Y. Wang, and R. Hawkins, 1998: Do regulations encourage innovation? - the case of energy efficiency in housing. *Build. Res. Inf.*, **26**, 280–296, https://doi.org/10.1080/096132198369760.

Gao, L., and B. A. Bryan, 2017: Finding pathways to national-scale land-sector sustainability. *Nature*, **544**, 217–222, https://doi.org/10.1038/nature21694.

Gao, X., and W. Zhang, 2013: Foreign investment, innovation capacity and environmental efficiency in China. *Math. Comput. Model.*, **58**, 1040–1046, https://doi.org/10.1016/j.mcm.2012.08.012.

Gao, X., and V. Rai, 2019: Local demand-pull policy and energy innovation: Evidence from the solar photovoltaic market in China. *Energy Policy*, **128**, 364–376, https://doi.org/10.1016/j.enpol.2018.12.056.

Gao, Y., and P. Newman, 2018: Beijing’s Peak Car Transition: Hope for Emerging Cities in the 1.5 °C Agenda. *Urban Plan.*, **3**, 82–93, https://doi.org/10.17645/up.v3i2.1246.

Geddes, A., T. S. Schmidt, and B. Steffen, 2018: The multiple roles of state investment banks in low-carbon energy finance: An analysis of Australia, the UK and Germany. *Energy Policy*, **115**, 158–170, https://doi.org/10.1016/j.enpol.2018.01.009.

Geels, F., 2005: *Technological Transitions and System Innovations*. Edward Elgar Publishing,.

Geels, F. W., 2002: Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Res. Policy*, **31**, 1257–1274, https://doi.org/10.1016/S0048-7333(02)00062-8.

Geels, F. W., 2004: From sectoral systems of innovation to socio-technical systems. *Res. Policy*, **33**, 897–920, https://doi.org/10.1016/j.respol.2004.01.015.

——, 2012: A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies. *J. Transp. Geogr.*, **24**, 471–482, https://doi.org/10.1016/j.jtrangeo.2012.01.021.

Geels, F. W., 2014: Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective. *Theory, Cult. Soc.*, **31**, 21–40, https://doi.org/10.1177/0263276414531627.

Geels, F. W., F. Berkhout, and D. P. van Vuuren, 2016: Bridging analytical approaches for low-carbon transitions. *Nat. Clim. Chang.*, **6**, 576–583, https://doi.org/10.1038/nclimate2980.

——, B. K. Sovacool, T. Schwanen, and S. Sorrell, 2017: The Socio-Technical Dynamics of Low-Carbon Transitions. *Joule*, **1**, 463–479, https://doi.org/10.1016/j.joule.2017.09.018.

Gerlagh, R., and O. Kuik, 2014: Spill or leak? Carbon leakage with international technology spillovers: A CGE analysis. *Energy Econ.*, **45**, 381–388, https://doi.org/10.1016/j.eneco.2014.07.017.

Gertner, J., 2013: *The idea factory: Bell Labs and the great age of American innovation*. Penguim Books, 422 pp.

GeSI, 2012: *GeSI SMARTer 2020: The Role of ICT in Driving a Sustainable Future*.

Gillingham, K., and J. Sweeney, 2012: Barriers to implementing low-carbon technologies. *Clim. Chang. Econ.*, **03**, 1250019, https://doi.org/10.1142/S2010007812500194.

Gillingham, K., H. Deng, R. Wiser, N. R. Darghouth, G. Nemet, G. Barbose, V. Rai, and C. Dong, 2016a: Deconstructing solar photovoltaic pricing: The role of market structure, technology, and policy. *Energy J.*, **37**, 231–250, https://doi.org/10.5547/01956574.37.3.kgil.

——, D. Rapson, and G. Wagner, 2016b: The Rebound Effect and Energy Efficiency Policy. *Rev. Environ. Econ. Policy*, **10**, 68–88, https://doi.org/10.1093/reep/rev017.

Girod, B., T. Stucki, and M. Woerter, 2017: How do policies for efficient energy use in the household sector induce energy-efficiency innovation? An evaluation of European countries. *Energy Policy*, **103**, 223–237, https://doi.org/10.1016/j.enpol.2016.12.054.

Glachant, M., and A. Dechezleprêtre, 2017: What role for climate negotiations on technology transfer? *Clim. Policy*, **17**, 962–981, https://doi.org/10.1080/14693062.2016.1222257.

Global Commission on Adaptation, 2019: *Adapt now. A global call for leadership on climate resilience*. 81 pp.

Goldfarb, A., and D. Trefler, 2018: *AI and International Trade*.

Goldfarb, B., 2011: Economic Transformations: General Purpose Technologies and Long-Term Economic Growth. By Richard G. Lipsey, Kenneth I. Carlaw, and Clifford T. Bekar. Oxford: Oxford University Press, 2005., $55.00, hardback. *J. Econ. Hist.*, **71**, 820–823, https://doi.org/10.1017/S0022050711002099.

Goldstein, A., C. Doblinger, E. Baker, and L. D. Anadón, 2020: Patenting and business outcomes for cleantech startups funded by the Advanced Research Projects Agency-Energy. *Nat. Energy*, **5**, 803–810, https://doi.org/10.1038/s41560-020-00683-8.

Goldstein, A. P., and V. Narayanamurti, 2018: Simultaneous pursuit of discovery and invention in the US Department of Energy. *Res. Policy*, **47**, 1505–1512, https://doi.org/10.1016/j.respol.2018.05.005.

——, and M. Kearney, 2020: Know when to fold 'em: An empirical description of risk management in public research funding. *Res. Policy*, **49**, 103873, https://doi.org/10.1016/j.respol.2019.103873.

Golombek, R., and M. Hoel, 2004: Unilateral Emission Reductions and Cross-Country Technology Spillovers. *Adv. Econ. Anal. Policy*, **3**, 57–83, https://doi.org/10.2202/1538-0637.1318.

González, F. G., and Coauthors, 2019: Field-grown transgenic wheat expressing the sunflower gene HaHB4 significantly outyields the wild type. *J. Exp. Bot.*, **70**, 1669–1681, https://doi.org/10.1093/jxb/erz037.

Goulder, L. H., and S. H. Schneider, 1999: Induced technological change and the attractiveness of CO2 abatement policies. *Resour. Energy Econ.*, **21**, 211–253, https://doi.org/10.1016/S0928-7655(99)00004-4.

Gram-Hanssen, K., and S. Georg, 2018: Energy performance gaps: promises, people, practices. *Build. Res. Inf.*, **46**, 1–9, https://doi.org/10.1080/09613218.2017.1356127.

Grandia, J., and D. Voncken, 2019: Sustainable Public Procurement: The Impact of Ability, Motivation, and Opportunity on the Implementation of Different Types of Sustainable Public Procurement. *Sustainability*, **11**, 5215, https://doi.org/10.3390/su11195215.

Grandstrand, O., and O. Granstrand, 2000: *The Economics and Management of Intellectual Property: Towards Intellectual Capitalism*. Edward Elgar, 480 pp.

Grau, H. R., R. Torres, N. I. Gasparri, P. G. Blendinger, S. Marinaro, and L. Macchi, 2015: Natural grasslands in the Chaco. A neglected ecosystem under threat by agriculture expansion and forest-oriented conservation policies. *J. Arid Environ.*, **123**, 40–46, https://doi.org/10.1016/j.jaridenv.2014.12.006.

Greaker, M., T. Heggedal, and K. E. Rosendahl, 2018: Environmental Policy and the Direction of Technical Change. *Scand. J. Econ.*, **120**, 1100–1138, https://doi.org/10.1111/sjoe.12254.

Green, M. A., 2019: How Did Solar Cells Get So Cheap? *Joule*, **3**, 631–633, https://doi.org/10.1016/j.joule.2019.02.010.

Griliches, Z., 1992: The Search for R&amp;D Spillovers. *Scand. J. Econ.*, **94**, S29, https://doi.org/10.2307/3440244.

Griscom, B. W., and Coauthors, 2017: Natural climate solutions. *Proc. Natl. Acad. Sci.*, **114**, 11645–11650, https://doi.org/10.1073/pnas.1710465114.

Gross, R., R. Hanna, A. Gambhir, P. Heptonstall, and J. Speirs, 2018: How long does innovation and commercialisation in the energy sectors take? Historical case studies of the timescale from invention to widespread commercialisation in energy supply and end use technology. *Energy Policy*, **123**, 682–699, https://doi.org/10.1016/j.enpol.2018.08.061.

Grubb, M., and C. Wieners, 2020: Modeling Myths: On the Need for Dynamic Realism in DICE and other Equilibrium Models of Global Climate Mitigation. *Inst. New Econ. Think. Work. Pap. Ser.*, 1–29, https://doi.org/10.36687/inetwp112.

——, J.-C. Hourcade, and K. Neuhoff, 2015: The Three Domains structure of energy-climate transitions. *Technol. Forecast. Soc. Change*, **98**, 290–302, https://doi.org/10.1016/j.techfore.2015.05.009.

Grubb, M., and Coauthors, 2021: Induced innovation in energy technologies and systems a review of evidence and potential implications for CO2 mitigation. *Environ. Res. Lett.*,.

Grubler, A., and C. Wilson, 2014: *Energy Technology Innovation: Learning from Historical Successes and Failures*. Cambridge University Press,.

——, and Coauthors, 2012: Policies for the Energy Technology Innovation System (ETIS). *Global Energy Assessment - Toward a Sustainable Future*, N. et al. Nakicenovic, Ed., Cambridge University Press, 1665–1744.

——, and Coauthors, 2018: A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat. Energy*, **3**, 515–527, https://doi.org/10.1038/s41560-018-0172-6.

Grübler, A., 1996: Time for a change: On the patterns of diffusion of innovation. *Daedalus*, **125**, 19–42.

——, 1998: *Technology and Global Change*. Cambridge University Press, 452 pp.

——, N. Nakićenović, and D. G. Victor, 1999: Dynamics of energy technologies and global change. *Energy Policy*, **27**, 247–280, https://doi.org/10.1016/S0301-4215(98)00067-6.

Gruebler, A., and Coauthors, 2012: Energy technology innovation systems. *The Global Energy Assessment*, N. et al. Nakicenovic, Ed., Cambridge University Press.

Guo, M., J. Nowakowska-Grunt, V. Gorbanyov, and M. Egorova, 2020: Green Technology and Sustainable Development: Assessment and Green Growth Frameworks. *Sustainability*, **12**, 6571, https://doi.org/10.3390/su12166571.

de Haan, F. J., and J. Rotmans, 2018: A proposed theoretical framework for actors in transformative change. *Technol. Forecast. Soc. Change*, **128**, 275–286, https://doi.org/10.1016/j.techfore.2017.12.017.

Haelg, L., M. Waelchli, and T. S. Schmidt, 2018: Supporting energy technology deployment while avoiding unintended technological lock-in: a policy design perspective. *Environ. Res. Lett.*, **13**, 104011, https://doi.org/10.1088/1748-9326/aae161.

Haenssgen, M. J., and P. Ariana, 2018: The place of technology in the Capability Approach. *Oxford Dev. Stud.*, **46**, 98–112, https://doi.org/10.1080/13600818.2017.1325456.

Hall, B., and C. Helmers, 2010: *The role of patent protection in (clean/green) technology transfer*. 39 pp.

Hall, B. H., and R. H. Ziedonis, 2001: The Patent Paradox Revisited: An Empirical Study of Patenting in the U.S. Semiconductor Industry, 1979-1995. *RAND J. Econ.*, **32**, 101, https://doi.org/10.2307/2696400.

——, and C. Helmers, 2019: The impact of international patent systems: Evidence from accession to the European Patent Convention. *Res. Policy*, **48**, 103810, https://doi.org/10.1016/j.respol.2019.103810.

Hall, M. J., and A. N. Link, 2015: Technology-based state growth policies: the case of North Carolina’s Green Business Fund. *Ann. Reg. Sci.*, **54**, 437–449, https://doi.org/10.1007/s00168-015-0661-5.

Halleck-Vega, S., A. Mandel, and K. Millock, 2018: Accelerating diffusion of climate-friendly technologies: A network perspective. *Ecol. Econ.*, **152**, 235–245, https://doi.org/10.1016/j.ecolecon.2018.05.007.

Halleck Vega, S., and A. Mandel, 2018: Technology Diffusion and Climate Policy: A Network Approach and its Application to Wind Energy. *Ecol. Econ.*, **145**, 461–471, https://doi.org/10.1016/j.ecolecon.2017.11.023.

Hallegatte, S., 2012: *A cost effective solution to reduce disaster losses in developing countries – hydro-meterological services, early warning and evacuation*.

Hanley, E. S., J. Deane, and B. Ó. Gallachóir, 2018: The role of hydrogen in low carbon energy futures–A review of existing perspectives. *Renew. Sustain. Energy Rev.*, **82**, 3027–3045, https://doi.org/10.1016/j.rser.2017.10.034.

Hao, H., S. Wang, Z. Liu, and F. Zhao, 2016: The impact of stepped fuel economy targets on automaker’s light-weighting strategy: The China case. *Energy*, **94**, 755–765, https://doi.org/10.1016/j.energy.2015.11.051.

Harrowsmith, M., and Coauthors, 2020: *The future of forecasts: Impact-based forecasting for early action*. 81 pp.

Haščič, I., and M. Migotto, 2015: Measuring environmental innovation using patent data. *OECD Environ. Work. Pap.*,.

Haselip, J., U. E. Hansen, D. Puig, S. Trærup, and S. Dhar, 2015: Governance, enabling frameworks and policies for the transfer and diffusion of low carbon and climate adaptation technologies in developing countries. *Clim. Change*, **131**, 363–370, https://doi.org/10.1007/s10584-015-1440-0.

Hassler, J., P. Krusell, and C. Olovsson, 2012: *Energy-Saving Technical Change*.

He, W., and R. Shen, 2019: ISO 14001 Certification and Corporate Technological Innovation: Evidence from Chinese Firms. *J. Bus. Ethics*, **158**, 97–117, https://doi.org/10.1007/s10551-017-3712-2.

Heffron, R. J., and D. McCauley, 2018: What is the 'Just Transition'? *Geoforum*, **88**, 74–77, https://doi.org/10.1016/J.GEOFORUM.2017.11.016.

Hekkert, M., R. Suurs, S. Negro, S. Kuhlmann, and R. Smits, 2007: Functions of innovation systems: A new approach for analysing technological change. *Technol. Forecast. Soc. Change*, **74**, 413–432.

Hekkert, M. P., and S. O. Negro, 2009: Functions of innovation systems as a framework to understand sustainable technological change: Empirical evidence for earlier claims. *Technol. Forecast. Soc. Change*, **76**, 584–594, https://doi.org/10.1016/j.techfore.2008.04.013.

——, M. J. Janssen, J. H. Wesseling, and S. O. Negro, 2020: Mission-oriented innovation systems. *Environ. Innov. Soc. Transitions*, **34**, 76–79, https://doi.org/10.1016/j.eist.2019.11.011.

Heller, M. A., and R. S. Eisenberg, 1998: Can Patents Deter Innovation? The Anticommons in Biomedical Research. *Science (80-. ).*, **280**, 698–701, https://doi.org/10.1126/science.280.5364.698.

Hellsmark, H., J. Frishammar, P. Söderholm, and H. Ylinenpää, 2016: The role of pilot and demonstration plants in technology development and innovation policy. *Res. Policy*, **45**, 1743–1761, https://doi.org/10.1016/j.respol.2016.05.005.

Helm, D., C. Hepburn, and R. Mash, 2003: Credible carbon policy. *Oxford Rev. Econ. Policy*, **19**, 438–450.

Helveston, J., and J. Nahm, 2019: China's key role in scaling low-carbon energy technologies. *Science (80-. ).*, **366**, 794–796, https://doi.org/10.1126/science.aaz1014.

Hémous, D., 2016: The dynamic impact of unilateral environmental policies. *J. Int. Econ.*, **103**, 80–95, https://doi.org/10.1016/j.jinteco.2016.09.001.

Henderson, R., and R. Newell, 2011: Introduction. *Accelerating Energy Innovation*, R. Henderson and R. Newell, Eds., Chicago University Press, p. 288.

Hertwich, E. G., and G. P. Peters, 2009: Carbon Footprint of Nations: A Global, Trade-Linked Analysis. *Environ. Sci. Technol.*, **43**, 6414–6420, https://doi.org/10.1021/es803496a.

Hofman, E., and W. van der Gaast, 2019: Enhancing ambition levels in nationally determined contributions—Learning from Technology Needs Assessments. *Wiley Interdiscip. Rev. Energy Environ.*, **8**, e311, https://doi.org/10.1002/wene.311.

Holt-Giménez, E., 2002: Measuring farmers' agroecological resistance after Hurricane Mitch in Nicaragua: a case study in participatory, sustainable land management impact monitoring. *Agric. Ecosyst. Environ.*, **93**, 87–105, https://doi.org/10.1016/S0167-8809(02)00006-3.

Hoppmann, J., M. Peters, M. Schneider, and V. H. Hoffmann, 2013: The two faces of market support—How deployment policies affect technological exploration and exploitation in the solar photovoltaic industry. *Res. Policy*, **42**, 989–1003, https://doi.org/10.1016/j.respol.2013.01.002.

——, J. Huenteler, and B. Girod, 2014: Compulsive policy-making—The evolution of the German feed-in tariff system for solar photovoltaic power. *Res. Policy*, **43**, 1422–1441, https://doi.org/10.1016/j.respol.2014.01.014.

——, F. Naegele, and B. Girod, 2019: Boards as a Source of Inertia: Examining the Internal Challenges and Dynamics of Boards of Directors in Times of Environmental Discontinuities. *Acad. Manag. J.*, **62**, 437–468, https://doi.org/10.5465/amj.2016.1091.

Horbach, J., C. Rammer, and K. Rennings, 2012: Determinants of eco-innovations by type of environmental impact — The role of regulatory push/pull, technology push and market pull. *Ecol. Econ.*, **78**, 112–122, https://doi.org/10.1016/j.ecolecon.2012.04.005.

Horner, N. C., A. Shehabi, and I. L. Azevedo, 2016: Known unknowns: indirect energy effects of information and communication technology. *Environ. Res. Lett.*, **11**, 103001, https://doi.org/10.1088/1748-9326/11/10/103001.

Horton, D., and R. Mackay, 2003: Using evaluation to enhance institutional learning and change: recent experiences with agricultural research and development. *Agric. Syst.*, **78**, 127–142, https://doi.org/10.1016/S0308-521X(03)00123-9.

Howell, S. T., 2017: Financing Innovation: Evidence from R&amp;D Grants. *Am. Econ. Rev.*, **107**, 1136–1164, https://doi.org/10.1257/aer.20150808.

Howlett, M., and P. del Rio, 2015: The parameters of policy portfolios: verticality and horizontality in design spaces and their consequences for policy mix formulation. *Environ. Plan. C Gov. Policy*, **33**, 1233–1245, https://doi.org/10.1177/0263774X15610059.

Hsu, S.-L., 2017: Capital Transitioning: An International Human Capital Strategy for Climate Innovation. *Transnatl. Environ. Law*, **6**, 153–176, https://doi.org/10.1017/S2047102516000169.

Hu, R., J. Skea, and M. J. Hannon, 2018: Measuring the energy innovation process: An indicator framework and a case study of wind energy in China. *Technol. Forecast. Soc. Change*, **127**, 227–244, https://doi.org/10.1016/j.techfore.2017.09.025.

Huang, R., M. Riddle, D. Graziano, J. Warren, S. Das, S. Nimbalkar, J. Cresko, and E. Masanet, 2016: Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. *J. Clean. Prod.*, **135**, 1559–1570, https://doi.org/10.1016/j.jclepro.2015.04.109.

Huenteler, J., T. S. Schmidt, J. Ossenbrink, and V. H. Hoffmann, 2016: Technology life-cycles in the energy sector — Technological characteristics and the role of deployment for innovation. *Technol. Forecast. Soc. Change*, **104**, 102–121, https://doi.org/10.1016/j.techfore.2015.09.022.

Huh, T., and H.-J. Kim, 2018: Korean Experimentation of Knowledge and Technology Transfer to Address Climate Change in Developing Countries. *Sustainability*, **10**, 1263, https://doi.org/10.3390/su10041263.

Hussein, A. K., 2015: Applications of nanotechnology in renewable energies—A comprehensive overview and understanding. *Renew. Sustain. Energy Rev.*, **42**, 460–476, https://doi.org/10.1016/j.rser.2014.10.027.

ICLEI, 2018: *Energy Innovation Procurement: A guide for city authorities*. 48 pp.

IEA, *4E: Achievements of Appliance Energy Efficiency Standards and Labelling Programs*.

——, 2010: *Global Gaps in Clean Energy Research, Development and Demonstration*.

——, 2017a: *Early-Stage Venture Capital for Energy Innovation*.

——, 2017b: Digitalisation and Energy.

——, 2017c: *Digitalization & Energy*. OECD,.

——, 2019: Energy technology RD&D – Data services.

——, 2020a: *Energy Technology Perspectives 2020*. IEA, 400 pp.

——, 2020b: *World Enery Outlook*.

Ing, J., and J.-P. Nicolaï, 2020: North-South diffusion of climate-mitigation technologies: the crowding-out effect on relocation. *Environ. Dev. Econ.*, **25**, 21–43, https://doi.org/10.1017/S1355770X19000445.

Inoue, E., T. H. Arimura, and M. Nakano, 2013: A new insight into environmental innovation: Does the maturity of environmental management systems matter? *Ecol. Econ.*, **94**, 156–163, https://doi.org/10.1016/j.ecolecon.2013.07.014.

IPBES, 2019: *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*.

IPCC, 2000: *Methodological and Technological Issues in Technology Transfer*. B. Metz, D. Ogunlade, J.-W. Martens, S. Van Rooijen, and L. Van Wie Mcgrory, Eds. Cambridge University Press, 432 pp.

——, 2007: *Climate Change 2007: Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007*. B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer, Eds. Cambridge University Press,.

——, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*. C.B. Field et al., Eds. Cambridge University Press, 582 pp.

——, 2014: *Climate Change 2014 Mitigation of Climate Change*. Cambridge University Press,.

——, 2018a: Summary for Policymakers. *Global Warming of 1.5 °C an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*.

——, 2018b: *Global Warming of 1.5 °C an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*.

IRENA, 2019: *Eletricity Power Generation Costs 2019*.

——, 2020: *Renewable energy statistics*.

Isoard, S., and A. Soria, 2001: Technical change dynamics: evidence from the emerging renewable energy technologies. *Energy Econ.*, **23**, 619–636, https://doi.org/10.1016/S0140-9883(01)00072-X.

Ito, K., and J. M. Sallee, 2018: The Economics of Attribute-Based Regulation: Theory and Evidence from Fuel Economy Standards. *Rev. Econ. Stat.*, **100**, 319–336, https://doi.org/10.1162/REST_a_00704.

Ivanova, D., G. Vita, R. Wood, C. Lausselet, A. Dumitru, K. Krause, I. Macsinga, and E. G. Hertwich, 2018: Carbon mitigation in domains of high consumer lock-in. *Glob. Environ. Chang.*, **52**, 117–130, https://doi.org/10.1016/j.gloenvcha.2018.06.006.

Iyengar, S., and D. S. Massey, 2019: Scientific communication in a post-truth society. *Proc. Natl. Acad. Sci.*, **116**, 7656–7661, https://doi.org/10.1073/pnas.1805868115.

Iyer, G., N. Hultman, J. Eom, H. McJeon, P. Patel, and L. Clarke, 2015: Diffusion of low-carbon technologies and the feasibility of long-term climate targets. *Technol. Forecast. Soc. Change*, **90**, 103–118, https://doi.org/10.1016/j.techfore.2013.08.025.

Jacobsen, M. R., 2013: Evaluating US Fuel Economy Standards in a Model with Producer and Household Heterogeneity. *Am. Econ. J. Econ. Policy*, **5**, 148–187, https://doi.org/10.1257/pol.5.2.148.

Jacobsson, S., and A. Bergek, 2006: A Framework for Guiding Policy-makers Intervening in Emerging Innovation Systems in 'Catching-Up' Countries. *Eur. J. Dev. Res.*, **18**, 687–707, https://doi.org/10.1080/09578810601094902.

——, B. Sandén, and L. Bångens, 2004: Transforming the Energy System — the Evolution of the German Technological System for Solar Cells. *Technol. Anal. Strateg. Manag.*, **16**, 3–30, https://doi.org/10.1080/0953732032000199061.

——, A. Bergek, and B. Sandén, 2017: Improving the European Commission's analytical base for designing instrument mixes in the energy sector: Market failures versus system weaknesses.

*Energy Res. Soc. Sci.*, **33**, 11–20, https://doi.org/10.1016/j.erss.2017.09.009.

Jaffe, A., and J. Lerner, 2006: *Innovation and its discontents: How our broken patent system is endangering innovation and progress, and what to do about it*. Princeton University Press,.

Jaffe, A. B., 2015: Technology diffusion. *Emerging Trends in the Social and Behavioral Sciences*, R. Scott and Kosslyn, Eds., John Wiley and Sons Inc.

——, and G. de Rassenfosse, 2017: Patent citation data in social science research: Overview and best practices. *J. Assoc. Inf. Sci. Technol.*, **68**, 1360–1374, https://doi.org/10.1002/asi.23731.

——, R. G. Newell, and R. N. Stavins, 2005: A tale of two market failures: Technology and environmental policy. *Ecol. Econ.*, **54**, 164–174, https://doi.org/10.1016/j.ecolecon.2004.12.027.

Jain, M., A. B. Rao, and A. Patwardhan, 2018: Appliance labeling and consumer heterogeneity: A discrete choice experiment in India. *Appl. Energy*, **226**, 213–224, https://doi.org/10.1016/j.apenergy.2018.05.089.

Jairaj, B., A. Agarwal, T. Parthasarathy, and S. Martin, 2016: *Strengthening Governance of India's Appliance Efficiency Standards and Labeling Program*. 28 pp.

Jamasb, T., 2007: Technical Change Theory and Learning Curves: Patterns of Progress in Energy Technologies. *Energy J.*, **28**, 51–72, https://doi.org/10.2307/41323109.

——, and M. Pollitt, 2008: Liberalisation and R&amp;D in network industries: The case of the electricity industry. *Res. Policy*, **37**, 995–1008, https://doi.org/10.1016/j.respol.2008.04.010.

Jasmab, T., and M. Pollitt, 2005: *Deregulation and R & D in Network Industries : The Case of the Electricity Industry*.

Jensen, M. B., B. Johnson, E. Lorenz, and B. Å. Lundvall, 2007: Forms of knowledge and modes of innovation. *Res. Policy*, **36**, 680–693, https://doi.org/10.1016/j.respol.2007.01.006.

Jones, N., 2018: How to stop data centres from gobbling up the world's electricity. *Nature*, **561**, 163–166, https://doi.org/10.1038/d41586-018-06610-y.

de Jong, P., A. Paulraj, and C. Blome, 2014: The Financial Impact of ISO 14001 Certification: Top-Line, Bottom-Line, or Both? *J. Bus. Ethics*, **119**, 131–149, https://doi.org/10.1007/s10551-012-1604-z.

Joshi, G. Y., P. A. Sheorey, and A. V. Gandhi, 2019: Analyzing the barriers to purchase intentions of energy efficient appliances from consumer perspective. *Benchmarking An Int. J.*, **26**, 1565–1580, https://doi.org/10.1108/BIJ-03-2018-0082.

Kahn, M. E., and N. Kok, 2014: The capitalization of green labels in the California housing market. *Reg. Sci. Urban Econ.*, **47**, 25–34, https://doi.org/10.1016/j.regsciurbeco.2013.07.001.

Kammen, D. M., and G. F. Nemet, 2007: Energy Myth Eleven – Energy R&amp;D Investment Takes Decades to Reach the Market. *Energy and American Society – Thirteen Myths*, B.K. Sovacool and M.A. Brown, Eds., Springer Netherlands, 289–309.

Karakosta, C., H. Doukas, and J. Psarras, 2012: Carbon market and technology transfer: statistical analysis for exploring implications. *Int. J. Sustain. Dev. World Ecol.*, **19**, 311–320, https://doi.org/10.1080/13504509.2011.644638.

Kavlak, G., J. McNerney, and J. E. Trancik, 2018: Evaluating the causes of cost reduction in photovoltaic modules. *Energy Policy*, **123**, 700–710, https://doi.org/10.1016/j.enpol.2018.08.015.

Kemp, R., 2005: Zero emission vehicle mandate in California: misguided policy or example of enlightened leadership. *Time Strategies, Innovation and Environmental Policy*, Sartorius; and Zundel, Eds., Edward Elgar.

——, 2011: Ten themes for eco-innovation policies in Europe. *Sapiens*, **4**, 1–20.

——, J. Schot, and R. Hoogma, 1998: Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technol. Anal. Strateg. Manag.*, **10**, 175–198, https://doi.org/10.1080/09537329808524310.

Kern, F., and M. Howlett, 2009: Implementing transition management as policy reforms: a case study of the Dutch energy sector. *Policy Sci.*, **42**, 391–408, https://doi.org/10.1007/s11077-009-9099-x.

Khalili, N. R., S. Duecker, W. Ashton, and F. Chavez, 2015: From cleaner production to sustainable development: the role of academia. *J. Clean. Prod.*, **96**, 30–43, https://doi.org/10.1016/j.jclepro.2014.01.099.

Khan, M., D. Mfitumukiza, and S. Huq, 2020: Capacity building for implementation of nationally determined contributions under the Paris Agreement. *Clim. Policy*, **20**, 499–510, https://doi.org/10.1080/14693062.2019.1675577.

Khanna, T., and Coauthors, 2021: Reducing carbon emissions of households through monetary incentives and behavioural interventions: a meta-analysis. *Submitted*,.

Khosla, R., A. Sagar, and A. Mathur, 2017: Deploying Low-carbon Technologies in Developing Countries: A view from India’s buildings sector. *Environ. Policy Gov.*, **27**, 149–162, https://doi.org/10.1002/eet.1750.

Kim, H. S., and S.-S. Kwak, 2020: Crop biotechnology for sustainable agriculture in the face of climate crisis. *Plant Biotechnol. Rep.*, **14**, 139–141, https://doi.org/10.1007/s11816-020-00619-4.

Kim, J., S. Jun, D. Jang, and S. Park, 2018: Sustainable technology analysis of artificial intelligence using Bayesian and social network models. *Sustain.*, **10**, https://doi.org/10.3390/su10010115.

Kim, Y. J., and M. Brown, 2019: Impact of domestic energy-efficiency policies on foreign innovation: The case of lighting technologies. *Energy Policy*, **128**, 539–552, https://doi.org/10.1016/j.enpol.2019.01.032.

Kimura, O., and T. Suzuki, 2006: 30 years of solar energy development in Japan : co-evolution process of technology , policies , and the market. *Power*, 17–18.

Kiso, T., 2019: Environmental Policy and Induced Technological Change: Evidence from Automobile Fuel Economy Regulations. *Environ. Resour. Econ.*, **74**, 785–810, https://doi.org/10.1007/s10640-019-00347-6.

Kivimaa, P., and F. Kern, 2016: Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. *Res. Policy*, **45**, 205–217, https://doi.org/10.1016/j.respol.2015.09.008.

Klaassen, G., A. Miketa, K. Larsen, and T. Sundqvist, 2005: The impact of R&amp;D on innovation for wind energy in Denmark, Germany and the United Kingdom. *Ecol. Econ.*, **54**, 227–240, https://doi.org/10.1016/j.ecolecon.2005.01.008.

Klein Woolthuis, R., M. Lankhuizen, and V. Gilsing, 2005: A system failure framework for innovation policy design. *Technovation*, **25**, 609–619, https://doi.org/10.1016/j.technovation.2003.11.002.

Klerkx, L., B. van Mierlo, and C. Leeuwis, 2012: Evolution of systems approaches to agricultural innovation: concepts, analysis and interventions. *Farming Systems Research into the 21st Century: The New Dynamic*, Springer Netherlands, 457–483.

——, E. Jakku, and P. Labarthe, 2019: A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS - Wageningen J. Life Sci.*, **90–91**, 100315, https://doi.org/10.1016/j.njas.2019.100315.

Kline, S., and N. Rosenberg, 1986: An overview of innovation. *The Positive Sum Strategy: Harnessing Technology for Economic Growth*, 275–306.

Knittel, C. R., 2011: Automobiles on Steroids: Product Attribute Trade-Offs and Technological Progress in the Automobile Sector. *Am. Econ. Rev.*, **101**, 3368–3399, https://doi.org/10.1257/aer.101.7.3368.

Knobloch, F., and J. F. Mercure, 2016: The behavioural aspect of green technology investments: A general positive model in the context of heterogeneous agents. *Environ. Innov. Soc. Transitions*, https://doi.org/10.1016/j.eist.2016.03.002.

Koch, N., G. Grosjean, S. Fuss, and O. Edenhofer, 2016: Politics matters: Regulatory events as catalysts for price formation under cap-and-trade. *J. Environ. Econ. Manage.*, **78**, 121–139, https://doi.org/10.1016/j.jeem.2016.03.004.

Koengkan, M., Y. E. Poveda, and J. A. Fuinhas, 2020: Globalisation as a motor of renewable energy development in Latin America countries. *GeoJournal*, **85**, 1591–1602, https://doi.org/10.1007/s10708-019-10042-0.

Koh, H., and C. L. Magee, 2008: A functional approach for studying technological progress: Extension to energy technology. *Technol. Forecast. Soc. Change*, **75**, 735–758, https://doi.org/10.1016/j.techfore.2007.05.007.

Kolleck, N., 2019: The emergence of a global innovation in education: diffusing Education for Sustainable Development through social networks. *Environ. Educ. Res.*, **25**, 1635–1653, https://doi.org/10.1080/13504622.2019.1675593.

Koohafkan, P., and M. Altieri, 2010: *Globally important agricultural heritage systems: a legacy for the future*.

Koronen, C., M. Åhman, and L. J. Nilsson, 2020: Data centres in future European energy systems—energy efficiency, integration and policy. *Energy Effic.*, **13**, 129–144, https://doi.org/10.1007/s12053-019-09833-8.

Kowarsch, M., J. Garard, P. Riousset, D. Lenzi, M. J. Dorsch, B. Knopf, J.-A. Harrs, and O. Edenhofer, 2016: Scientific assessments to facilitate deliberative policy learning. *Palgrave Commun.*, **2**, 16092, https://doi.org/10.1057/palcomms.2016.92.

Krey, V., and Coauthors, 2019: Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models. *Energy*, **172**, 1254–1267, https://doi.org/10.1016/j.energy.2018.12.131.

Kriegler, E., and Coauthors, 2015: Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technol. Forecast. Soc. Change*, **90**, 24–44, https://doi.org/10.1016/j.techfore.2013.09.021.

Kuhl, L., K. Van Maanen, and S. Scyphers, 2020: An analysis of UNFCCC-financed coastal adaptation projects: Assessing patterns of project design and contributions to adaptive capacity. *World Dev.*, **127**, 104748, https://doi.org/10.1016/j.worlddev.2019.104748.

Kumar, V., U. Kumar, and A. Persaud, 1999: Building Technological Capability Through Importing Technology: The Case of Indonesian Manufacturing Industry. *J. Technol. Transf.*, **24**, 81–96, https://doi.org/10.1023/A:1007728921126.

Kuntze, J.-C., and T. Moerenhout, 2012: Local Content Requirements and the Renewable Energy Industry - A Good Match? *SSRN Electron. J.*, 19, https://doi.org/10.2139/ssrn.2188607.

Kypreos, S., and O. Bahn, 2003: A MERGE Model with Endogenous Technological Progress. *Environ. Model. Assess.*, **8**, 249–259, https://doi.org/https://doi.org/10.1023/A:1025551408939.

Lachapelle, E., R. MacNeil, and M. Paterson, 2017: The political economy of decarbonisation: from green energy 'race' to green 'division of labour.' *New Polit. Econ.*, **22**, 311–327, https://doi.org/10.1080/13563467.2017.1240669.

Lafond, F., A. G. Bailey, J. D. Bakker, D. Rebois, R. Zadourian, P. McSharry, and J. D. Farmer, 2018: How well do experience curves predict technological progress? A method for making distributional forecasts. *Technol. Forecast. Soc. Change*, **128**, 104–117, https://doi.org/10.1016/j.techfore.2017.11.001.

Laine, J., K. Kontu, J. Heinonen, and S. Junnila, 2020: Uncertain greenhouse gas implication in waste heat utilization – A case study with a data center. *J. Sustain. Dev. Energy, Water Environ. Syst.*, **8**, 360–372, https://doi.org/10.13044/j.sdewes.d7.0301.

Laird, F. N., 2001: *Solar Energy, Technology Policy, and Institutional Values*. Cambridge University Press,.

Lambin, E. F., and P. Meyfroidt, 2011: Global land use change, economic globalization, and the looming land scarcity. *Proc. Natl. Acad. Sci.*, **108**, 3465–3472, https://doi.org/10.1073/pnas.1100480108.

Lamperti, F., G. Dosi, M. Napoletano, A. Roventini, and A. Sapio, 2020: Climate change and green transitions in an agent-based integrated assessment model. *Technol. Forecast. Soc. Change*, **153**, 119806, https://doi.org/10.1016/j.techfore.2019.119806.

Lance H. Gunderson, C. S. H., 2002: *Understanding Transformations in Human and Natural Systems*. Island Press, 509 pp.

Lansing, J. S., 1987: Balinese “Water Temples” and the Management of Irrigation. *Am. Anthropol.*, **89**, 326–341, https://doi.org/10.1525/aa.1987.89.2.02a00030.

Lauber, V., and S. Jacobsson, 2016: The politics and economics of constructing, contesting and restricting socio-political space for renewables – The German Renewable Energy Act. *Environ. Innov. Soc. Transitions*, **18**, 147–163, https://doi.org/10.1016/j.eist.2015.06.005.

Lee, J., F. M. Veloso, D. A. Hounshell, and E. S. Rubin, 2010: Forcing technological change: A case of automobile emissions control technology development in the US. *Technovation*, **30**, 249–264, https://doi.org/10.1016/j.technovation.2009.12.003.

Lee, T., 2017: The effect of clean energy regulations and incentives on green jobs: panel analysis of the United States, 1998-2007. *Nat. Resour. Forum*, **41**, 145–155, https://doi.org/10.1111/1477-8947.12125.

Lehmann, P., 2012: Justifying a policy mix for pollution control: A review of economic literature. *J. Econ. Surv.*, **26**, 71–97, https://doi.org/10.1111/j.1467-6419.2010.00628.x.

Lehoux, N., S. D’Amours, and A. Langevin, 2014: Inter-firm collaborations and supply chain coordination: review of key elements and case study. *Prod. Plan. Control*, **25**, 858–872, https://doi.org/10.1080/09537287.2013.771413.

Levin, K., Cashore, B., Berstein, S., and Auld, G., 2012: Overcoming the tragedy of super wicked problems. *Policy Sci.*, **45**, 123–152.

Levine, A. S., and R. Kline, 2019: Loss-Framed Arguments Can Stifle Political Activism. *J. Exp. Polit. Sci.*, **6**, 171–179, https://doi.org/10.1017/XPS.2018.28.

Levinson, A., 2019: Energy Efficiency Standards Are More Regressive Than Energy Taxes: Theory and Evidence. *J. Assoc. Environ. Resour. Econ.*, **6**, S7–S36, https://doi.org/10.1086/701186.

Lewis, J. I., 2014: Industrial policy, politics and competition: Assessing the post-crisis wind power industry. *Bus. Polit.*, **16**, 511–547, https://doi.org/10.1515/bap-2014-0012.

Ley, M., T. Stucki, and M. Woerter, 2016: The Impact of Energy Prices on Green Innovation. *Energy J.*, **37**, https://doi.org/10.5547/01956574.37.1.mley.

Li, D., F. Tang, and J. Jiang, 2019a: Does environmental management system foster corporate green innovation? The moderating effect of environmental regulation. *Technol. Anal. Strateg. Manag.*, **31**, 1242–1256, https://doi.org/10.1080/09537325.2019.1602259.

Li, J., O. E. Omoju, J. Zhang, E. E. Ikhide, G. Lu, A. I. Lawal, and V. A. Ozue, 2020: DOES INTELLECTUAL PROPERTY RIGHTS PROTECTION CONSTITUTE A BARRIER TO RENEWABLE ENERGY? AN ECONOMETRIC ANALYSIS. *Natl. Inst. Econ. Rev.*, **251**, R37–R46, https://doi.org/10.1017/nie.2020.5.

Li, Z., H. Dong, Z. Huang, and P. Failler, 2019b: Impact of Foreign Direct Investment on Environmental

Performance. *Sustainability*, **11**, 3538, https://doi.org/10.3390/su11133538.

Liebowitz, S. J., and S. E. Margolis, 1995: Path Dependence, Lock-In, and History. *SSRN Electron. J.*, **11**, 205–226, https://doi.org/10.2139/ssrn.1706450.

Lilliestam, J., A. Patt, and G. Bersalli, 2020: The effect of carbon pricing on technological change for full energy decarbonization: A review of empirical ex-post evidence. *WIREs Clim. Chang.*, https://doi.org/10.1002/wcc.681.

Lin, B., and Y. Chen, 2019: Does electricity price matter for innovation in renewable energy technologies in China? *Energy Econ.*, **78**, 259–266, https://doi.org/10.1016/j.eneco.2018.11.014.

Littleton, M., 2008: *The TRIPS Agreement and Transfer of Climate- Change-Related Technologies to Developing Countries*. 48 pp.

——, 2009: The TRIPS Agreement and transfer of climate-change-related technologies to developing countries. *Nat. Resour. Forum*, **33**, 233–244, https://doi.org/10.1111/j.1477-8947.2009.01228.x.

Lo, K., 2014: A critical review of China's rapidly developing renewable energy and energy efficiency policies. *Renew. Sustain. Energy Rev.*, **29**, 508–516, https://doi.org/10.1016/j.rser.2013.09.006.

Lovering, J. R., A. Yip, and T. Nordhaus, 2016: Historical construction costs of global nuclear power reactors. *Energy Policy*, **91**, 371–382, https://doi.org/10.1016/j.enpol.2016.01.011.

Lundvall, B.-Å., 1988: Innovation as an interactive process: from user-producer interaction to the national system of innovation. *Technical Change and Economic Theory*, G. Dosi, C. Freeman, R. Nelson, G. Silverberg, and L. Soete, Eds., Pinter Publishers.

——, 1992: *National Systems of Innovation: Toward a Theory of Innovation and Interactive Learning*. B.-A. Lundvall, Ed. Pinter Publishers, 342 pp.

Lundvall, B. Å., K. J. Joseph, and C. Chaminade, 2009: *Handbook of innovation systems and developing countries: Building domestic capabilities in a global setting*.

Lytle, W., T. K. Meyer, N. G. Tanikella, L. Burnham, J. Engel, C. Schelly, and J. M. Pearce, 2020: Conceptual Design and Rationale for a New Agrivoltaics Concept: Pasture-Raised Rabbits and Solar Farming. *J. Clean. Prod.*, 124476, https://doi.org/10.1016/j.jclepro.2020.124476.

Machlup, F., 1958: *An economic review of the patent system, Subcommittee on Patents, Trademarks & Copyrights of the Senate Committee on the Judiciary, 85th Cong., 2d Sess.*

——, and E. Penrose, 1950: The Patent Controversy in the Nineteenth Century. *J. Econ. Hist.*, **10**, 1–29, https://doi.org/10.1017/S0022050700055893.

Malhotra, A., A. Mathur, S. Diddi, and A. D. Sagar, The role of capacity-building in policies for climate change mitigation and sustainable development: The case of energy efficiency in India.

Mankins, J., 1995: *Technology Readiness Level – A White Paper*. 6 pp.

Mankins, J. C., 2009: Technology readiness assessments: A retrospective. *Acta Astronaut.*, **65**, 1216–1223, https://doi.org/10.1016/j.actaastro.2009.03.058.

Marangoni, G., and M. Tavoni, 2014: THE CLEAN ENERGY R&amp;D STRATEGY FOR 2°C. *Clim. Chang. Econ.*, **05**, 1440003, https://doi.org/10.1142/S201000781440003X.

Maria, C. Di, and E. van der Werf, 2008: Carbon leakage revisited: unilateral climate policy with directed technical change. *Environ. Resour. Econ.*, **39**, 55–74, https://doi.org/10.1007/s10640-007-9091-x.

Mas-Colell, A., M. D. Whinston, and J. R. Green, 1995: *Microeconomic Theory*. Oxford University Press, 981 pp.

Masanet, E., A. Shehabi, N. Lei, S. Smith, and J. Koomey, 2020: Recalibrating global data center energy-use estimates. *Science (80-. ).*, **367**, 984–986, https://doi.org/10.1126/science.aba3758.

Maskus, K., 2010: Differentiated Intellectual Property Regimes for Environmental and Climate

Technologies. *OECD Environ. Work. Pap.*, https://doi.org/10.1787/5kmfwjvc83vk-en.

Maskus, K. E., and J. H. Reichman, 2017: The globalization of private knowledge goods and the privatization of global public goods. *Globalization and Intellectual Property*, Vol. 7 of, Routledge, 335–377.

Mastropietro, P., C. Batlle, L. A. Barroso, and P. Rodilla, 2014: Electricity auctions in South America: Towards convergence of system adequacy and RES-E support. *Renew. Sustain. Energy Rev.*, **40**, 375–385, https://doi.org/10.1016/j.rser.2014.07.074.

Matsuo, T., and T. S. Schmidt, 2019: Managing tradeoffs in green industrial policies: The role of renewable energy policy design. *World Dev.*, **122**, 11–26, https://doi.org/10.1016/j.worlddev.2019.05.005.

May, P., 2019: Valuing externalities of cattle and soy-maize systems in the Brazilian amazon: A Test of the TEEBAgriFood Framework. *TEEB Agric.*,.

Mayer, J., 2001: *Technology Diffusion, Human Capital and Economic Growth in Developing Countries*. 47 pp.

Mayer, T., D. Kreyenberg, J. Wind, and F. Braun, 2012: Feasibility study of 2020 target costs for PEM fuel cells and lithium-ion batteries: A two-factor experience curve approach. *Int. J. Hydrogen Energy*, **37**, 14463–14474, https://doi.org/10.1016/j.ijhydene.2012.07.022.

Mazzucato, M., 2013: *The Entrepreneurial State*. Anthem Press, 288 pp.

——, 2015: 6. Innovation, the State and Patient Capital. *Polit. Q.*, **86**, 98–118, https://doi.org/10.1111/1467-923X.12235.

——, 2016: From market fixing to market-creating: a new framework for innovation policy. *Ind. Innov.*, **23**, 140–156, https://doi.org/10.1080/13662716.2016.1146124.

Mazzucato, M., 2018: *Mission-Oriented Research & Innovation in the European Union.*

Mazzucato, M., and G. Semieniuk, 2017: Public financing of innovation: new questions. *Oxford Rev. Econ. Policy*, **33**, 24–48, https://doi.org/10.1093/oxrep/grw036.

——, and ——, 2018: Financing renewable energy: Who is financing what and why it matters. *Technol. Forecast. Soc. Change*, **127**, 8–22, https://doi.org/10.1016/j.techfore.2017.05.021.

McDonald, A., and L. Schrattenholzer, 2001: Learning rates for energy technologies. *Energy Policy*, **29**, 255–261, https://doi.org/10.1016/S0301-4215(00)00122-1.

McGee, J., and J. Wenta, 2014: Technology Transfer Institutions in Global Climate Governance: The Tension between Equity Principles and Market Allocation. *Rev. Eur. Comp. Int. Environ. Law*, **23**, 367–381, https://doi.org/10.1111/reel.12075.

McNeil, M. A., M. Iyer, S. Meyers, V. E. Letschert, and J. E. McMahon, 2008: Potential benefits from improved energy efficiency of key electrical products: The case of India. *Energy Policy*, **36**, 3467–3476, https://doi.org/10.1016/j.enpol.2008.05.020.

McNerney, J., J. Doyne Farmer, and J. E. Trancik, 2011: Historical costs of coal-fired electricity and implications for the future. *Energy Policy*, **39**, 3042–3054, https://doi.org/10.1016/j.enpol.2011.01.037.

Meckling, J., 2019: A New Path for U.S. Climate Politics: Choosing Policies That Mobilize Business for Decarbonization. *Ann. Am. Acad. Pol. Soc. Sci.*, **685**, 82–95, https://doi.org/10.1177/0002716219862515.

——, and J. Nahm, 2019: The politics of technology bans: Industrial policy competition and green goals for the auto industry. *Energy Policy*, **126**, 470–479, https://doi.org/10.1016/j.enpol.2018.11.031.

——, N. Kelsey, E. Biber, and J. Zysman, 2015: Winning coalitions for climate policy. *Science (80-. ).*, **349**, 1170–1171, https://doi.org/10.1126/science.aab1336.

——, T. Sterner, and G. Wagner, 2017: Policy sequencing toward decarbonization. *Nat. Energy*, **2**, 918–922, https://doi.org/10.1038/s41560-017-0025-8.

Meckling, J. O., and G. Y. Chung, 2009: Sectoral approaches for a post-2012 climate regime: a taxonomy. *Clim. Policy*, **9**, 652–668, https://doi.org/10.3763/cpol.2009.0629.

Melissen, F., and H. Reinders, 2012: A reflection on the Dutch Sustainable Public Procurement Programme. *J. Integr. Environ. Sci.*, **9**, 27–36, https://doi.org/10.1080/1943815X.2012.658815.

Meng, J., R. Way, E. Verdolini, and L. Anadon, Comparing expert elicitation and model-based probabilistic to technology cost forecasts for the energy transition.

Mercure, J. F., F. Knobloch, H. Pollitt, R. Lewney, K. Rademakers, L. Eichler, J. van der Laan, and L. Paroussos, 2016: *Policy-induced energy technological innovation and finance for low-carbon economic growth: Study on the macroeconomics of energy and climate policies*.

Mian, A., L. Straub, and A. Sufi, 2020: *Indebted Demand*. 70 pp.

Michaelowa, A., I. Shishlov, and D. Brescia, 2019: Evolution of international carbon markets: lessons for the Paris Agreement. *Wiley Interdiscip. Rev. Clim. Chang.*, **10**, https://doi.org/10.1002/wcc.613.

Mignon, I., and A. Bergek, 2016: System-and actor-level challenges for diffusion of renewable electricity technologies: an international comparison. *J. Clean. Prod.*, **128**, 105–115.

Milojevic-Dupont, N., and F. Creutzig, 2021: Machine learning for geographically differentiated climate change mitigation in urban areas. *Sustain. Cities Soc.*, **64**, 102526, https://doi.org/10.1016/j.scs.2020.102526.

Miremadi, I., Y. Saboohi, and S. Jacobsson, 2018: Assessing the performance of energy innovation systems: Towards an established set of indicators. *Energy Res. Soc. Sci.*, **40**, 159–176, https://doi.org/10.1016/j.erss.2018.01.002.

Mitcham, C., 2003: Co-responsibility for research integrity. *Sci. Eng. Ethics*, **9**, 273–290, https://doi.org/10.1007/s11948-003-0014-0.

Mockshell, J., and M. E. J. Villarino, 2019: Agroecological Intensification: Potential and Limitations to Achieving Food Security and Sustainability. *Encyclopedia of Food Security and Sustainability*, Elsevier, 64–70.

Mohammadi, A., B. Khoshnevisan, G. Venkatesh, and S. Eskandari, 2020: A Critical Review on Advancement and Challenges of Biochar Application in Paddy Fields: Environmental and Life Cycle Cost Analysis. *Processes*, **8**, 1275, https://doi.org/10.3390/pr8101275.

Moon, S., S. Bae, and M.-G. Jeong, 2014: Corporate Sustainability and Economic Performance: an Empirical Analysis of a Voluntary Environmental Program in the USA. *Bus. Strateg. Environ.*, **23**, 534–546, https://doi.org/10.1002/bse.1800.

Mormina, M., 2019: Science, Technology and Innovation as Social Goods for Development: Rethinking Research Capacity Building from Sen’s Capabilities Approach. *Sci. Eng. Ethics*, **25**, 671–692, https://doi.org/10.1007/s11948-018-0037-1.

Mowery, D., and N. Rosenberg, 1979: The influence of market demand upon innovation: a critical review of some recent empirical studies. *Res. Policy*, **8**, 102–153, https://doi.org/10.1016/0048-7333(79)90019-2.

Mukherjee, P. K., E. Gibbs, A. Walia, and C. Taylor, 2020: Staying cool: The development of India’s pioneering energy efficiency policy for chillers. *WIREs Energy Environ.*, **9**, https://doi.org/10.1002/wene.372.

Mulgan, G., 2012: *The theoretical foundation of social innovation*. Palgrave Macmillan, 33–65 pp.

Munene, M. B., Å. G. Swartling, and F. Thomalla, 2018: Adaptive governance as a catalyst for transforming the relationship between development and disaster risk through the Sendai

Framework? *Int. J. Disaster Risk Reduct.*, **28**, 653–663, https://doi.org/10.1016/j.ijdrr.2018.01.021.

Murphy, K., G. A. Kirkman, S. Seres, and E. Haites, 2015: Technology transfer in the CDM: an updated analysis. *Clim. Policy*, **15**, 127–145, https://doi.org/10.1080/14693062.2013.812719.

Myslikova, Z., and K. S. Gallagher, 2020: Mission Innovation is mission critical. *Nat. Energy*, **5**, 732–734, https://doi.org/10.1038/s41560-020-00694-5.

Nagy, B., J. D. Farmer, Q. M. Bui, and J. E. Trancik, 2013: Statistical Basis for Predicting Technological Progress. *PLoS One*, **8**, e52669, https://doi.org/10.1371/journal.pone.0052669.

Nahm, J., and E. S. Steinfeld, 2014: Scale-up Nation: China's Specialization in Innovative Manufacturing. *World Dev.*, https://doi.org/10.1016/j.worlddev.2013.09.003.

Nanda, R., K. Younge, and L. Fleming, 2016: Economic Value Creation in Mobile Applications. *The Changing Frontier*, A.B. Jaffe and B.F. Jones, Eds., University of Chicago Press, 233–286.

Napp, T., D. Bernie, R. Thomas, J. Lowe, A. Hawkes, and A. Gambhir, 2017: Exploring the Feasibility of Low-Carbon Scenarios Using Historical Energy Transitions Analysis. *Energies*, **10**, 116, https://doi.org/10.3390/en10010116.

Narayanamurti, V; Odumosu, T., 2016: *Cycles of Invention and Discovery*. Harvard University Press, 176 pp.

Narayanamurti, V., L. Anadon, and A. Sagar, 2009: Narayanamurti_IS&amp;T. *Issues Sci. Technol.*, **XXIV**.

Narita, D., and U. J. Wagner, 2017: Strategic uncertainty, indeterminacy, and the formation of international environmental agreements. *Oxf. Econ. Pap.*, **69**, 432–452, https://doi.org/10.1093/oep/gpx001.

National Science Board, 2018: *Research and Development - Research Trends and Comparisons*. 108 pp.

Negro, S. O., F. Alkemade, and M. P. Hekkert, 2012: Why does renewable energy diffuse so slowly? A review of innovation system problems. *Renew. Sustain. Energy Rev.*, **16**, 3836–3846, https://doi.org/10.1016/j.rser.2012.03.043.

Neij, L., and K. Åstrand, 2006: Outcome indicators for the evaluation of energy policy instruments and technical change. *Energy Policy*, **34**, 2662–2676, https://doi.org/10.1016/j.enpol.2005.03.012.

Nelson, R., 1959: The simple economics of basic scientific research. *J. Polit. Econ.*, **67**, 297–306.

——, 1993: *National Innovation Systems: A Comparative Analysis*. Oxford University Press, 552 pp.

——, and E. Phelps, 1966: Investment in Humans, Technology Diffusion and Economic Growth. *Am. Econ. Rev.*, **56**, 69–75.

Nelson, R., and R. Mazzoleni, 1996: Economic Theories About the Costs and Benefits of Patents. *National Research Council, Intellectual Property Rights and Research Tools in Molecular Biology*, The National Academies Press.

Nemet, G., 2012a: Solar Water Heater Innovation in the US. *Global Energy Assessment. Historical Case Studies of Energy Technology Innovation*, A. Grubler et al., Eds., Cambridge University Press.

——, 2013: Technological change and climate change policy. *Encyclopedia of Energy, Natural Resource and Environmental Economics*, J. Shogren, Ed., Elsevier.

Nemet, G. F., 2006: Beyond the learning curve: factors influencing cost reductions in photovoltaics. *Energy Policy*, **34**, 3218–3232, https://doi.org/10.1016/j.enpol.2005.06.020.

——, 2009a: Interim monitoring of cost dynamics for publicly supported energy technologies. *Energy Policy*, **37**, 825–835, https://doi.org/10.1016/j.enpol.2008.10.031.

——, 2009b: Demand-pull, technology-push, and government-led incentives for non-incremental technical change. *Res. Policy*, **38**, 700–709, https://doi.org/10.1016/j.respol.2009.01.004.

——, 2010: Robust incentives and the design of a climate change governance regime. *Energy Policy*, **38**, 7216–7225, https://doi.org/10.1016/j.enpol.2010.07.052.

——, 2012b: Inter-technology knowledge spillovers for energy technologies. *Energy Econ.*, **34**, 1259–1270, https://doi.org/10.1016/j.eneco.2012.06.002.

Nemet, G. F., 2019a: *How solar became cheap*. Routledge, 14–18 pp.

——, P. Braden, and E. Cubero, 2013: *Credibility, ambition, and discretion in long-term U.S. energy policy targets from 1973 to 2011*. University of Wisconsin-Madison La Follette School of Public Affairs, Working Paper 2013-007,.

Nemet, G. F., M. Jakob, J. C. Steckel, and O. Edenhofer, 2017: Addressing policy credibility problems for low-carbon investment. *Glob. Environ. Chang.*, **42**, 47–57, https://doi.org/10.1016/j.gloenvcha.2016.12.004.

——, V. Zipperer, and M. Kraus, 2018: The valley of death, the technology pork barrel, and public support for large demonstration projects. *Energy Policy*, **119**, 154–167, https://doi.org/10.1016/j.enpol.2018.04.008.

Nemet, G. G. F., 2019b: *How solar became cheap: A model for low-carbon innovation*. Earthscan Routledge, 223 pp.

Newell, P., and D. Mulvaney, 2013: The political economy of the “just transition.” *Geogr. J.*, https://doi.org/10.1111/geoj.12008.

Newell, R. G., A. B. Jaffe, and R. N. Stavins, 1999: The Induced Innovation Hypothesis and Energy-Saving Technological Change. *Q. J. Econ.*, **114**, 941–975, https://doi.org/10.1162/003355399556188.

Newman, C., J. Rand, T. Talbot, and F. Tarp, 2015: Technology transfers, foreign investment and productivity spillovers. *Eur. Econ. Rev.*, **76**, 168–187, https://doi.org/10.1016/j.euroecorev.2015.02.005.

Newman, P., 2017: Decoupling Economic Growth from Fossil Fuels. *Mod. Econ.*, **08**, 791–805, https://doi.org/10.4236/me.2017.86055.

Nicholls, C. I., and M. A. Altieri, 2018: Pathways for the amplification of agroecology. *Agroecol. Sustain. Food Syst.*, **42**, 1170–1193, https://doi.org/10.1080/21683565.2018.1499578.

Nikas, A., H. Doukas, J. Lieu, R. Alvarez Tinoco, V. Charisopoulos, and W. van der Gaast, 2017: Managing stakeholder knowledge for the evaluation of innovation systems in the face of climate change. *J. Knowl. Manag.*, **21**, 1013–1034, https://doi.org/10.1108/JKM-01-2017-0006.

——, ——, and L. Martínez López, 2018: A group decision making tool for assessing climate policy risks against multiple criteria. *Heliyon*, **4**, e00588, https://doi.org/10.1016/j.heliyon.2018.e00588.

Nilsson, M., D. Griggs, and M. Visbeck, 2016: Policy: Map the interactions between Sustainable Development Goals. *Nature*, **534**, 320–322, https://doi.org/10.1038/534320a.

——, and Coauthors, 2018: Mapping interactions between the sustainable development goals: lessons learned and ways forward. *Sustain. Sci.*, **13**, 1489–1503, https://doi.org/10.1007/s11625-018-0604-z.

Noailly, J., 2012: Improving the energy efficiency of buildings: The impact of environmental policy on technological innovation. *Energy Econ.*, **34**, 795–806, https://doi.org/10.1016/j.eneco.2011.07.015.

——, and R. Smeets, 2015: Directing technical change from fossil-fuel to renewable energy innovation: An application using firm-level patent data. *J. Environ. Econ. Manage.*, **72**, 15–37, https://doi.org/10.1016/j.jeem.2015.03.004.

Nordhaus, W., 2011: Designing a friendly space for technological change to slow global warming. *Energy Econ.*, **33**, 665–673, https://doi.org/10.1016/j.eneco.2010.08.005.

Nordhaus, W. D., 2014: The Perils of the Learning Model for Modeling Endogenous Technological Change. *Energy J.*, **35**, https://doi.org/10.5547/01956574.35.1.1.

North, D. C., 1991: Institutions. *J. Econ. Perspect.*, **5**, 97–112.

Nygaard, I., and U. E. Hansen, 2015: The conceptual and practical challenges to technology categorisation in the preparation of technology needs assessments. *Clim. Change*, **131**, 371–385, https://doi.org/10.1007/s10584-015-1367-5.

Nyserda, 2020: *NYSERDA Innovation & Research Demonstration Project Impact Evaluation*.

Oberthür, S., G. Khandekar, and T. Wyns, 2020: Global governance for the decarbonization of energy-intensive industries: Great potential underexploited. *Earth Syst. Gov.*, 100072, https://doi.org/10.1016/j.esg.2020.100072.

Ockwell, D., and R. Byrne, 2016: Improving technology transfer through national systems of innovation: climate relevant innovation-system builders (CRIBs). *Clim. Policy*, **16**, 836–854, https://doi.org/10.1080/14693062.2015.1052958.

——, A. Sagar, and H. de Coninck, 2015: Collaborative research and development (R&amp;D) for climate technology transfer and uptake in developing countries: towards a needs driven approach. *Clim. Change*, **131**, 401–415, https://doi.org/10.1007/s10584-014-1123-2.

——, R. Byrne, U. E. Hansen, J. Haselip, and I. Nygaard, 2018: The uptake and diffusion of solar power in Africa: Socio-cultural and political insights on a rapidly emerging socio-technical transition. *Energy Res. Soc. Sci.*, **44**, 122–129, https://doi.org/10.1016/j.erss.2018.04.033.

OECD, 2005: *Oslo manual : guidelines for collecting and interpreting technological innovation data.* Organisation for Economic Co-operation and Development. Statistical Office of the European Communities., 163 pp.

——, 2006: *Innovation in energy technology: Comparing national innovation systems at sectoral level*.

——, 2011a: *Industrial Biotechnology and Climate Change: Opportunities and Challenges*.

——, 2011b: *Tools for delivering green growth*.

——, 2015a: *Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development, The Measurement of Scientific Technological and Innovation Activities*.

——, 2015b: *Green Investment Banks*. 1–20 pp.

——, 2017: *OECD Digital Economy Outlook 2017*. OECD,.

——, and ITF, 2020: *Good to go? Assessing the environmental performance of new mobility*. 87 pp.

Oh, C., 2020: Contestations over the financial linkages between the UNFCCC's Technology and Financial Mechanism: using the lens of institutional interaction. *Int. Environ. Agreements Polit. Law Econ.*, **20**, 559–575, https://doi.org/10.1007/s10784-020-09474-8.

Ohl, R. S., 1946: Light-sensitive electric device.

Olawuyi, D. S., 2018: From technology transfer to technology absorption: addressing climate technology gaps in Africa. *J. Energy Nat. Resour. Law*, **36**, 61–84, https://doi.org/10.1080/02646811.2017.1379667.

Olhoff, A., 2015: Adaptation in the context of technology development and transfer. *Clim. Policy*, **15**, 163–169, https://doi.org/10.1080/14693062.2014.873665.

Olsson, O., and B. S. Frey, 2002: Entrepreneurship as recombinant growth. *Small Bus. Econ.*, https://doi.org/10.1023/A:1016261420372.

Otto, I. M., and Coauthors, 2020: Social tipping dynamics for stabilizing Earth's climate by 2050. *Proc. Natl. Acad. Sci.*, **117**, 2354–2365, https://doi.org/10.1073/pnas.1900577117.

Pagani, R. N., G. Zammar, J. L. Kovaleski, and L. M. Resende, 2016: Technology transfer models: typology and a generic model. *Int. J. Technol. Transf. Commer.*, **14**, 20, https://doi.org/10.1504/IJTTC.2016.079923.

Pandey, N., H. de Coninck, and A. D. Sagar, Beyond technology transfer: Innovation cooperation to advance sustainable development in developing countries. *WIREs Energy Environ.*,.

Parida, V., D. Sjödin, and W. Reim, 2019: Reviewing Literature on Digitalization, Business Model Innovation, and Sustainable Industry: Past Achievements and Future Promises. *Sustainability*, **11**, 391, https://doi.org/10.3390/su11020391.

Paroussos, L., K. Fragkiadakis, and P. Fragkos, 2020: Macro-economic analysis of green growth policies: the role of finance and technical progress in Italian green growth. *Clim. Change*, **160**, 591–608, https://doi.org/10.1007/s10584-019-02543-1.

Pascual, U., and Coauthors, 2017: Valuing nature's contributions to people: the IPBES approach. *Curr. Opin. Environ. Sustain.*, **26–27**, 7–16, https://doi.org/10.1016/j.cosust.2016.12.006.

Patt, A., O. van Vliet, J. Lilliestam, and S. Pfenninger, 2019: Will policies to promote energy efficiency help or hinder achieving a 1.5 °C climate target? *Energy Effic.*, **12**, 551–565, https://doi.org/10.1007/s12053-018-9715-8.

Penasco, C., L. D. Anadon, and E. Verdolini, 2020: Systematic Review of the ouctomes and tradeoffs of ten decarbonisation policy instruments. *Nat. Clim. Chang.*,.

Pengue, W., and Coauthors, 2018: 'Eco-agri-food systems': today's realities and tomorrow's challenges. *TEEB for Agriculture & Food: Scientific and Economic Foundations*, UN Environment, 57–109.

Pereirinha, P. G., M. González, I. Carrilero, D. Anseán, J. Alonso, and J. C. Viera, 2018: Main Trends and Challenges in Road Transportation Electrification. *Transp. Res. Procedia*, **33**, 235–242, https://doi.org/10.1016/j.trpro.2018.10.096.

Perlin, J., 1999: From space to Earth: the story of solar electricity. *From Space to Earth*.

Persoon, P. G. J., R. N. A. Bekkers, and F. Alkemade, 2020: The science base of renewables. *Technol. Forecast. Soc. Change*, **158**, 120121, https://doi.org/10.1016/j.techfore.2020.120121.

Pless, J., 2019: Are "Complementary Policies" Substitutes? Evidence from R&amp;amp;D Subsidies in the UK. *SSRN Electron. J.*, 57, https://doi.org/10.2139/ssrn.3379256.

Popp, D., 2002: Induced Innovation and Energy Prices. *Am. Econ. Rev.*, **92**, 160–180, https://doi.org/10.1257/000282802760015658.

——, 2004: ENTICE: endogenous technological change in the DICE model of global warming. *J. Environ. Econ. Manage.*, **48**, 742–768, https://doi.org/10.1016/j.jeem.2003.09.002.

——, 2019: International Review of Environmental and Resource Economics. *Int. Rev. Environ. Resour. Econ.*, **13**, 265–337, https://doi.org/10.1561/101.00000111.

——, and R. Newell, 2012: Where does energy R&D come from? Examining crowding out from energy R&amp;D. *Energy Econ.*, **34**, 980–991, https://doi.org/10.1016/j.eneco.2011.07.001.

Pretty, J., C. Toulmin, and S. Williams, 2011: Sustainable intensification in African agriculture. *Int. J. Agric. Sustain.*, **9**, 5–24, https://doi.org/10.3763/ijas.2010.0583.

Probst, B., V. Anatolitis, A. Kontoleon, and L. D. Anadón, 2020a: The short-term costs of local content requirements in the Indian solar auctions. *Nat. Energy*, **5**, 842–850, https://doi.org/10.1038/s41560-020-0677-7.

——, L. Westermann, A. Kontoleon, and L. D. Anadon, 2020b: Leveraging private investment to expand renewable power generation: Evidence on financial additionality and productivity gains from Uganda. *World Dev.*,.

Qiu, Y., and L. D. Anadon, 2012: The price of wind power in China during its expansion: Technology adoption, learning-by-doing, economies of scale, and manufacturing localization. *Energy Econ.*, **34**, 772–785, https://doi.org/10.1016/j.eneco.2011.06.008.

Quan, S. J., J. Park, A. Economou, and S. Lee, 2019: Artificial intelligence-aided design: Smart Design for sustainable city development. *Environ. Plan. B Urban Anal. City Sci.*, **46**, 1581–1599, https://doi.org/10.1177/2399808319867946.

Quirapas, M. A. J. R., and A. Taeihagh, 2020: Ocean renewable energy development in Southeast Asia: Opportunities, risks and unintended consequences. *Renew. Sustain. Energy Rev.*, 110403, https://doi.org/10.1016/j.rser.2020.110403.

Quitzow, R., 2015: Dynamics of a policy-driven market: The co-evolution of technological innovation systems for solar photovoltaics in China and Germany. *Environ. Innov. Soc. Transitions*, **17**, 126–148, https://doi.org/10.1016/j.eist.2014.12.002.

Ramos-Mejía, M., M.-L. Franco-Garcia, and J. M. Jauregui-Becker, 2018: Sustainability transitions in the developing world: Challenges of socio-technical transformations unfolding in contexts of poverty. *Environ. Sci. Policy*, **84**, 217–223, https://doi.org/10.1016/j.envsci.2017.03.010.

De Rassenfosse, G., H. Dernis, D. Guellec, L. Picci, and B. Van Pottelsberghe De La Potterie, 2013: The worldwide count of priority patents: A new indicator of inventive activity. *Res. Policy*, **42**, https://doi.org/10.1016/j.respol.2012.11.002.

Reder, M. W., and J. R. Hicks, 1965: The Theory of Wages. *Economica*, **32**, 88, https://doi.org/10.2307/2552450.

Reichman, J., 2009: Compulsory Licensing of Patented Pharmaceutical Inventions: Evaluating the Options. *J. Law, Med. Ethics*, **37**, 247–263.

Reinders, F. B., 2020: New products and emerging irrigation technologies in light of the ICID vision 2030. *Irrig. Drain.*, **69**, 294–298, https://doi.org/10.1002/ird.2432.

Reitzig, M., J. Henkel, and C. Heath, 2007: On sharks, trolls, and their patent prey—Unrealistic damage awards and firms' strategies of "being infringed." *Res. Policy*, **36**, 134–154, https://doi.org/10.1016/j.respol.2006.10.003.

Remer, D. S., and F. B. Mattos, 2003: Cost and scale-up factors, international inflation indexes and location factors. *Int. J. Prod. Econ.*, **84**, 1–16, https://doi.org/10.1016/S0925-5273(02)00374-2.

Repo, P., and K. Matschoss, 2019: Social Innovation for Sustainability Challenges. *Sustainability*, **12**, 319, https://doi.org/10.3390/su12010319.

RESA, 2001: Act on Granting Priority to Renewable Energy Sources (Renewable Energy Sources Act, Germany, 2000). *Sol. Energy*, **70**, 489–504, https://doi.org/10.1016/S0038-092X(00)00144-4.

Riahi, K., and Coauthors, 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.*, **42**, 153–168, https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Rihani, S., 2002: Implications of adopting a complexity framework for development. *Prog. Dev. Stud.*, **2**, 133–143, https://doi.org/10.1191/1464993402ps033pr.

Rikap, C., 2020: Amazon: A story of accumulation through intellectual rentiership and predation. *Compet. Chang.*, 102452942093241, https://doi.org/10.1177/1024529420932418.

del Río, P., 2010: Analysing the interactions between renewable energy promotion and energy efficiency support schemes: The impact of different instruments and design elements. *Energy Policy*, **38**, 4978–4989, https://doi.org/10.1016/j.enpol.2010.04.003.

——, and E. Cerdá, 2014: The policy implications of the different interpretations of the cost-effectiveness of renewable electricity support. *Energy Policy*, **64**, 364–372, https://doi.org/10.1016/j.enpol.2013.08.096.

——, and ——, 2017: The missing link: The influence of instruments and design features on the interactions between climate and renewable electricity policies. *Energy Res. Soc. Sci.*, **33**, 49–58, https://doi.org/10.1016/j.erss.2017.09.010.

Rivera-Batiz, L. A., and P. M. Romer, 1991: Economic Integration and Endogenous Growth. *Q. J. Econ.*, **106**, 531, https://doi.org/10.2307/2937946.

Roberts, C., F. W. Geels, M. Lockwood, P. Newell, H. Schmitz, B. Turnheim, and A. Jordan, 2018: The politics of accelerating low-carbon transitions: Towards a new research agenda. *Energy Res. Soc. Sci.*, **44**, 304–311, https://doi.org/10.1016/j.erss.2018.06.001.

Rogers, D., and V. Tsirkunov, 2010: Costs and benefits of Early Warning Systems. *Global Assessment Report on Disaster Risk Reduction,* International Stragey for Disaster Reduction (ISDR) - The World Bank, 1–17.

Rogers, E. M., 2003: *Diffusion of innovations*. 5th ed. Free Press,.

Rogge, K. S., and K. Reichardt, 2016: Policy mixes for sustainability transitions: An extended concept and framework for analysis. *Res. Policy*, **45**, 1620–1635, https://doi.org/10.1016/j.respol.2016.04.004.

——, F. Kern, and M. Howlett, 2017: Conceptual and empirical advances in analysing policy mixes for energy transitions. *Energy Res. Soc. Sci.*, **33**, 1–10, https://doi.org/10.1016/j.erss.2017.09.025.

Rolnick, D., and Coauthors, 2019: Tackling Climate Change with Machine Learning. 111.

Romer, P. M., 1990: Endogenous Technological Change. *J. Polit. Econ.*, **98**, S71–S102, https://doi.org/10.1086/261725.

Romero-Lankao, P., and Coauthors, 2018: Urban transformative potential in a changing climate. *Nat. Clim. Chang.*, **8**, 754–756, https://doi.org/10.1038/s41558-018-0264-0.

De Rose, A., M. Buna, C. Strazza, N. Olivieri, T. Stevens, P. Leen, and T.-J. Daniel, 2017: *Technology Readiness Level : Guidance Principles for Renewable Energy technologies*. European Commission, 48 pp.

Rosenberg, N., 1996: Uncertainty and Technological Change. *The Economic Impact of Knowledge,* Elsevier, 17–34.

Rover, O. J., B. C. de Gennaro, and L. Roselli, 2017: Social innovation and sustainable rural development: The case of a Brazilian agroecology network. *Sustain.*, **9**, https://doi.org/10.3390/su9010003.

Rubin, E. S., I. M. L. Azevedo, P. Jaramillo, and S. Yeh, 2015: A review of learning rates for electricity supply technologies. *Energy Policy*, **86**, 198–218, https://doi.org/10.1016/j.enpol.2015.06.011.

Rubio, S. J., 2017: Sharing R&amp;D investments in breakthrough technologies to control climate change. *Oxf. Econ. Pap.*, **69**, gpw067, https://doi.org/10.1093/oep/gpw067.

Ruby, T. M., 2015: Innovation-enabling policy and regime transformation towards increased energy efficiency: the case of the circulator pump industry in Europe. *J. Clean. Prod.*, **103**, 574–585, https://doi.org/10.1016/j.jclepro.2015.02.017.

Sadras, V. O., 2020: Agricultural technology is unavoidable, directional, combinatory, disruptive, unpredictable and has unintended consequences. *Outlook Agric.*, **49**, 293–297, https://doi.org/10.1177/0030727020960493.

Sagar, A., and A. Majumdar, 2014: *Facilitating a sustainability transition in developing countries: proposal for a global Advanced Research Project Agency for Sustainable Development*. 30 pp.

Sagar, A. D., and J. P. Holdren, 2002: Assessing the global energy innovation system: some key issues. *Energy Policy*, **30**, 465–469, https://doi.org/10.1016/S0301-4215(01)00117-3.

Sagar, A. D., C. Bremner, and M. Grubb, 2009: Climate Innovation Centres: A partnership approach to meeting energy and climate challenges. *Nat. Resour. Forum*, **33**, 274–284, https://doi.org/10.1111/j.1477-8947.2009.001252.x.

Samadi, S., 2018: The experience curve theory and its application in the field of electricity generation technologies – A literature review. *Renew. Sustain. Energy Rev.*, **82**, 2346–2364, https://doi.org/10.1016/j.rser.2017.08.077.

Samuelson, P. A., 1965: A Theory of Induced Innovation along Kennedy-Weisacker Lines. *Rev. Econ. Stat.*, **47**, 343, https://doi.org/10.2307/1927763.

Sanchez, D. L., and V. Sivaram, 2017: Saving innovative climate and energy research: Four recommendations for Mission Innovation. *Energy Res. Soc. Sci.*, **29**, 123–126, https://doi.org/10.1016/j.erss.2017.05.022.

Sanni, M., C. M. Adelowo, D. A. Ogunkanbi, A. A. Oyewale, A. D. Dada, and B. R. Muritala, 2016: Climate change and intellectual property rights in Africa: Environmental necessity-economic opportunity. *African J. Sci. Technol. Innov. Dev.*, **8**, 377–385, https://doi.org/10.1080/20421338.2016.1219482.

Sanyal, P., and L. R. Cohen, 2009: Powering Progress: Restructuring, Competition, and R&D in the U.S. Electric Utility Industry. *Energy J.*, **30**, 41–79.

Sarker, M. N. I., M. Wu, G. M. Alam, and R. C. Shouse, 2020: Livelihood resilience of riverine island dwellers in the face of natural disasters: Empirical evidence from Bangladesh. *Land use policy*, **95**, 104599, https://doi.org/10.1016/j.landusepol.2020.104599.

Sarr, M., and T. Swanson, 2017: Will Technological Change Save the World? The Rebound Effect in International Transfers of Technology. *Environ. Resour. Econ.*, **66**, 577–604, https://doi.org/10.1007/s10640-016-0093-4.

Sawulski, J., and J. Witajewski-Baltvilks, 2020: Optimal Diversity in Auctions for Renewable Energy Sources under Technological Uncertainty. *Int. Rev. Environ. Resour. Econ.*, **14**, 299–347, https://doi.org/10.1561/101.00000118.

Schindele, S., and Coauthors, 2020: Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications. *Appl. Energy*, **265**, 114737, https://doi.org/10.1016/j.apenergy.2020.114737.

Schmid, N., S. Sewerin, and T. S. Schmidt, 2020: Explaining Advocacy Coalition Change with Policy Feedback. *Policy Stud. J.*, **48**, 1109–1134, https://doi.org/10.1111/psj.12365.

Schmidt, T. S., and S. Sewerin, 2017: Technology as a driver of climate and energy politics. *Nat. Energy*, **2**, 17084, https://doi.org/10.1038/nenergy.2017.84.

——, and ——, 2019: Measuring the temporal dynamics of policy mixes – An empirical analysis of renewable energy policy mixes' balance and design features in nine countries. *Res. Policy*, **48**, 103557, https://doi.org/10.1016/j.respol.2018.03.012.

Schumpeter, J. A., 1934: *The Theory of Economic Development*. Harvard University Press,.

Scoones, I., 2015: *The Politics of Green Transformations*. 1st Editio. Routledge, 238 pp.

Scotchmer, S., 1991: Standing on the Shoulders of Giants: Cumulative Research and the Patent Law. *J. Econ. Perspect.*, **5**, 29–41.

Scotchmer, S., and J. Green, 1990: Novelty and Disclosure in Patent Law. *RAND J. Econ.*, **21**, 131, https://doi.org/10.2307/2555499.

Seebregts, A., T. Kram, G. Schaeffer, A. Stoffer, S. Kypreos, L. Barreto, and L. Messner, S Schrattenholzer, 1998: Endogenous Technological Change in Energy Systems Models: Synthesis of Experience with ERIS, MARKAL, and MESSAGE. *Paul Scherrer Institute, IIASA , Villigen, Switz. IIASA, Laxenburg, Austria,* https://doi.org/ECN-C-99-025.

Sen, A., 1990: Development as Capability Expansion. *Human Development and the International Development Strategy for the 1990s*.

Sendzimir, J., C. P. Reij, and P. Magnuszewski, 2011: Rebuilding Resilience in the Sahel: Regreening in the Maradi and Zinder Regions of Niger. *Ecol. Soc.*, **16**, art1, https://doi.org/10.5751/ES-04198-160301.

Seres, S., E. Haites, and K. Murphy, 2009: Analysis of technology transfer in CDM projects: An update. *Energy Policy*, **37**, 4919–4926, https://doi.org/10.1016/j.enpol.2009.06.052.

Serrenho, T., and P. Bertoldi, 2019: *Smart home and appliances: State of the art*. 1st ed. European Commission Joint Research Center, Ed. Publications Office of the European Union, 1–59 pp.

Shapiro, C., 2001: Navigating the Patent Thicket: Cross Licences, Patent Pools and Standard Setting BT - Innovation Policy and the Economy. *Innovation Policy and the Economy*.

Sierzchula, W., and G. Nemet, 2015: Using patents and prototypes for preliminary evaluation of technology-forcing policies: Lessons from California’s Zero Emission Vehicle regulations. *Technol. Forecast. Soc. Change*, **100**, 213–224, https://doi.org/10.1016/j.techfore.2015.07.003.

da Silva, V. L., J. L. Kovaleski, and R. N. Pagani, 2019: Technology transfer in the supply chain oriented to industry 4.0: a literature review. *Technol. Anal. Strateg. Manag.*, **31**, 546–562, https://doi.org/10.1080/09537325.2018.1524135.

Singh, R. P., R. Handa, and G. Manchanda, 2020: Nanoparticles in sustainable agriculture: An emerging opportunity. *J. Control. Release*, https://doi.org/10.1016/j.jconrel.2020.10.051.

Sivaram, V., 2019: *Taming the Sun: Innovations to Harness Solar Energy and Power the Planet*. MIT Press, 392 pp.

Skelton, A. C. H., L. Paroussos, and J. M. Allwood, 2020: Comparing energy and material efficiency rebound effects: an exploration of scenarios in the GEM-E3 macroeconomic model. *Ecol. Econ.*, **173**, 106544, https://doi.org/10.1016/j.ecolecon.2019.106544.

Skene, K. R., 2020: No goal is an island: the implications of systems theory for the Sustainable Development Goals. *Environ. Dev. Sustain.*, https://doi.org/10.1007/s10668-020-01043-y.

van Sluisveld, M. A. E., A. F. Hof, S. Carrara, F. W. Geels, M. Nilsson, K. Rogge, B. Turnheim, and D. P. van Vuuren, 2020: Aligning integrated assessment modelling with socio-technical transition insights: An application to low-carbon energy scenario analysis in Europe. *Technol. Forecast. Soc. Change*, **151**, 119177, https://doi.org/10.1016/j.techfore.2017.10.024.

Solow, R. M., 1957: Technical change and the aggregate production function. *Rev. Econ. Stat.*, **39**, 312–320.

Somanathan, E., and Coauthors, 2014: National and Sub-national Policies and Institutions. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, O. Edenhofer et al., Eds., Cambridge University Press, 1141–1205.

Song, Y., T. Yang, and M. Zhang, 2019: Research on the impact of environmental regulation on enterprise technology innovation—an empirical analysis based on Chinese provincial panel data. *Environ. Sci. Pollut. Res.*, **26**, 21835–21848, https://doi.org/10.1007/s11356-019-05532-0.

Sorrell, S., 2015: Reducing energy demand: A review of issues, challenges and approaches. *Renew. Sustain. Energy Rev.*, **47**, 74–82, https://doi.org/10.1016/j.rser.2015.03.002.

——, E. O’Malley, J. Schleich, S. Scott, E. O’Malley, J. Schleich, and S. Scott, 2004: *The Economics of Energy Efficiency*. Edward Elgar Publishing, 360 pp.

Soto Golcher, C., and I. J. Visseren-Hamakers, 2018: Framing and integration in the global forest, agriculture and climate change nexus. *Environ. Plan. C Polit. Sp.*, **36**, 1415–1436, https://doi.org/10.1177/2399654418788566.

Spence, A. M., 1981: The Learning Curve and Competition. *Bell J. Econ.*, **12**, 49, https://doi.org/10.2307/3003508.

Stavins, R., and Coauthors, 2014: International Cooperation: Agreements and Instruments. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, O. Edenhofer et al., Eds., Cambridge University Press, 1001–1082.

Steneck, N. H., 2006: Fostering integrity in research: Definitions, current knowledge, and future directions. *Science and Engineering Ethics*, Vol. 12 of, 53–74.

Stern, N., 2007: *The Economics of Climate Change*. Cambridge University Press, Volume 39 pp.

Stiglitz, J. E., 2008: Economic foundations of intellectual property rights. *Duke Law J.*, **57**, 1693–1724.

Stilgoe, J., R. Owen, and P. Macnaghten, 2013: Developing a framework for responsible innovation. *Res. Policy*, **42**, 1568–1580, https://doi.org/10.1016/j.respol.2013.05.008.

Stocker, T. F., 2013: The Closing Door of Climate Targets. *Science (80-. ).*, **339**, 280–282, https://doi.org/10.1126/science.1232468.

Stokes, L. C., 2016: Electoral Backlash against Climate Policy: A Natural Experiment on Retrospective Voting and Local Resistance to Public Policy. *Am. J. Pol. Sci.*, **60**, 958–974, https://doi.org/10.1111/ajps.12220.

Stokes, L. C., and C. Warshaw, 2017: Renewable energy policy design and framing influence public support in the United States. *Nat. Energy*, **2**, 17107, https://doi.org/10.1038/nenergy.2017.107.

——, and H. L. Breetz, 2018: Politics in the U.S. energy transition: Case studies of solar, wind, biofuels and electric vehicles policy. *Energy Policy*, **113**, 76–86, https://doi.org/10.1016/j.enpol.2017.10.057.

Stoll, C., L. Klaaßen, and U. Gallersdörfer, 2019: The Carbon Footprint of Bitcoin. *Joule*, **3**, 1647–1661, https://doi.org/10.1016/j.joule.2019.05.012.

Sue Wing, I., 2006: Representing induced technological change in models for climate policy analysis. *Energy Econ.*, **28**, 539–562, https://doi.org/10.1016/j.eneco.2006.05.009.

——, 2008: Explaining the declining energy intensity of the U.S. economy. *Resour. Energy Econ.*, **30**, 21–49, https://doi.org/10.1016/j.reseneeco.2007.03.001.

Sundaramoorthy, S., and A. Walia, 2017: India's experience in implementing strategic schemes to enhance appliance energy efficiency & futuristic integrated policy approaches to adopt most efficient technologies. *ECEEE 2017 Summer Study – Consum. Effic. Limits*,.

Supran, G., and N. Oreskes, 2017: Assessing ExxonMobil's climate change communications (1977–2014). *Environ. Res. Lett.*, **12**, 084019, https://doi.org/10.1088/1748-9326/aa815f.

Surana, K., and L. D. Anadon, 2015: Public policy and financial resource mobilization for wind energy in developing countries: A comparison of approaches and outcomes in China and India. *Glob. Environ. Chang.*, **35**, 340–359, https://doi.org/10.1016/j.gloenvcha.2015.10.001.

——, C. Doblinger, L. D. Anadon, and N. Hultman, 2020a: Effects of technology complexity on the emergence and evolution of wind industry manufacturing locations along global value chains. *Nat. Energy*, **5**, 811–821, https://doi.org/10.1038/s41560-020-00685-6.

——, A. Singh, and A. D. Sagar, 2020b: Strengthening science, technology, and innovation-based incubators to help achieve Sustainable Development Goals: Lessons from India. *Technol. Forecast. Soc. Change*, **157**, 120057, https://doi.org/10.1016/j.techfore.2020.120057.

——, E. Williams, W. Krawczyk, M. Montgomery, J. O'Neill, Z. Thomas, and Y. Zhang, 2020c: *Regional Clean Energy Innovation*.

Sutherland, R. J., 2006: The Distributional Effects of Direct Regulation: A Case Study of Energy Efficiency Appliance Standards. *The Distributional Effects of Environmental Policy*, Serret; and

P. Johnstone, Eds., Edward Elgar Publishing.

Sweerts, B., R. J. Detz, and B. van der Zwaan, 2020: Evaluating the Role of Unit Size in Learning-by-Doing of Energy Technologies. *Joule*, **4**, 967–970, https://doi.org/10.1016/j.joule.2020.03.010.

Swilling, M., J. Musango, and J. Wakeford, 2016: Developmental States and Sustainability Transitions: Prospects of a Just Transition in South Africa. *J. Environ. Policy Plan.*, **18**, 650–672, https://doi.org/10.1080/1523908X.2015.1107716.

Tassey, G., 2014: Competing in Advanced Manufacturing: The Need for Improved Growth Models and Policies. *J. Econ. Perspect.*, **28**, 27–48, https://doi.org/10.1257/jep.28.1.27.

Taylor, M. R., 2012: Innovation under cap-and-trade programs. *Proc. Natl. Acad. Sci.*, **109**, 4804–4809, https://doi.org/10.1073/pnas.1113462109.

Technology Executive Committee, 2015: *TEC Brief #7: Strengthening National Systems of Innovationto Enhance Action on Climate Change*. 12 pp.

——, 2017: *Enhancing financing for the research, development and demonstration of climate technologies*. 26 pp.

——, 2021: Compilation of Good practices and lessons learned on international collaborative research, development and demonstration initiatives of climate technology.

TEEB, 2018: *TEEB for Agriculture & Food: Scientific and Economic Foundations*. UN Environment,.

Tigabu, A. D., 2018: Analysing the diffusion and adoption of renewable energy technologies in Africa: The functions of innovation systems perspective. *African J. Sci. Technol. Innov. Dev.*, **10**, 615–624, https://doi.org/10.1080/20421338.2017.1366130.

Tigabu, A. D., F. Berkhout, and P. van Beukering, 2015: Functional evolution and accumulation of technological innovation systems: The case of renewable energy in East Africa. *Sci. Public Policy*, **42**, 614–631, https://doi.org/10.1093/scipol/scu073.

Timilsina, R., 2020: *Demystifying the Costs of Electricity Generation Technologies*. 39 pp.

Tittonell, P., 2014: Ecological intensification of agriculture—sustainable by nature. *Curr. Opin. Environ. Sustain.*, **8**, 53–61, https://doi.org/10.1016/j.cosust.2014.08.006.

Toke, D., 2015: Renewable Energy Auctions and Tenders: How good are they? *Int. J. Sustain. Energy Plan. Manag.*, **8**, 43–56, https://doi.org/https://doi.org/10.5278/ijsepm.2015.8.5.

Tonn, B. E., and D. Stiefel, 2019: Anticipating the Unanticipated-Unintended Consequences of Scientific and Technological Purposive Actions. *World Futur. Rev.*, **11**, 19–50, https://doi.org/10.1177/1946756718789413.

Townsend, R., and Coauthors, 2019: *Future of Food : Harnessing Digital Technologies to Improve Food System Outcomes*. 44 pp.

Trajtenberg, M., 2018: *AI as the next GPT: a Political-Economy Perspective*.

Trianni, A., E. Cagno, and E. Worrell, 2013: Innovation and adoption of energy efficient technologies: An exploratory analysis of Italian primary metal manufacturing SMEs. *Energy Policy*, **61**, 430–440, https://doi.org/10.1016/j.enpol.2013.06.034.

Trutnevyte, E., L. F. Hirt, N. Bauer, A. Cherp, A. Hawkes, O. Y. Edelenbosch, S. Pedde, and D. P. van Vuuren, 2019: Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. *One Earth*, **1**, 423–433, https://doi.org/10.1016/j.oneear.2019.12.002.

Tsur, Y., and A. Zemel, 2007: Towards endogenous recombinant growth. *J. Econ. Dyn. Control*, **31**, 3459–3477, https://doi.org/10.1016/j.jedc.2006.12.002.

Turner, R., P. McConney, and I. Monnereau, 2020: Climate Change Adaptation and Extreme Weather in the Small-Scale Fisheries of Dominica. *Coast. Manag.*, **48**, 436–455, https://doi.org/10.1080/08920753.2020.1795970.

Turnheim, B., F. Berkhout, F. Geels, A. Hof, A. McMeekin, B. Nykvist, and D. van Vuuren, 2015: Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Glob. Environ. Chang.*, **35**, 239–253, https://doi.org/10.1016/j.gloenvcha.2015.08.010.

Twomey, P., 2012: Rationales for Additional Climate Policy Instruments under a Carbon Price. *Econ. Labour Relations Rev.*, **23**, 7–31, https://doi.org/10.1177/103530461202300102.

U.S. National Academies of Sciences Engineering and Medicine, 2017: *An Assessment of ARPA-E*.

Ugur, M., and A. Mitra, 2017: Technology Adoption and Employment in Less Developed Countries: A Mixed-Method Systematic Review. *World Dev.*, **96**, 1–18, https://doi.org/10.1016/j.worlddev.2017.03.015.

Ulsrud, K., H. Rohracher, and C. Muchunku, 2018: Spatial transfer of innovations: South-South learning on village-scale solar power supply between India and Kenya. *Energy Policy*, **114**, 89–97, https://doi.org/10.1016/j.enpol.2017.11.064.

UN Environment, Frankfurt School, and Bloomberg New Energy Initiative, 2020: *Global Trends in Renewable Energy Investment 2020*. 76 pp.

UNEP, 2013: *Assessing Global Land Use: Balancing Consumption with Sustainable Supply. A Report of the Working Group on Land and Soils of the International Resource Panel*. S. Bringezu et al., Eds. UN Environment, 46 pp.

——, 2015: *Policy Coherence of the Sustainable Development Goals A Natural Resource Perspective*. UNEP, 29 pp.

——, 2017: *Assessing global resource use: A systems approach to resource efficiency and pollution reduction*. S. Bringezu et al., Eds. United Nations Environment Programme,.

UNFCCC, 2015: *Paris Agreement*. 32 pp.

——, 2016: Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015. FCCC/CP/2015/10/Add.1.

——, 2020a: Paris Committee on Capacity-building Review report on the status and progress of work under the Strategic Plan for Stakeholder Engagement, Communications and Resource Mobilization (June 2019–June 2020). 13.

——, 2020b: Workplan of the Paris Committee on Capacity-building for 2021–2024.

Unruh, G. C., 2000: Understanding carbon lock-in. *Energy Policy*, **28**, 817–830, https://doi.org/10.1016/S0301-4215(00)00070-7.

Unruh, G. C., 2002: Escaping carbon lock-in. *Energy Policy*, **30**, 317–325, https://doi.org/10.1016/S0301-4215(01)00098-2.

Upadhyaya, P., M. K. Shrivastava, G. Gorti, and S. Fakir, 2020: Capacity building for proportionate climate policy: Lessons from India and South Africa. *Int. Polit. Sci. Rev.*, **0**, 019251212096388, https://doi.org/10.1177/0192512120963883.

Urban, F., 2018: China's rise: Challenging the North-South technology transfer paradigm for climate change mitigation and low carbon energy. *Energy Policy*, **113**, 320–330, https://doi.org/10.1016/j.enpol.2017.11.007.

US Department of Energy, 2011: *DOE G 413.3-4A, Technology Readiness Assessment Guide*. 73 pp.

Vanier, A., 2014: The Canada-FIT case and the WTO subsidies agreement: failed fact-finding, needless complexity, and missed judicial economy. *McGill J. Sustain. Dev. Law Policy*, **10**, 239–257.

Varian, H., 2018: *Artificial Intelligence, Economics, and Industrial Organization*. 24 pp.

Veefkind, V., J. Hurtado-Albir, S. Angelucci, K. Karachalios, and N. Thumm, 2012: A new EPO classification scheme for climate change mitigation technologies. *World Pat. Inf.*, **34**, 106–111, https://doi.org/10.1016/j.wpi.2011.12.004.

Verdolini, E., and M. Galeotti, 2011: At home and abroad: An empirical analysis of innovation and diffusion in energy technologies. *J. Environ. Econ. Manage.*, **61**, 119–134, https://doi.org/10.1016/j.jeem.2010.08.004.

——, and V. Bosetti, 2017: Environmental Policy and the International Diffusion of Cleaner Energy Technologies. *Environ. Resour. Econ.*, **66**, 497–536, https://doi.org/10.1007/s10640-016-0090-7.

——, L. D. Anadón, E. Baker, V. Bosetti, and L. Aleluia Reis, 2018: The Future Prospects of Energy Technologies: Insights from Expert Elicitations. *Rev. Environ. Econ. Policy*, **12**, 133–153, https://doi.org/10.1093/reep/rex028.

Verma, P., R. Savickas, S. M. Buettner, J. Strüker, O. Kjeldsen, and X. Wang, 2020: Digitalization: enabling the new phase of energy efficiency. *Group of Experts on Energy Efficiency Seventh session Geneva, 22 and 25 September 2020 Item 5 of the Annotated provisional agenda Regulatory and policy dialogue addressing barriers to improve energy efficiency*.

Vermeulen, S. J., B. M. Campbell, and J. S. I. Ingram, 2012: Climate Change and Food Systems. *Annu. Rev. Environ. Resour.*, **37**, 195–222, https://doi.org/10.1146/annurev-environ-020411-130608.

Veugelers, R., 2012: Which policy instruments to induce clean innovating? *Res. Policy*, **41**, 1770–1778, https://doi.org/10.1016/j.respol.2012.06.012.

Vinuesa, R., and Coauthors, 2020: The role of artificial intelligence in achieving the Sustainable Development Goals. *Nat. Commun.*, **11**, https://doi.org/10.1038/s41467-019-14108-y.

van Vliet, M., K. Kok, and T. Veldkamp, 2010: Linking stakeholders and modellers in scenario studies: The use of Fuzzy Cognitive Maps as a communication and learning tool. *Futures*, **42**, 1–14, https://doi.org/10.1016/j.futures.2009.08.005.

Vogel, B., D. Henstra, and G. McBean, 2020: Sub-national government efforts to activate and motivate local climate change adaptation: Nova Scotia, Canada. *Environ. Dev. Sustain.*, **22**, 1633–1653, https://doi.org/10.1007/s10668-018-0242-8.

Vranken, H., 2017: Sustainability of bitcoin and blockchains. *Curr. Opin. Environ. Sustain.*, **28**, 1–9, https://doi.org/10.1016/j.cosust.2017.04.011.

Wahlroos, M., M. Pärssinen, J. Manner, and S. Syri, 2017: Utilizing data center waste heat in district heating – Impacts on energy efficiency and prospects for low-temperature district heating networks. *Energy*, **140**, 1228–1238, https://doi.org/10.1016/j.energy.2017.08.078.

——, ——, S. Rinne, S. Syri, and J. Manner, 2018: Future views on waste heat utilization – Case of data centers in Northern Europe. *Renew. Sustain. Energy Rev.*, **82**, 1749–1764, https://doi.org/10.1016/j.rser.2017.10.058.

Wallerstein, M., M. Mogee, R. Schoen, and P. David, 1993: Intellectual property institutions and the panda's thumb: Patents, copyrights, and trade secrets in economic theory and history. *Global Dimensions of Intellectual Property Rights in Science and Technology*, M. Wallerstein, M. Mogee, and R. Schoen, Eds., National Academies Press, 19–62.

Walsh, H., A. Dong, and I. Tumer, 2019: Towards a Theory for Unintended Consequences in Engineering Design. *Proc. Des. Soc. Int. Conf. Eng. Des.*, **1**, 3411–3420, https://doi.org/10.1017/dsi.2019.348.

Wang, F., J. Yu, P. Yang, L. Miao, and B. Ye, 2017a: Analysis of the Barriers to Widespread Adoption of Electric Vehicles in Shenzhen China. *Sustainability*, **9**, 522, https://doi.org/10.3390/su9040522.

Wang, J., Y.-N. Lee, and J. P. Walsh, 2018: Funding model and creativity in science: Competitive versus block funding and status contingency effects. *Res. Policy*, **47**, 1070–1083, https://doi.org/10.1016/j.respol.2018.03.014.

Wang, Z., X. Wang, and D. Guo, 2017b: Policy implications of the purchasing intentions towards energy-efficient appliances among China's urban residents: Do subsidies work? *Energy Policy*,

**102**, 430–439, https://doi.org/10.1016/j.enpol.2016.12.049.

Watanabe, C., K. Wakabayashi, and T. Miyazawa, 2000: Industrial dynamism and the creation of a “virtuous cycle” between R&amp;D, market growth and price reduction. *Technovation,* **20**, 299–312, https://doi.org/10.1016/S0166-4972(99)00146-7.

Watkins, A., T. Papaioannou, J. Mugwagwa, and D. Kale, 2015: National innovation systems and the intermediary role of industry associations in building institutional capacities for innovation in developing countries: A critical review of the literature. *Res. Policy*, **44**, 1407–1418, https://doi.org/10.1016/j.respol.2015.05.004.

Way, R., F. Lafond, F. Lillo, V. Panchenko, and J. D. Farmer, 2019: Wright meets Markowitz: How standard portfolio theory changes when assets are technologies following experience curves. *J. Econ. Dyn. Control*, **101**, 211–238, https://doi.org/10.1016/j.jedc.2018.10.006.

Weber, K. M., and H. Rohracher, 2012: Legitimizing research, technology and innovation policies for transformative change. *Res. Policy*, **41**, 1037–1047, https://doi.org/10.1016/j.respol.2011.10.015.

——, and B. Truffer, 2017: Moving innovation systems research to the next level: towards an integrative agenda. *Oxford Rev. Econ. Policy*, **33**, 101–121, https://doi.org/10.1093/oxrep/grx002.

Wei, M., S. J. Smith, and M. D. Sohn, 2017: Non-constant learning rates in retrospective experience curve analyses and their correlation to deployment programs. *Energy Policy*, **107**, 356–369, https://doi.org/10.1016/j.enpol.2017.04.035.

Weingärtner, L., T. Pforr, and E. Wilkinson, 2020: *The evidence base on anticipatory action*. 48 pp.

Weiss, C., and W. B. Bonvillian, 2013: Legacy sectors: barriers to global innovation in agriculture and energy. *Technol. Anal. Strateg. Manag.*, **25**, 1189–1208, https://doi.org/10.1080/09537325.2013.843658.

Weiss, M., M. Junginger, M. K. Patel, and K. Blok, 2010: A review of experience curve analyses for energy demand technologies. *Technol. Forecast. Soc. Change*, **77**, 411–428, https://doi.org/10.1016/j.techfore.2009.10.009.

Weitzman, M. L., 1998: Recombinant Growth. *Q. J. Econ.*, **113**, 331–360, https://doi.org/10.1162/003355398555595.

Wesseling, J. H., and A. Van der Vooren, 2017: Lock-in of mature innovation systems: the transformation toward clean concrete in the Netherlands. *J. Clean. Prod.*, **155**, 114–124, https://doi.org/https://doi.org/10.1016/j.jclepro.2016.08.115.

Wesseling, J. H., J. C. M. Farla, and M. P. Hekkert, 2015: Exploring car manufacturers’ responses to technology-forcing regulation: The case of California’s ZEV mandate. *Environ. Innov. Soc. Transitions*, **16**, 87–105, https://doi.org/10.1016/j.eist.2015.03.001.

Westley, F., and Coauthors, 2011: Tipping Toward Sustainability: Emerging Pathways of Transformation. *Ambio,* **40**, 762–780, https://doi.org/10.1007/s13280-011-0186-9.

Weyant, J. P., 2011: Accelerating the development and diffusion of new energy technologies: Beyond the “valley of death.” *Energy Econ.*, **33**, 674–682, https://doi.org/10.1016/j.eneco.2010.08.008.

Wezel, A., G. Soboksa, S. McClelland, F. Delespesse, and A. Boissau, 2015: The blurred boundaries of ecological, sustainable, and agroecological intensification: a review. *Agron. Sustain. Dev.*, **35**, 1283–1295, https://doi.org/10.1007/s13593-015-0333-y.

——, B. G. Herren, R. B. Kerr, E. Barrios, A. L. R. Gonçalves, and F. Sinclair, 2020: Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agron. Sustain. Dev.*, **40**, 40, https://doi.org/10.1007/s13593-020-00646-z.

WHO, 2020: *The DOHA declaration on the trips agreement and public health*.

Wieczorek, A. J., and M. P. Hekkert, 2012: Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. *Sci. Public Policy*, **39**, 74–87, https://doi.org/10.1093/scipol/scr008.

——, S. O. Negro, R. Harmsen, G. J. Heimeriks, L. Luo, and M. P. Hekkert, 2013: A review of the European offshore wind innovation system. *Renew. Sustain. Energy Rev.*, **26**, 294–306, https://doi.org/10.1016/j.rser.2013.05.045.

Wiel, S., C. Egan, and M. delta Cava, 2006: Energy efficiency standards and labels provide a solid foundation for economic growth, climate change mitigation, and regional trade. *Energy Sustain. Dev.*, **10**, 54–63, https://doi.org/10.1016/S0973-0826(08)60544-X.

Wigand, F., S. Föster, A. Amazo, S. Tiedemann, S. Förster, A. Amazo, and S. Tiedemann, 2016: *Auctions for Renewable Energy Support: effective use and efficient implementation options.* 1–46 pp.

Williams, D. S., S. Rosendo, O. Sadasing, and L. Celliers, 2020: Identifying local governance capacity needs for implementing climate change adaptation in Mauritius. *Clim. Policy*, **20**, 548–562, https://doi.org/10.1080/14693062.2020.1745743.

Wilson, C., 2012: Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. *Energy Policy*, **50**, 81–94, https://doi.org/10.1016/j.enpol.2012.04.077.

Wilson, C., A. Grubler, N. Bento, S. Healey, S. De Stercke, and C. Zimm, 2020: Granular technologies to accelerate decarbonization. *Science (80-. ).*, **368**, 36–39, https://doi.org/10.1126/science.aaz8060.

WIPO, 2020: WIPO Member States.

Witajewski-Baltvilks, J., E. Verdolini, and M. Tavoni, 2015: Bending the learning curve. *Energy Econ.*, **52**, S86–S99, https://doi.org/10.1016/j.eneco.2015.09.007.

——, ——, and ——, 2017: Induced technological change and energy efficiency improvements. *Energy Econ.*, **68**, 17–32, https://doi.org/10.1016/j.eneco.2017.10.032.

World Bank, 2014: *World Development Indicators 2014*. The World Bank,.

World Intellectual Property Organization, 2008: *WIPO Intellectual Property Handbook: Policy, Law and Use*.

WTO, 1994: *Trade-Related Aspects of Intellectual Property Rights, Annex 1C of the Marrakesh Agreement Establishing the World Trade Organization*.

——, 2020: *Compulsory licensing of pharmaceuticals and TRIPS*.

Wu, F., 2016: Shaping China's Climate Diplomacy: Wealth, Status, and Asymmetric Interdependence. *J. Chinese Polit. Sci.*, **21**, 199–215, https://doi.org/10.1007/s11366-016-9404-4.

Yan, Z., K. Du, Z. Yang, and M. Deng, 2017: Convergence or divergence? Understanding the global development trend of low-carbon technologies. *Energy Policy*, **109**, 499–509, https://doi.org/10.1016/j.enpol.2017.07.024.

Yi, H., 2013: Clean energy policies and green jobs: An evaluation of green jobs in U.S. metropolitan areas. *Energy Policy*, **56**, 644–652, https://doi.org/10.1016/j.enpol.2013.01.034.

——, and Y. Liu, 2015: Green economy in China: Regional variations and policy drivers. *Glob. Environ. Chang.*, **31**, 11–19, https://doi.org/10.1016/j.gloenvcha.2014.12.001.

Youn, H., D. Strumsky, L. M. A. Bettencourt, and J. Lobo, 2015: Invention as a combinatorial process: evidence from US patents. *J. R. Soc. Interface*, **12**, 20150272, https://doi.org/10.1098/rsif.2015.0272.

Young, A., 1993: Invention and Bounded Learning by Doing. *J. Polit. Econ.*, **101**, 443–472, https://doi.org/10.1086/261882.

Yu, C. F., W. G. J. H. M. van Sark, and E. A. Alsema, 2011: Unraveling the photovoltaic technology learning curve by incorporation of input price changes and scale effects. *Renew. Sustain. Energy*

*Rev.*, **15**, 324–337, https://doi.org/10.1016/j.rser.2010.09.001.

Zangheri, Serrenho, and Bertoldi, 2019: Energy Savings from Feedback Systems: A Meta-Studies' Review. *Energies*, **12**, 3788, https://doi.org/10.3390/en12193788.

Zhan, L., M. Ju, and J. Liu, 2011: Improvement of China Energy Label System to Promote Sustainable Energy Consumption. *Energy Procedia*, **5**, 2308–2315, https://doi.org/10.1016/j.egypro.2011.03.397.

Zhang, L., H. Liu, and J. Wu, 2017: The price premium for green-labelled housing: Evidence from China. *Urban Stud.*, **54**, 3524–3541, https://doi.org/10.1177/0042098016668288.

Zhang, N., Y. Choi, and W. Wang, 2019: Does energy research funding work? Evidence from the Natural Science Foundation of China using TEI@I method. *Technol. Forecast. Soc. Change*, **144**, 369–380, https://doi.org/10.1016/j.techfore.2018.02.001.

Zhou, C., 2019a: Enabling Law and Policy Environment for Climate Technology Transfer: From Perspectives of Host Countries. *J. East Asia Int. Law*, **12**, 45–70, https://doi.org/10.14330/jeail.2019.12.1.03.

——, 2019b: Can intellectual property rights within climate technology transfer work for the UNFCCC and the Paris Agreement? *Int. Environ. Agreements Polit. Law Econ.*, **19**, 107–122, https://doi.org/10.1007/s10784-018-09427-2.

Zhou, N., M. D. Levine, and L. Price, 2010: Overview of current energy-efficiency policies in China. *Energy Policy*, **38**, 6439–6452, https://doi.org/10.1016/j.enpol.2009.08.015.

Zhuang, W., 2017: *Intellectual Property Rights and Climate Change*. Cambridge University Press, 428 pp.

Ziervogel, G., J. Enqvist, L. Metelerkamp, and J. van Breda, Supporting transformative climate adaptation: Community-level capacity building and knowledge co-creation in South Africa. *Clim. Policy*,.