Energy Technology Perspectives 2020

Special Report on Clean Energy Innovation

Accelerating technology progress for a sustainable future

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Foreword

There is no doubt that the energy sector will only reach net-zero emissions if there is a significant and concerted global push to accelerate innovation. It is also clear that there is a disconnect between the climate goals that governments and companies have set for themselves and the efforts underway to develop better and cheaper technologies to realise those goals. While we have witnessed tremendous progress in technologies like solar PV, wind turbines and lithium-ion batteries, the technological advances that will be needed demand a step change in both the speed at which innovation occurs and the scale at which new technologies are deployed. And this progress must be achieved in a way that makes our energy systems more secure and resilient.

The energy innovation challenge facing the world extends to sectors that have not significantly changed for many decades and that do not yet have commercially available low-carbon options. It also requires a rapid evolution of the technology mix, particularly in some emerging economies that are just starting out on their decarbonisation journeys. The under-appreciation of these urgent challenges in today's energy debate is a real concern. However, this *Energy Technology Perspectives Special Report on Clean Energy Innovation* provides reason for hope. It pinpoints the areas where innovation is most urgently needed and, crucially, recommends that governments integrate clean energy innovation into the heart of their energy policy making.

This report represents a new chapter in the International Energy Agency's (IEA) work under the *Energy Technology Perspectives* (*ETP*) banner. It is three years since the IEA released its last *ETP* report, and we have used that time to reflect on the critical technology challenges that need to be addressed in such sectors as long-distance transport and heavy industry, which are all too often neglected. The time away has also allowed us to develop improved modelling tools that now provide us with unparalleled capacity to answer key technology questions in more detail.

The return of *ETP*, starting with this Special Report and continuing with the release of the flagship *ETP 2020* publication later in 2020, could not come at a more pivotal moment as Covid-19 has further complicated efforts to accelerate clean energy transitions. Since the crisis erupted, the IEA has mobilised its resources to support governments and other energy stakeholders, notably with the publication of our Sustainable Recovery Plan as part of the *World Energy Outlook* (*WEO*) series. The plan shows how specific policies and targeted investments over the next three years could simultaneously boost economic growth, create millions of jobs and make 2019 the definitive peak in global greenhouse gas emissions. This *ETP* Special Report builds on that foundation by setting out the key priorities for innovation to continually drive emissions down from that peak, all the way to net-zero.

Together, the *ETP* and *WEO* reports will provide the foundation for the IEA Clean Energy Transitions Summit, which will bring together dozens of ministers and CEOs, as well as leaders from the investment community and civil society, with the aim of driving economic development by accelerating transitions towards clean, resilient and inclusive energy systems. It is my firm conviction that the efforts we are now making – including the revamp of the *ETP* series – are significant advances in the IEA's modernisation agenda that I launched in 2015, which is putting the Agency at the forefront of sustainable and secure clean energy transitions globally.

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Acknowledgements

This report was prepared by the Energy Technology Policy Division within the Directorate on Sustainability, Technology and Outlooks (STO) in co-operation with other directorates and offices of the International Energy Agency. The study was designed and directed by Timur Gül (Head of the Energy Technology Policy Division). The analysis and production of the report was co-ordinated by Araceli Fernandez Pales. The main authors were Araceli Fernandez Pales and Simon Bennett.

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Mechthild Wörsdörfer, Director of STO, provided encouragement and support throught the project. Valuable comments and feedback were provided by other senior management and other colleagues within the IEA, in particular Nick Johnstone, Keisuke Sadamori, Laura Cozzi, Laszlo Varro, Joel Couse, Paolo Frankl, Tim Gould, Brian Motherway and Samantha McCulloch.

Thanks also go to the Communications and Digital Office (CDO) for their help in producing the report, including Jad Mouawad, Head of CDO, and Jon Custer, Astrid Dumond, Tanya Dyhin, Christopher Gully, Maria Kyriacou, Jethro Mullen, Isabelle Nonain-Semelin, Julie Puech and Therese Walsh.

The work could not have been achieved without the support provided by the Japanese Ministry of Economy, Trade and Industry and the Netherlands Ministry of Economic Affairs and Climate Policy.

The analysis and findings in this report draw on strategic guidance received during an ETP-2020 consultation meeting with high-level energy officials and experts from government, industry, international organisations, finance and academia on 3 July 2019. Additional guidance came from insights, feedback and data obtained at a high-level workshop on accelerating energy innovation organised by the IEA organised in Paris on 18 December 2019. The work also benefited from information and views provided by participants within the Technology Collaboration Programme by the IEA, which brings together thousands of experts across government, academia and industry from 55 countries in order to accelerate energy technology innovation.

Many experts from outside the IEA provided input, commented on the underlying analytical work and reviewed the report. Their comments and suggestions were of great value. They include:

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Executive summary

Why we need innovation

Without a major acceleration in clean energy innovation, net-zero emissions targets will not be achievable. The world has seen a proliferating number of pledges by numerous governments and companies to reach net-zero carbon dioxide (CO_2) emissions in the coming decades as part of global efforts to meet long-term sustainability goals, such as the Paris Agreement on climate change. But there is a stark disconnect between these high-profile pledges and the current state of clean energy technology. While the technologies in use today can deliver a large amount of the emissions reductions called for by these goals, they are insufficient on their own to bring the world to net zero while ensuring energy systems remain secure – even with much stronger policies supporting them.

Energy efficiency and renewables are fundamental for achieving climate goals, but there are large portions of emissions that will require the use of other technologies. Much of these emissions come from sectors where the technology options for reducing them are limited – such as shipping, trucks, aviation and heavy industries like steel, cement and chemicals. Decarbonising these sectors will largely demand the development of new technologies not yet in use. And many of the clean energy technologies available today need more work to bring down costs and accelerate deployment.

Innovation is the key to fostering new technologies and advancing existing ones. This report assesses the ways in which clean energy innovation can be significantly accelerated with a view to achieving net zero emissions and enhancing energy security.

Innovation is not the same as invention. After a new idea makes its way from the drawing board to the laboratory and out into the world, there are four key stages in the clean energy innovation pipeline. But this pathway to maturity can be long, and success is not guaranteed:

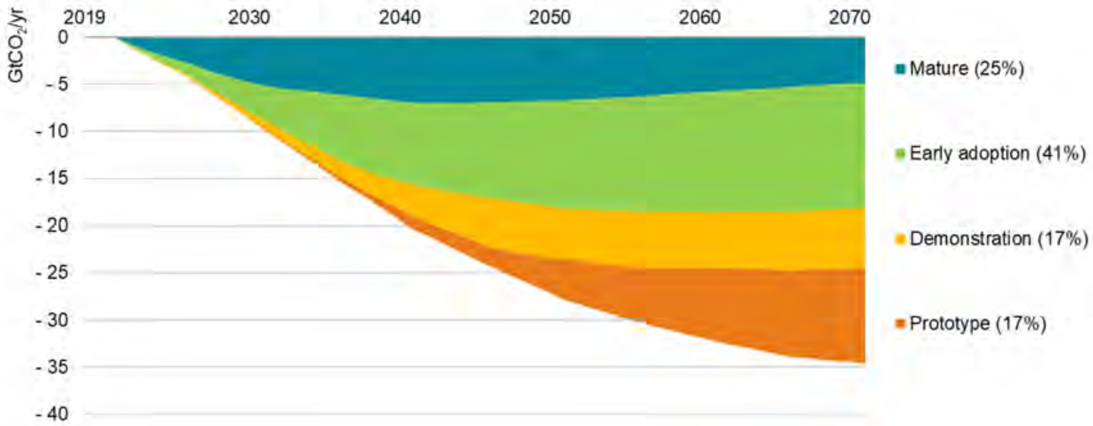
- **Prototype:** A concept is developed into a design, and then into a prototype for a new device (e.g. a furnace that produces steel with pure hydrogen instead of coal).
- **Demonstration:** The first examples of a new technology are introduced at the size of a full-scale commercial unit (e.g. a system that captures CO_2 emissions from cement plants).
- **Early adoption:** At this stage, there is still a cost and performance gap with established technologies, which policy attention must address (e.g. electric and hydrogen-powered cars).
- **Mature:** As deployment progresses, the product moves into the mainstream as a common choice for new purchases (e.g. hydropower turbines).

Understanding the scale of the energy innovation challenge

There are no single or simple solutions to putting the world on a sustainable path to net-zero emissions. Reducing global CO_2 emissions will require a broad range of different technologies working across all sectors of the economy in various combinations and applications. These technologies are at widely varying stages of development, but we can already map out how much they are likely to need to contribute to the emissions reductions necessary to meet international energy and climate goals.

The key technologies the energy sector needs to reach net-zero emissions are known today, but not all of them are ready. Around half of the cumulative emissions reductions that would move the world onto a sustainable trajectory[1] come from four main technology approaches. These are the electrification of end-use sectors such as heating and transport; the application of carbon capture, utilisation and storage; the use of low-carbon hydrogen and hydrogen-derived fuels; and the use of bioenergy. However, each of these areas faces challenges in making all parts of its value chain commercially viable in the sectors where reducing emissions is hardest. Our new *ETP Clean Energy Technology Guide*[2] provides a framework for comparing the readiness for the market of more than 400 component technologies.

CO_2 emissions reductions by technology readiness category in the Sustainable Development Scenario



Notes: Percentages refer to cumulative emissions reductions by 2070 between the Sustainable Development Scenario and baseline trends enabled by technologies at a given level of maturity today.

Technologies that are at the prototype or demonstration stage today contribute more than one-third of the cumulative emissions reductions in the IEA Sustainable Development Scenario.

[1] Sustainable trajectory or path to net-zero emissions refers to the Sustainable Development Scenario.

[2] A new interactive tool developed by the IEA that provides detailed information and analysis on the level of maturity of over 400 different technology designs and components, as well as a compilation of cost and performance improvement targets and leading players in the field. Available online at www.iea.org/articles/etp-clean-energy-technology-guide.

Early-stage technologies play an outsized role. Around 35% of the cumulative CO_2 emissions reductions needed to shift to a sustainable path come from technologies currently at the prototype or demonstration phase. A further 40% of the reductions rely on technologies not yet commercially deployed on a mass-market scale. This calls for urgent efforts to accelerate innovation. The fastest energy-related examples in recent decades include consumer products like LEDs and lithium ion batteries, which took 10-30 years to go from the first prototype to the mass market. These examples must be the benchmarks for building the array of energy technologies to get to net-zero emissions.

How innovation can help reach net-zero emissions goals faster

If governments and companies want to move more quickly towards net-zero emissions, progress on early stage technologies needs to be accelerated. In this report, we present a Faster Innovation Case that explores how net-zero emissions could be achieved globally in 2050, partly by assuming that technologies currently only in the laboratory or at the stage of small prototypes today are quickly made available for commercial investment. There are big uncertainties around these technologies' costs and timelines, but this theoretical case indicates what could be achieved through a global push on innovation.

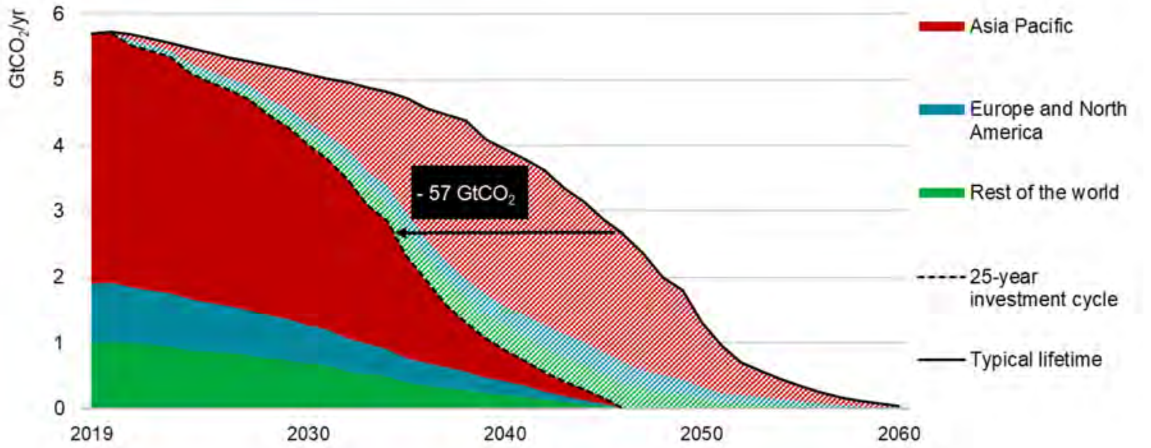
In our Faster Innovation Case, almost half of all the additional emissions reductions in 2050 relative to current policy plans would be from technologies that have not yet reached the market today. Relative to a case in which there is no improvement to technologies already in use today, early-stage technologies provide about one-third of the emissions reductions in the Faster Innovation Case. In practice, this case would require, for example, an average of two new hydrogen-based steel plants to begin operating every month between now and 2050. Currently, technology for these plants is only at the prototype stage. At the same time, 90 new bioenergy plants that capture and store their own CO_2 emissions would need to be built every year. Today, there is only one large-scale facility in operation.

Failure to accelerate progress now risks pushing the transition to net-zero emissions further into the future. The pace of innovation in coming decades will depend on the policies governments put in place today. A delay in demonstration projects and a slowdown in deployment of early adoption technologies following the Covid-19 crisis would require greater government efforts down the line, such as supporting new technologies for longer until they are competitive. For example, capital costs of key technologies like hydrogen electrolysers could increase by up to 10% by 2030, making it harder to scale up production.

Avoiding huge amounts of "locked-in" emissions is crucial

Aligning investment cycles with net-zero targets can create large markets for new technologies and avoid huge amounts of "locked in" emissions. For some energy sectors, 2050 is just one investment cycle away, making the timing of investments and the availability of new technologies critical. Boosting spending on low-carbon research and development and increasing investments in key demonstration projects for the most challenging sectors can be particularly effective. If the right technologies in the steel, cement and chemical sectors can reach the market in time for the next 25-year refurbishment cycle – due to start around 2030 – they can prevent nearly 60 gigatonnes of CO_2 emissions ($GtCO_2$).

"Unlocking" emissions reductions at the end of the next investment cycle in heavy industrial sectors



Notes: Typical lifetimes for steel and cement are 40 years; for chemicals, the average is 30 years. In the Sustainable Development Scenario, shown here, all assets are replaced by or converted to clean alternatives at the first 25-year refurbishment interval once the new technologies are commercially available.

The end of the next 25-year investment cycle is an opportunity to reduce projected emissions from existing equipment in the steel, cement and chemicals industries by nearly 60 $GtCO_2$, or 38%.

The Covid-19 crisis could cripple or catalyse energy innovation

At a time when faster innovation is sorely needed, the Covid-19 pandemic has delivered a major setback. In the immediate future, the world's capacity to bring new technologies to market will be weaker as a result of the disruptions caused by the pandemic. Market and policy uncertainties threaten to reduce the funds available to entrepreneurs.

Innovation involves a wide range of participants, but governments have a pivotal role that goes far beyond simply funding research and development. They set overall national objectives and priorities, and are vital in determining market expectations, ensuring the flow of knowledge, investing in essential infrastructure, and enabling major demonstration projects to go ahead.

If governments rise to the challenge created by the Covid-19 crisis, they have an opportunity to accelerate clean energy innovation. This can help protect the approximately 750 000 jobs in energy research and development. And it can be a strategic opportunity for governments to ensure that their industries come out of the Covid-19 crisis stronger and ready to supply future domestic and international growth markets. On a path towards meeting sustainable energy and climate goals, we project that investments in technologies that are today at the stage of large prototype and demonstration would average around USD 350 billion a year over the next two decades.

Some areas deserve immediate attention from governments looking to revitalise economic activity. In particular, it is important to maintain research and development funding at planned levels through 2025 and to consider raising it in strategic areas. Market-based policies and funding can help scale up value chains for small, modular technologies – as they did for solar panels – significantly advancing technology progress. Synergies with other technologies across sectors is a relatively low-cost way to innovate. Electrochemistry, which underpins batteries, electrolysers and fuel cells is a clear example.

The IEA proposes five key innovation principles

For governments aiming to achieve net-zero emissions goals while maintaining energy security, these principles primarily address national policy challenges in the context of global needs, but are relevant to all policy makers and strategists concerned with energy technologies and transitions:

1. **Prioritise, track and adjust.** Review the processes for selecting technology portfolios for public support to ensure that they are rigorous, collective, flexible and aligned with local advantages.
2. **Raise public R&D and market-led private innovation.** Use a range of tools – from public research and development to market incentives – to expand funding according to the different technologies.
3. **Address all links in the value chain.** Look at the bigger picture to ensure that all components of key value chains are advancing evenly towards the next market application and exploiting spillovers.
4. **Build enabling infrastructure.** Mobilise private finance to help bridge the "valley of death" by sharing the investment risks of network enhancements and commercial-scale demonstrators.
5. **Work globally for regional success.** Co-operate to share best practices, experiences and resources to tackle urgent and global technology challenges, including via existing multilateral platforms.

As countries around the world pursue a more secure and sustainable energy future, the IEA will continue to support governments, industry, investors and other stakeholders in advancing energy innovation with the aim of accelerating transitions to cleaner and more resilient energy systems.

Chapter 1. Clean energy technology innovation and the vital role of governments

HIGHLIGHTS

- A cleaner and more resilient future energy system with net-zero emissions will require a wide range of technologies, some of which are still at an early stage of development. For these new technologies, innovation is an uncertain and competitive process: many ideas fall by the wayside. This report looks at how to manage uncertainty and expand the number of available and affordable clean energy technologies in support of net-zero emissions on a timetable compatible with international energy and climate goals. It features new IEA modelling that highlights candidates – including electrification (supported by batteries), hydrogen (and its derived fuels), CO_2 capture and bioenergy – that could speed up progress in long-distance transport and heavy industry, sectors that in most cases lack readily scalable low-carbon technologies today. For policy makers, it offers recommendations for action.
- Successful technology concepts eventually pass through four stages: prototype, demonstration, early adoption and maturity. Feedback between the stages means that technology options are always evolving. Size, consumer value and synergies with other technologies are all attributes that determine the speed with which technologies pass through the stages.
- The process of innovation involves a wide range of participants: governments, researchers, investors, entrepreneurs, corporations and civil society all play important roles in generating ideas for new or improved technologies and in improving and financing them right through to market entry and deployment. Innovation systems are complex and rest on four pillars: resource push, knowledge management, market pull and socio-political support.
- Governments have a particularly central and wide-ranging role to play that goes far beyond the provision of funds for R&D. They set overall national objectives and priorities and play a vital role in determining market expectations. They also have unique responsibilities for ensuring the flow of knowledge, investing in enabling infrastructure and facilitating major demonstration projects.
- The remarkable 70-year history of almost continuous cost reductions for solar PV illustrates how governments can effect change. At different stages, the US, German, Chinese and other governments used R&D and market-pull policies, including targets and revenue guarantees, to encourage investments all along the value chain that supported innovation and economies of scale. The way in which lithium-ion batteries have developed has showed similar patterns.
- The Covid-19 pandemic potentially brings about a major and unanticipated setback to clean energy innovation, and an IEA survey reveals that companies that are developing net-zero emissions technologies consider it likely that their R&D budgets will be reduced. The economic recovery plans now being developed on a large scale by a range of countries, however, provide an opportunity for governments to support clean energy innovation jobs and accelerate technology progress, at a time when the need for such innovation has never been greater.

Introduction

A rapid shift to net-zero emissions of greenhouse gases is needed if we are to meet the energy-related Sustainable Development Goals of the United Nations, including by mitigating climate change in line with the Paris Agreement. This requires the use of a wide range of clean energy technologies. Some of these are well established; others are still at an early stage of development, or exist only as prototypes. Further technologies may emerge in due course from current research work. These energy technologies also offer the prospect of other benefits, including cleaner air and greater energy security as a result of, for example, improved electricity systems flexibility.

Success will not be easy or straightforward. It depends upon technological innovation, and this takes time: it has taken decades for solar photovoltaics and batteries to reach their current stage of development, for example. And not every technology that is developed will be successful; the evolution of existing and new technologies is inherently uncertain. But these points merely serve to underline the importance of finding ways to innovate that are successful in bringing about rapid change.

It is against this background that this Energy Technology Perspectives Special Report focuses on accelerating technology progress for a sustainable future. It emphasises that we are at a critical point, and it concludes with recommendations to help bring about real change.

Structure of the report

Chapter 1 describes the steps involved in clean energy technology innovation and the role that government and other actors play throughout the innovation process, building on historical experience. It explains why strong and cohesive innovation systems are vital for clean energy transitions and looks at the risks and opportunities that may arise from the Covid-19 crisis.

Chapter 2 provides an overview of the status of clean energy technology innovation. It reviews the different resources that support innovation, from government and public sector funding for research and development (R&D) through to venture capital investment and also patents. It then assesses the potential impacts of the Covid-19 crisis on these different resources.

Chapter 3 looks at long-term clean energy technology innovation needs through the lens of the IEA Sustainable Development Scenario, which maps out a way to meet the key energy-related goals of the United Nations Sustainable Development Agenda, including by mitigating climate change in line with the Paris Agreement. The trajectory for emissions in the Sustainable Development Scenario is consistent with reaching global "net-zero" CO_2 emissions by around 2070.

Chapter 4 discusses the opportunities and challenges arising from the Covid-19 crisis for clean energy technology innovation. It presents a Faster Innovation Case, which sets out what would be needed in terms of clean energy technology innovation to achieve net-zero carbon emissions by 2050. It also presents a Reduced Innovation Case, which sets out the risks and consequences of a delay in scaling-up key emerging clean energy technologies.

Chapter 5 concludes with recommendations for policy makers to boost clean energy technology innovation. It distinguishes near-term priorities from structural changes, and makes the case for immediate action in the light of the scale of the challenges we face and the long lead times involved.

What do we mean by innovation?

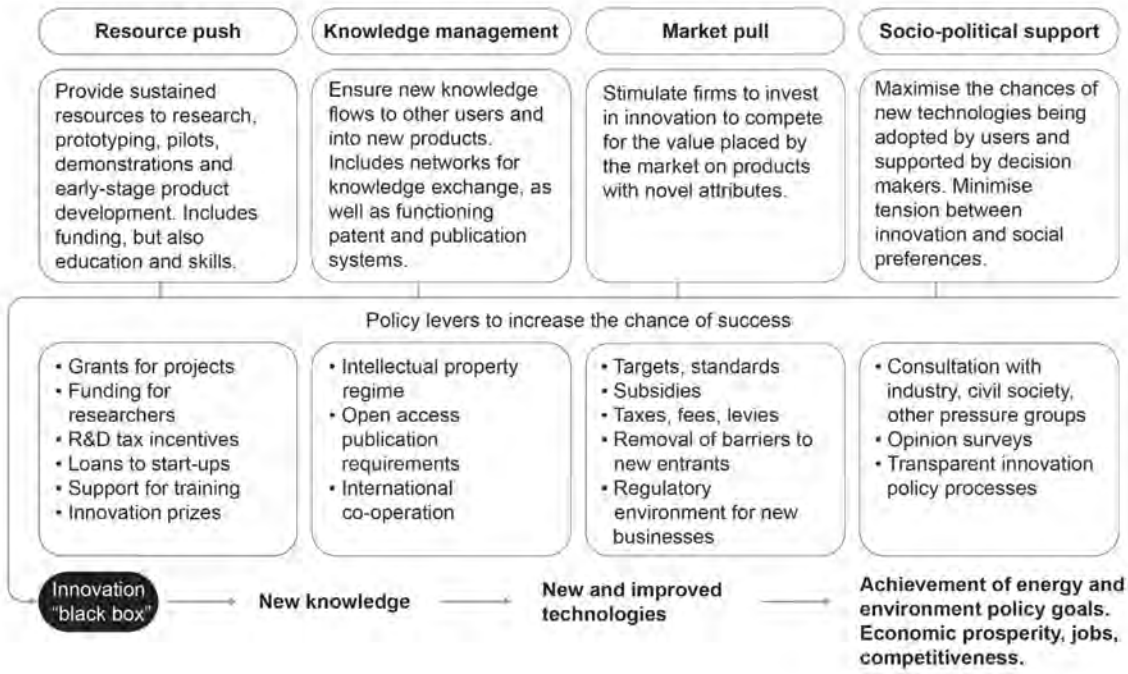
This report treats technology innovation as the process of generating ideas for new products or production processes and guiding their development all the way from the lab to their mainstream diffusion into the market (Box 1.1). At each stage of development there are funding risks, technical risks and market risks, which are influenced by various social and political factors. As a result, only a minority of products ever make it as far as mass market deployment in practice.

The innovation journey of any given technology is evolutionary. There are three main ways by which a technology evolves with experience to become better adapted to its environment, notably through improved costs and performance: 1) learning-by-researching; 2) learning-by-doing; and 3) economies of scale. As the technology is improved, it is more likely to be chosen by R&D funders and new users with different selection criteria. This creates a virtuous cycle and so-called "increasing returns to adoption". However, in the early stages, when costs are usually higher than those of competitors, these feedback loops are much weaker and it takes concerted, risky investments to access the first market opportunities. Both radical and incremental advances are vital to the process of innovation.

Choices about technology are made in an environment that is constantly changing, as companies, consumers, policies, competing technologies, infrastructure and social norms change. Technologies can become more attractive to users for a variety of reasons. These include changes in related technologies, consumer behaviour, policy and, sometimes, a change in the information available to users. Each of these variables can also change in ways that cause a technology to be overlooked in favour of alternatives, or lead to a technology that was previously rejected finding new market opportunities. Governments and private sector actors raise their chances of successful innovation by simultaneously addressing the improvement of technology, for example through research, and of the selection environment, for example though regulation, advertising or the development of new business models.

Successful innovation systems involve a wide range of actors with aligned interests and a wide variety of functions, each of which can be enhanced by public policy (Gallagher et al., 2012). These functions can be grouped under four headings (Figure 1.1). An innovation system will struggle to translate research into technological change without action under each of these headings. A sustained flow of R&D funding, a skilled workforce (e.g. researchers and engineers) and research infrastructure (laboratories, research institutes and universities) is required: these resources can come from private, public or even charitable sources, and can be directed to specific problems or basic research (resource push). It must be possible for knowledge arising to be exchanged easily between researchers, academia, companies, policy makers and international partners (knowledge management). The expected market value of the new product or service must be large enough to make the R&D risks worthwhile, and this is often a function of market rules and incentives established by legislation. If the market incentives are high, then much of the risk of developing a new idea can be borne by the private sector (market pull). And there needs to be broad socio-political support for the new product or service, despite potential opposition from those whose interests might be threatened (socio-political support).

Figure 1.1 Four pillars of effective energy innovation systems



Source: Adapted from IEA (2019), Clean Energy Transitions: Accelerating Energy Technology Innovation Beyond 2020: Focus on India, IEA, Paris, https://webstore.iea.org/clean-energy-transitions-accelerating-innovation-beyond-2020-focus-on-india.

A simplified framework of four pillars can help decision makers to think holistically about innovation support.

Box 1.1 Key innovation-related concepts

- **Technology:** Any device, component of a device or process for its use that is dedicated to the production, storage and distribution of energy, or the provision of new or improved energy services or commodities to users. Where necessary for clarity, this report differentiates between "technology application" (e.g. renewable power), "technology type" (e.g. solar PV), "technology design" (e.g. perovskite cells) and "technology component" (e.g. smart inverters).
- **Technology innovation:** The process of improving the means of performing tasks through the practical application of science and knowledge, usually resulting in higher performing equipment as measured by, for example, energy efficiency, user friendliness or cost. This process includes learning-by-researching (R&D) and learning-by-doing, and their interaction with the technology innovation systems to which they contribute.
- **Technology innovation system:** The dynamic and evolving interactions of the tangible and intangible factors that determine each stage of the innovation process for a given technology. It comprises the innovators, users, institutions, financers, civil society actors and the perceptions, networks and rules that govern their actions.
- **Learning-by-researching:** The accumulation of knowledge by devoting R&D resources to the search for new ideas and their development into viable products and services, including prototypes and demonstration projects.
- **Learning-by-doing:** The accumulation of knowledge from direct experience of undertaking the activity through repetition, trial and feedback.
- **Economies of scale:** Cost advantages reaped in manufacturing and installation when fixed and variable costs rise more slowly than the number of units of output. It is associated with mass production of similar goods as well as the use of larger equipment, such as pipelines for which material needs do not scale linearly with throughput. Though much rarer, diseconomies of scale have also been seen (Coulomb and Neuhoff, 2006).
- **Forgetting-by-not-doing:** Interruptions in production or use of a technology that cause accumulated knowledge to be lost and lead to higher unit costs for the next unit put into service after the interruption.
- **Spillovers:** Positive externalities of learning-by-doing or learning-by-researching that increase the rate of innovation in an area that was not the target of the original innovative activity. Spillovers can be considered to be "free" inputs to parallel innovation ecosystems, related by geography or scientific proximity. Knowledge spillovers refer to the incorporation of new principles, e.g. the

adoption of breakthroughs in semiconductor manufacturing by those producing solar PV. Application spillovers refer to the adoption of a technology in a new application only once it has been refined through innovation targeted at a separate, original application, e.g. the adoption of lithium-ion (Li-ion) batteries in vehicles after their development for consumer goods.

- **Public goods market failure:** The private sector has limited incentive to produce knowledge if firms cannot fully exploit the returns on their investment because that knowledge is easily available to others. Patents and public spending on R&D are in part a response to this market failure.
- **Materiality:** A threshold above which a technology is considered to have sufficient market share for its impact on supply chains to be "material", defined in this report as 1% of national stock in a given sector. Beyond this threshold, most technologies are sufficiently mature in their design, production and familiarity for the next stage of deployment to be more straightforward.

Successful new ideas pass through four stages… eventually

Innovation processes are rarely linear, and no technology passes all the way from idea to market without being modified. Their trajectories are influenced by feedback loops and spillovers between technologies at different stages of maturity and in different applications, and often involve setbacks and redesign. It is nevertheless worth considering the four distinct stages through which all successful technologies eventually pass because each stage has different characteristics and requirements (Figure 1.2). These stages are relevant to all the different levels of technology definition – type, design, component – but are most applicable to technology designs.

Prototype: Following its initial definition, a new concept is developed into a design and then a prototype for a new device, a new configuration of existing devices or a new component to improve a product on the market. The probability of success at this stage is low, but the costs per project are also generally low.

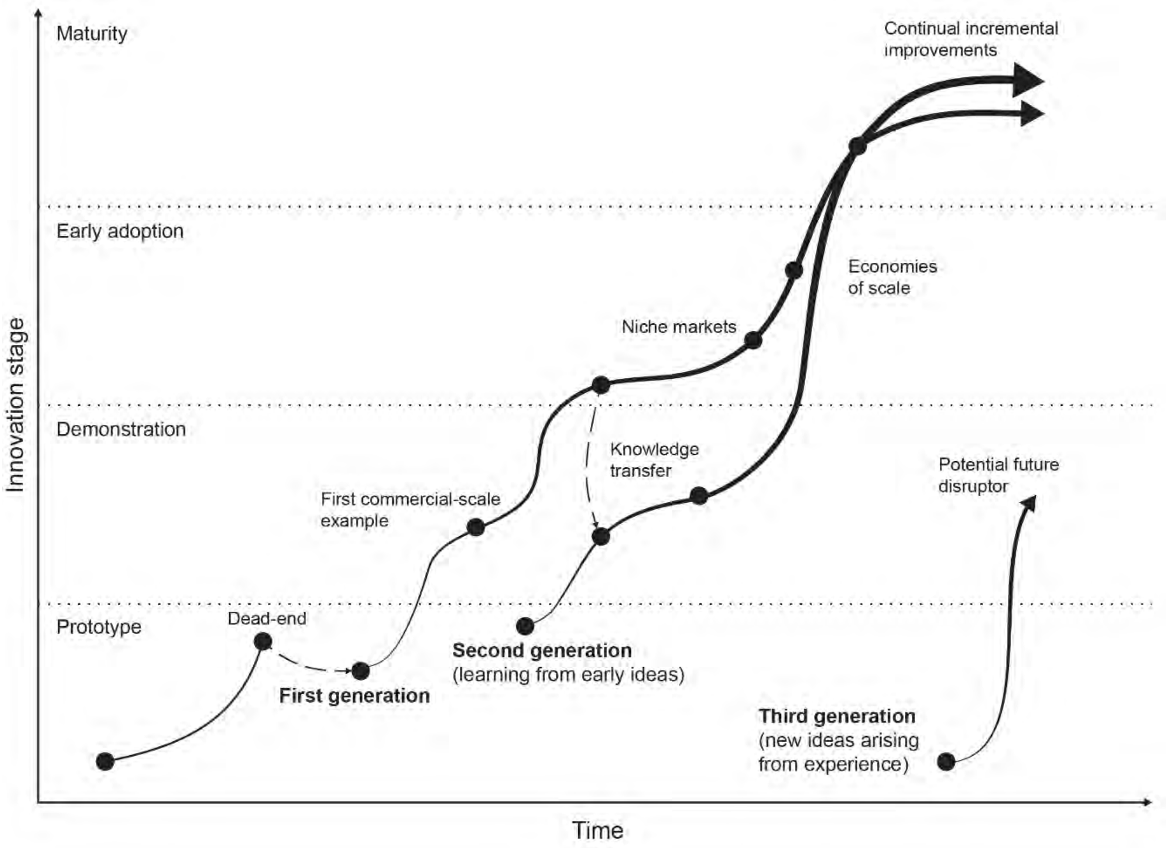
Demonstration: The first examples of the new technology are introduced onto a given market at the size of a single full-scale commercial unit. The purpose is to show that the technology is effective and to reduce the perception of risk for financiers: potential customers will generally not consider a new product until it is shown to work at a profitable scale and cost. Demonstration involves more time, cost and risk than the prototype stage. This phase is often referred to as the "valley of death", especially for large-scale, tangible technologies.

Early adoption: At this stage, there is still a high cost and performance gap compared with existing technologies, but the technology is used by customers who want to try it out or need it for a particular purpose. This period represents a continuation of the "valley of death," and in many cases revenue from early niche markets doesn't cover costs. In cases where governments see a broader social, environmental or economic benefit from its wider diffusion, they may help, for example through discretionary procurement or financial support. Operating in a commercial environment means, however, that more of the costs and risks can be borne by the private sector, with competition driving down costs and encouraging refinements. As the number of niches grows, the technology arrives at a material share of 1% or more of the addressable market.

Maturity: As deployment progresses beyond materiality to maturity, the product moves into the mainstream for new purchases and may even start to compete with the stock of existing assets, leading to early retirement of those assets and driving even faster diffusion. Incremental learning-by-doing continues during this stage, as feedback from engineers and users stimulates new ideas for more radical enhancements to be prototyped. Although there may still be some cost or performance gaps at the beginning of this stage, a dominant design has become accepted and the risks are generally familiar enough for private investors to bear.

Throughout the early adoption and maturity stages, innovation continues to improve the technology. In some cases, significant discontinuous improvements occur long after mainstream diffusion into the market has started, as for example with as Li-ion batteries for electric vehicles. In other cases, technologies reach a point where only very incremental changes are expected from the ongoing learning processes, as for example with large hydropower plants.

Figure 1.2 Four stages of technology innovation and the feedbacks and spillovers that improve successive generations of designs



Successful technologies eventually pass through four stages of innovation, with R&D contributing improvements and spurring ideas for novel prototypes at each stage.

Roles of governments and other actors in innovation systems

At each stage of the energy innovation journey, public and private sector actors, including not-for-profit research institutions and funders, play essential roles (Table 1.1). For all actors, competition is a major driver of energy innovation. Firms of all sizes, including state-owned enterprises, have incentives to refresh their offering to customers to increase market share and to avoid losing out to competitors with cheaper or better performing products. Investment funds seek new companies that can deliver the highest returns and help the funds compete for more capital. Countries also often compete to secure investment and market share for companies and workers in their countries. The same is true for subnational governments, which are playing an increasingly important role in reshaping urban energy systems.

The role of governments is particularly crucial. It encompasses educating people, funding R&D, providing network infrastructure, protecting intellectual property, supporting exporters, buying new products, helping small and medium-sized enterprises, shaping public values, and setting the overall regulatory framework for markets and finance (Hekkert et al., 2007; Bergek et al., 2008; Kim and Wilson, 2019; Grubler et al., 2012; Roberts and Geels, 2018). The essential justification for public intervention in innovation is that new ideas and technologies are undersupplied by the market – the so-called public goods market failure that leads companies to prioritise expenditures from which profits are more certain. In particular, radical new concepts, or "disruptive" technologies, often arising from basic scientific research, are rarely supplied by incumbent companies, which tend to focus on incremental improvements to their existing technology portfolio (OECD, 2015). Disruptive technologies can be of particular importance in relation to social or environmental outcomes that are desired by governments but have low market value.

While there is legitimate concern that public sector R&D might "crowd out" corporate incentives, the evidence suggests that the productivity of corporate research is increasingly dependent on ideas arising from publicly funded R&D (Fleming et al., 2019). Public funding for energy R&D may well stimulate more private sector spending, not less (Nemet and Kammen, 2007).

A mechanistic description of how governments fill gaps left by the private sector underplays their ability to make things happen. They have in the past used their powers to set incentives for, and work with, the private sector to deliver desirable outcomes: examples include space exploration, vaccines and nuclear power. It is increasingly recognised that many of the biggest clean energy technology challenges could benefit from a "mission-oriented" approach (Díaz Anadón, 2012; Mazzucato, 2018). Support for industrial clusters, strategic use of public procurement and investment in enabling infrastructure could all play a part in such an approach, increasing the probability of innovation success.

The innovation story of solar PV illustrates how concerted government action can steer and accelerate technology development while harnessing the advantages of private sector leadership (Box 1.2). This brings out the importance of government support from R&D through to the scaling-up of demand in successive niche markets, starting with the highest value and simplest applications. It also brings out how global the process of innovation can be: governments in several different countries played an important part in bringing solar PV from the laboratory to the market, responding to external events in ways that increased the chances of solar PV successfully moving along the learning curve. Importantly, although there were times when demand growth for solar PV dipped in individual countries in response to policy changes, the global market continued to grow as it was reliant on different national incentives around world.

The development of Li-ion shows some similarities (Kittner, Lill and Kammen, 2017), with Canada, the People's Republic of China (hereafter "China"), Japan, Norway and the United States all playing a role. R&D efforts appear to have been important drivers of cost reduction, for example through the development of new cathode materials with improved specific capacity and higher share of utilised charge capacity.[3] While falling cathode and anode material prices played a role, R&D also enabled the use of lower cost metals instead of cobalt.

The stories of PV and Li-ion innovation are far from finished. PV patenting activity remained far higher in 2017 than at any time before 2005, and Li-ion patents have not yet peaked: successful new components and designs are likely to make an appearance in the coming years. Their history to date, however, underlines the importance of R&D at the start of the innovation journey, and the key role of governments around the world in helping major new technologies achieve success.

[3] Ziegler, M. and J.E. Trancik (2020), Personal communication on 1 March 2020, Massachusetts Institute of Technology.

Table 1.1 Selected examples of the different roles of the main actors at each stage of the energy innovation process

Stage	Private sector	Government	Investor community	Civil society
Across all stages from prototype to maturity	• Helps create the space and political legitimacy that enables policy to be made. • Spreads knowledge through professional societies, international investment and standardisation	• Sets the market framework and incentives for investors. Helps to determine the attractiveness of entrepreneurship and the openness of markets to new entrants. Directs the innovation and investments of state-owned enterprises. • Raises public expectations and confidence in technological change. • Ensures new knowledge is appropriately protected and, if publicly funded, used, as appropriate. Supports knowledge sharing via conferences, open access publishing and societies.	• Accounts for future climate and other policy risks in assessment of incumbent technologies.	• Advocates policies that support desirable new technologies, including consumer incentives and public procurement
Prototype	• Funds and operates corporate labs. • Collaborates with and funds universities, and collaborates with firms not in direct competition or on projects too risky for one firm alone.	• Prioritises research topics to direct research towards societal goals. Funds basic and speculative R&D at public research institutes and private labs. Funds or co-funds complex multi-stakeholder applied research projects to test pre-commercial technologies. Establishes prizes for desired technology advances. • Adjusts the tax regime to stimulate private spending on research.	• Provides angel funds to help a small start-up or entrepreneur get off the ground.	• Channels funds to radical innovation through foundations and donations to universities.

Stage	Private sector	Government	Investor community	Civil society
Demonstration	• Uses corporate venture capital to incubate new technologies to move from lab to market, if successful. • Takes the risks of constructing, hosting and/or operating pilots and first-of-a-kind commercial plants.	• Funds projects and start-ups with grants and loans. May also buy equity. • Supports entrepreneurs by funding incubators and investor networks or reducing investment risks for third-party capital. • Ensures revenue for demonstration projects and puts in place appropriate regulations to manage first-mover risks.	Provides venture capital funds and growth equity to bring technologies to markets.	Supplies the first consumers for demonstration projects and supports projects that align with local values and promise jobs.
Early adoption	• Develops and hones the business models and marketing for new products and services. • Fosters learning-by-doing from manufacturing and operations.	• Uses various types of finance (including concessional loans, grants and equity financing) to bridge gaps in capital markets to support entrepreneurs to scale-up. • Uses public procurement, portfolio standards and purchase incentives to create successive "niche" markets. • Prevents abuse of monopoly power and allows regulatory experimentation for projects in natural monopoly markets. • Ensures that any necessary enabling infrastructure and networks are constructed in a timely manner.	• Adjusts risk perception for technologies with technical progress. • Shares investor needs and opportunities with firms.	Provides the early adopters

Box 1.2 Government involvement in solar PV development

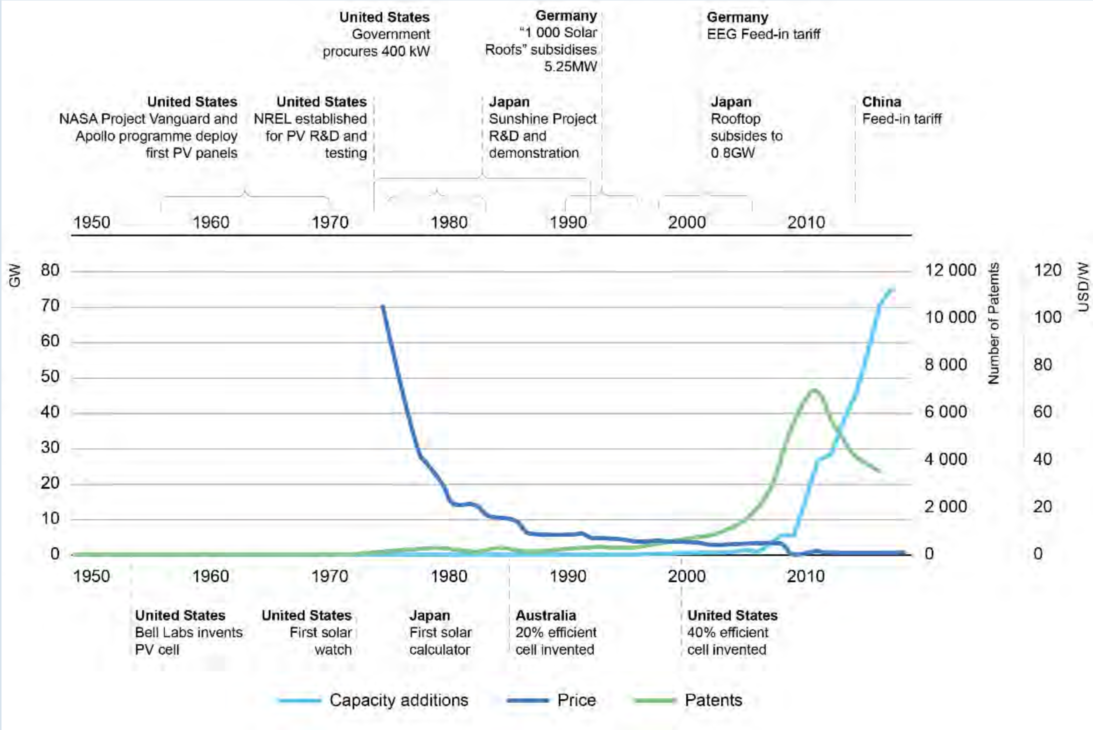
Governments were critical in bringing solar PV from the laboratory to the market, stimulating early adoption and spurring continuing innovation, but no single country was instrumental.

The first demonstrations of PV cells were made in the 1950s in the United States by Bell Labs, which was granted the right to spend a certain share of AT&T and Western Electric's operating budget on risky and basic R&D as part of its government-regulated telecommunications license. US dominance of the technology persisted through the 1970s under the supervision of the National Aeronautics and Space Administration (NASA), which had sizeable public R&D funds, and which began using PV in satellites and shuttles. The oil shocks of the 1970s spurred Japan and the United States to increase their public funding for PV research in a quest for more secure energy sources. In the United States, companies were spun off from government-regulated laboratories and found niche business opportunities for PV. In Japan, companies like Sharp were helped by the government to build production facilities and they too found market niches.

Throughout the 1980s and 1990s, PV for electricity production was uncompetitive except for off-grid customers with a willingness to pay a high price for small amounts of power. Suppliers in the United States, then Japan and then Germany were, however, able to scale-up as a result of government procurement and incentive policies in these countries. As the potential became more apparent to researchers in more countries, R&D funding increased, the number of patents accelerated and costs fell. Of particular significance in helping to create a market were government feed-in tariff programmes, first in Germany in the 1990s, then in Italy, Spain, the United States, China and India by the 2010s. These programmes, backed by rising deployment targets, targeted grid-connected systems and provided the guaranteed scale-up needed for global supply chains. At this point, patenting peaked and the market consolidated around a dominant design.

Even though the development of solar PV to this point took around 60 years, progress would almost certainly have been slower if these countries – and others not mentioned here – had not shared the responsibility for these innovation stages (Gallagher, 2014; Nemet, 2019).

Key government programmes (top) and milestones (bottom) in PV development

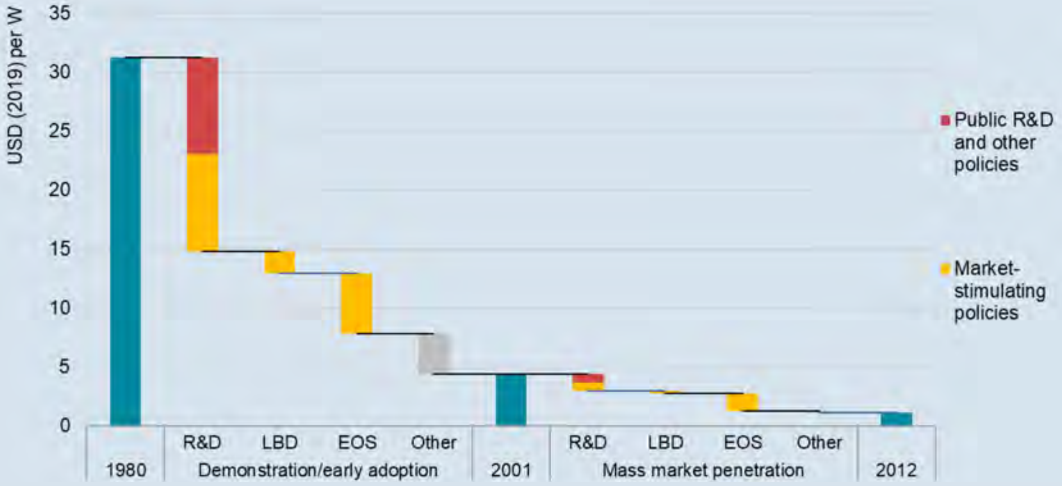


Note: NREL = National Renewable Energy Laboratory; EEG = Renewable Energy Sources Act in German; PV = photovoltaics; R&D = research and development.

Source: Nemet (2019); Persat et al. (2019); Kavlak, McNerney and Trancik (2018).

It is possible to assess the relative importance of resource push and market-pull measures by estimating the contribution to cost reductions made by different technical elements and allocating them to their high-level drivers using generalised assumptions (Kavlak, McNerney and Trancik, 2018). Technical improvements attributable to market pull measures – a combination of learning-by-researching by the private sector, learning-by-doing (repeated routine manufacturing activity) and economies of scale – are estimated to have contributed two-thirds of the cost reductions in producing solar PV panels between 1980 and 2012.[1] While economies of scale contributed only around 22% of cost reductions over the entire period, they grew greatly in importance after 2001.[2] It is likely that silicon prices, wafer area and factory design all benefited from developments in the semiconductor sector, indicating the importance of spillovers. Overall, this suggests that around 60% of the cost reductions arose from R&D, both public and privately funded. The incentives for R&D may have been particularly strong prior to 2001, during a period when competition between crystalline and thin film PV technologies created uncertainty about which design would dominate. The market leading technology in terms of share of global production changed twice in less than a decade before economies of scale in mass production of the more efficient crystalline technology in China reduced thin film's market share to below 10% (Hoppmann, 2018).

Contributions to solar PV cost declines by high-level mechanism and driver



Notes: R&D = learning-by-researching; LBD = learning-by-doing; EOS = economies of scale. Other includes externally driven input prices and costs. Assumption: R&D funding was equally split between public and private sector and equally impactful on costs.

Source: IEA calculations based on Kavlak, McNerney and Trancik (2018).

Notes: 1. Including module efficiency, non-silicon materials costs, wafer area and yield. 2. Including some non-silicon materials costs, plant size and silicon price.

Covid-19: A threat or an opportunity for clean energy technology innovation?

The Covid-19 pandemic has delivered a brutal shock to countries around the world. By mid-May 2020, around one-third of the global population was under full or partial lockdown. Assuming that containment measures are gradually phased out during the second half of the year, the global economy is expected to contract by at least by 3% in 2020; this would be the largest economic dip since the global depression of the 1930s (IEA, 2020). If outbreaks and containment measures last longer, there is a significant risk that the global economy could shrink by as much as 6%, with GDP contracting in nearly every country in 2020. Some low-income countries face particular pressures in dealing with the pandemic and its fallout.

As described earlier in this chapter, technology innovation is a driver of structural change. New technologies outcompete older ways of doing things and bring new services to society. This process attracts investment at each stage – from governments; high-yield, voluntary contribution funds; and, ultimately, cautious institutional investors. The evidence suggests that clean energy technology innovation brings particular economic benefits, as well as being essential for the creation of a more sustainable energy system. One study of the automotive sector finds that clean energy innovation is more productive in terms of its ability to stimulate knock-on inventions than innovation activity directed to incumbent technologies (Aghion et al., 2016). While the macro relationship between jobs and R&D expenditures is complicated, other studies suggest that R&D that supports new high-tech products is correlated with increased employment (Calvino and Virgillito, 2017). Clean energy innovation can also generate good value for taxpayers: reviews of six public clean energy R&D programmes in the United States found a return on investment of 27% since 1975, and a benefit-to-cost ratio of 33:1 (11:1 at a 7% discount rate; Dowd, 2017).

Worldwide, some 300 million full-time jobs could be lost as a result of Covid-19, and nearly 450 million companies are facing the risk of serious disruption. Clean energy innovation is labour intensive: we conservatively estimate that over 750 000 people are currently employed in energy R&D around the world, representing 1.5% of the approximately 40 billion workers in the global energy system, with half of these jobs being in China, Japan, the United States, France and Germany. If these workers are lost to the sector, it will be hard to build up the expertise associated with them again: it takes many years to acquire the specialist skills and experiences necessary to identify technology needs, formulate improved concepts and build the teams to test them. Our ability to meet the major energy challenges ahead – to develop the first zero-emissions flights or the next generation of solar panels, for example – will be enhanced if the numbers of those working on energy R&D are maintained and indeed increased.

There are several ways in which clean energy innovation jobs and outputs are threatened by the Covid-19 pandemic. These include pressures on public and private budgets, a riskier environment for clean energy venture capital and disrupted global supply chains (see Chapter 2). Public R&D is expected to hold up better than private R&D, and there is a reasonable chance that the governments of major economies will seek to boost innovation funding as a response to the crisis. Companies face lower revenue and a lack of cash flow for capital investments to meet near-term growth targets, but there is little sign of those who have made commitments to reduce their emissions intensity and test new energy technologies seeking to back away from those commitments. For a rapid assessment of the likely impacts of Covid-19 on their ability to support innovation towards longer term goals, we surveyed industrial contacts in May 2020. Responses indicated no change in long-term commitments and an expectation that R&D budgets would be resilient, but overall sentiment about the impact on the full range of innovation activities was gloomy (Box 1.3).

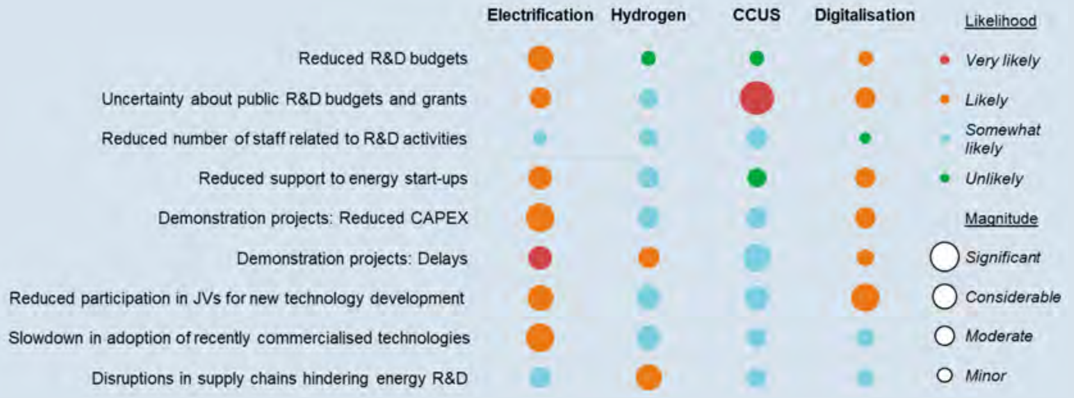
The second half of 2020 presents a unique opportunity to double down on clean energy innovation. While near-term responses to the crisis have understandably focused on mitigating health, employment and liquidity risks, attention is now turning to the speed of the recovery, the creation of new jobs and the future shape of the economy. New players with new ideas aiming to displace high-carbon producers and to scale-up quickly may find a supportive environment if they are able to enter the market at the right moment. Economic stimulus plans now being proposed in countries around the world offer a once-in-a-generation opportunity to boost clean energy technology innovation. Many of the sectors that are critical to achieving net-zero emissions have investment cycles of many decades, so there is no time to lose.

Box 1.3 Corporate perceptions of the impacts of Covid-19 on energy innovation

In May 2020, the IEA contacted a number of large companies that are active in the development of technologies expected to play a significant role in the achievement of net-zero emissions, focusing on four specific technology areas: 1) direct electrification; 2) hydrogen; 3) carbon capture, utilisation and storage (CCUS); and 4) digitalisation. We included end-user companies outside the energy sector, including companies from the iron and steel, cement and chemicals sectors. The 28 companies that responded represent nearly 1.5 million employees worldwide.

The responses indicate serious disquiet among experts about keeping their innovation pipelines flowing over the next couple of years. Most respondents think it is at least "somewhat likely" that all elements of their R&D, demonstration and deployment strategies will be affected. Companies that are prioritising technologies for the electrification of energy demand, especially those in heavy industry, consider it likely that their R&D budgets will be considerably or significantly reduced. Companies pursuing CCUS consider it very likely that public budgets and grants for these technologies will be more uncertain and possibly reduced.

Expected impacts of Covid-19 on clean energy innovation from corporate experts in May 2020



Notes: CCUS: carbon capture, utilisation and storage; JV: joint venture; CAPEX: capital expenditure. IEA web-based survey results from 28 respondents in a range of sectors: oil and gas and electric utilities (7 respondents), iron and steel (5 respondents), cement (2 respondents), chemicals and hydrogen (5 respondents), equipment manufacturers (5 respondents), and mining (4 respondents).

Taking account of perceptions of risk in terms of both the magnitude of the impact and its likelihood, the highest levels of unease are focused on the demonstration and early adoption stages of the innovation process. There is unease in particular about the stability of public R&D funds, which are generally sought by corporations for testing in the field; the ability to execute large-scale demonstration projects; the resilience of collaborations; and a slowdown in adoption of new clean energy technologies. While these results take account of firm size, the sample of responses shows more concern among smaller firms, with larger firms indicating a higher expectation of avoiding significant cuts to R&D budgets.

A positive message from many respondents was that their strategic priorities for clean energy technology development will not change. Respondents also expressed little change in their appetite for risk-taking in their priority technology areas. If the flow of funding can be maintained and policies are supportive of growing demand for the technologies, then major companies seem likely to be ready to continue to support innovation.

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Chapter 2. Global status of clean energy innovation in 2020

HIGHLIGHTS

- Technology innovation is widely recognised as critically important for tackling climate change and energy policy objectives, including increasing energy access and reducing air pollution. Yet tracking progress on innovation is challenging. The correlation between inputs – finances and skills – and intermediate outputs – patents and products – is sometimes unclear. Policy objectives such as cheaper technologies, industrial transformation and economic growth can be hard to measure or assign to the inputs. Despite this, a range of indicators can shed light on clean energy innovation globally, including funding and patenting. Broader sets of metrics are needed to identify and share good practices, and are being developed by some governments.
- Low-carbon energy R&D spending in IEA member countries has been broadly stable since 2012, after doubling between 2000 and 2012. It remains below the levels in the 1980s, however. Low-carbon energy technology represents around 80% of total public energy R&D spending, which in 2019 grew by 3% to USD 30 billion globally. In general, the share of GDP represented by public energy R&D spending has remained fairly constant over the last decade, and other public research objectives, such as health and defence, receive around five times more R&D funding than energy.
- Over the last decade, corporate energy R&D has seen years of growth, punctuated by slowdowns in response to economic challenges such as the 2007-08 financial crisis, the 2014 oil price crash and, now, the Covid-19 pandemic. In 2019, reported spending reached USD 90 billion, with a notable slowdown in the automobile sector, typically the highest spending sector for energy-related R&D but where revenues dipped and R&D spending was flat. While companies active in renewable energy showed an impressive 74% growth in R&D spending between 2010 and 2019, their share remains below one tenth of total corporate R&D. Meanwhile sectors that do not yet have commercially viable solutions for deep decarbonisation, such as cement and iron and steel, typically spend relatively little on R&D.
- Early-stage venture capital (VC) investment stood at USD 4 billion in 2019. Investment in growth areas, such as hydrogen and batteries, is broadening the impact of VC across sectors, and VC investment is growing in Europe, the People's Republic of China (hereafter "China") and the United States. However, the share of global VC deals accounted for by clean energy halved since 2012, indicating that the relative attractiveness of clean energy is not keeping pace with other technology areas, such as biotechnology and information technology. It is noteworthy in this context that, while the initial value of many energy technology start-ups lies in the patents they hold, fewer patents have been filed for low-carbon energy technologies each year since 2011.
- The Covid-19 pandemic has had a rapid and negative impact on private sector funding for clean energy innovation, and is likely to set back the speed with which clean energy technologies can be developed and improved. In the absence of policy interventions, demonstration, early adoption and learning-by-doing are expected to suffer the most in the first instance. A number of energy-related companies reported year-on-year declines in R&D budgets in the first quarter of 2020, and the number of VC deals was also down. The impacts are likely to be uneven across countries, with emerging economies finding it hardest to plug gaps in innovation systems.

Introduction

This report is written in the middle of one of the largest shocks to the global economy and the energy system in history. It is too early to tell with any certainty how lockdowns, the damage to economic activity, or changed attitudes towards risk and values will impact clean energy innovation. However, some data are already available for the first half of 2020, including from an IEA survey of companies conducted for this report, and this sheds some light on early trends. Other possible effects can be predicted from the trends observed in the wake of the global financial crisis of 2007-08.

This chapter reviews the main elements of a tracking framework for clean energy innovation systems before looking at what a selection of clean energy innovation indicators tells up for the period up to 2019. It then sets out the latest information on energy innovation activity in 2020. It ends by exploring how energy innovation might be affected in the future by the Covid-19 pandemic.

Tracking clean energy innovation progress

A clean energy transition to net-zero emissions requires a radical change in both the direction and scale of energy innovation. Drawing from the descriptions in the previous chapter, a national innovation system that is designed to support net-zero emissions could be expected to exhibit the following characteristics, among others:

- Widely communicated and broadly supported visions of how clean energy will be supplied and used in different end-use sectors by mid-century and at intermediate milestones, backed up by published strategies and timetables, and processes for updating them.
- R&D plans that support overall mid-century energy plans and show a coherent match between the level of technological maturity, risk profiles and the type of capital support allocated.
- A rising share of R&D spending allocated by both the public and private sectors to technologies needed for sectors that currently have limited commercially available and scalable options for achieving deep emissions reductions.[4]

[4] These include heavy industry (iron and steel, cement, chemicals, and users of high temperature heat) and long-distance transport (road freight, shipping and aviation). While clean energy solutions have been demonstrated in some of these sectors, they are not yet commercially available with industry-standard performance guarantees and the price gap is high.

- A falling share of R&D spending by the public and private sectors on technologies that extract and convert fossil fuels to energy without carbon capture utilisation and storage (CCUS).
- A good match between spending on clean energy R&D priorities and spending on expanding and upgrading network infrastructure, including electricity grids, telecommunications, gas pipelines, CO_2 networks, and district heat and cooling.
- Rising patenting activity and rising numbers of scientific publications in key enabling technology areas required for net-zero emissions, including for technology types already commercialised.
- Active participation in multilateral and bilateral initiatives for international collaboration on energy innovation challenges that match national priorities and comparative advantages.
- An increasing flow of patient private risk capital into innovative net-zero emissions technologies, for example via VC and more patient impact investors.
- An increasing contribution from low-carbon products and components to the national balance of trade, including revenues from the licensing of intellectual property.
- Regular raising of capital by companies that are highly dependent on revenue from the early adoption phase of low-carbon technologies in sectors that currently have limited commercially available and scalable options for achieving deep emissions reductions. This indicates investor confidence in the markets created for these products.

Not all of these trends can be tracked closely using data available today, and there are further indicators of healthy innovation systems that are even less quantifiable. Despite this, a picture of the performance of clean energy innovation systems can be constructed using information that is available across the four pillars described in Chapter 1. At the more general level of the whole economy, this type of approach is followed for the Global Innovation Index, which aggregates 80 indicators (Cornell University, INSEAD and WIPO, 2018).

The IEA has developed methodologies for tracking a number of key indicators of "resource push" factors and intermediate outputs for clean energy innovation on an annual basis. While it is important to remember that this set of indicators presents only a partial view based on data available at the global level, it nevertheless offers an important insight into the level of innovation effort around the world, and there is scope for it to be expanded in the future. Better quality data on demonstration projects, technology-level corporate R&D, component-level import-export trends, public sentiment and bilateral energy innovation collaborations would be valuable additions: so would much-needed improvements to data quality for public energy R&D spending.

There are benefits for policy makers and investors in such tracking activities. In the early 1990s, few analysts attempted to assess the rate of effort dedicated to developing solar PV and Lithium-ion (Li-ion) batteries and their technical progress: better data might have helped governments allocate resources more effectively and accelerated the development of these technologies. At a national or regional level, more granular analysis is sometimes already possible (Wilson and Kim, 2019).

Government R&D funding

Government energy R&D spending in 2019 grew by 3% to USD 30 billion globally, around 80% of which was directed to low-carbon energy technologies. While the growth rate in 2019 was below that of the previous two years, it remained above the annual average since 2014. In China, the low-carbon component of energy R&D grew by 10% in 2019, with big increases in R&D for energy efficiency and hydrogen in particular. In Europe and the United States, spending on public energy R&D rose by 7% in both economies, above the recent annual trend.

Raising public energy R&D spending and aligning it more closely with decarbonisation needs was behind the pledge made in 2015 by 24 leading countries and the European Commission to double their public investment in clean energy R&D over five years under the Mission Innovation initiative.[5] Governments of major economies have been increasing energy research investments since then, with some countries, such as India, making clear links between their R&D activity and their membership of Mission Innovation.

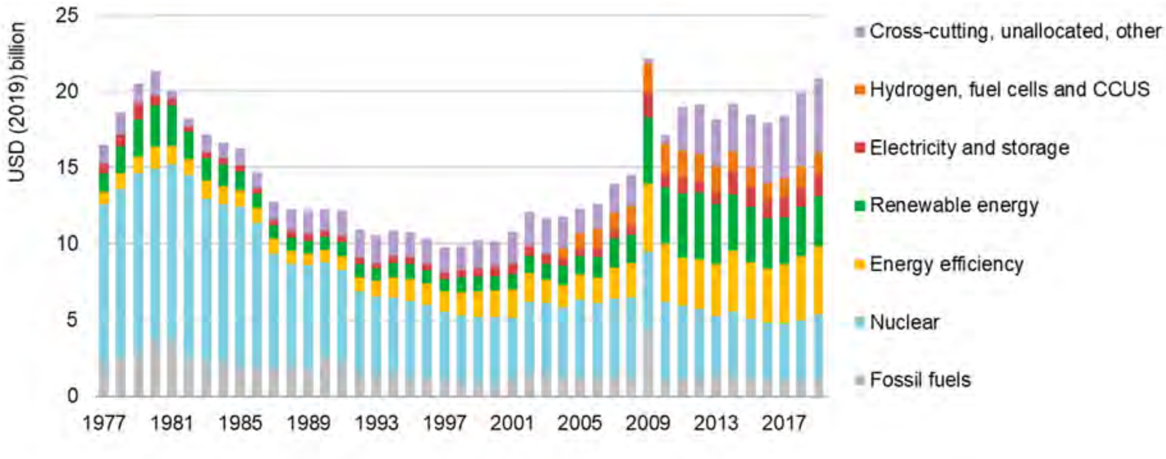
The IEA has maintained a consistent dataset of national public budgets allocated to energy R&D since the 1970s.[6] When adjusted for inflation, these data show that spending on low-carbon energy R&D in IEA member countries doubled between 2000 and 2012, but has been broadly stable since (Figure 2.1). However, it remains just below the levels observed in the early 1980s, when nuclear energy research

[5] Definitions of clean energy and the precise types of spending to be doubled vary between countries.

[6] Based on national data submissions, the dataset covers IEA member countries plus the EU and is open to any other country wishing to participate. Its scope includes spending allocated to demonstration projects (i.e. RD&D). In general, countries report energy-specific research programme spending regardless of the sponsoring government department, but differ in reporting of budgets versus actual spending, and the extent to which they include basic research on energy-related topics or demonstration project funds (IEA, 2020a). While basic energy research is sometimes managed by funding institutions with oversight for energy technology, for example in the United States, in many other countries this research is not isolated and reported as such. Given the outsized importance of publicly funded R&D in the basic sciences, which leads directly to the breakthroughs that underpin new energy technologies and start-ups, it is likely that reported data underestimate total spending. Tax exemptions, loans and general support to innovative energy technology companies are not included (IEA, 2011).

dominated the national budget in several countries. In absolute terms, spending on fossil fuels has remained roughly constant, though its share in total energy R&D has fallen with growth in total spending.

Figure 2.1 IEA public energy technology R&D and demonstration spending by technology



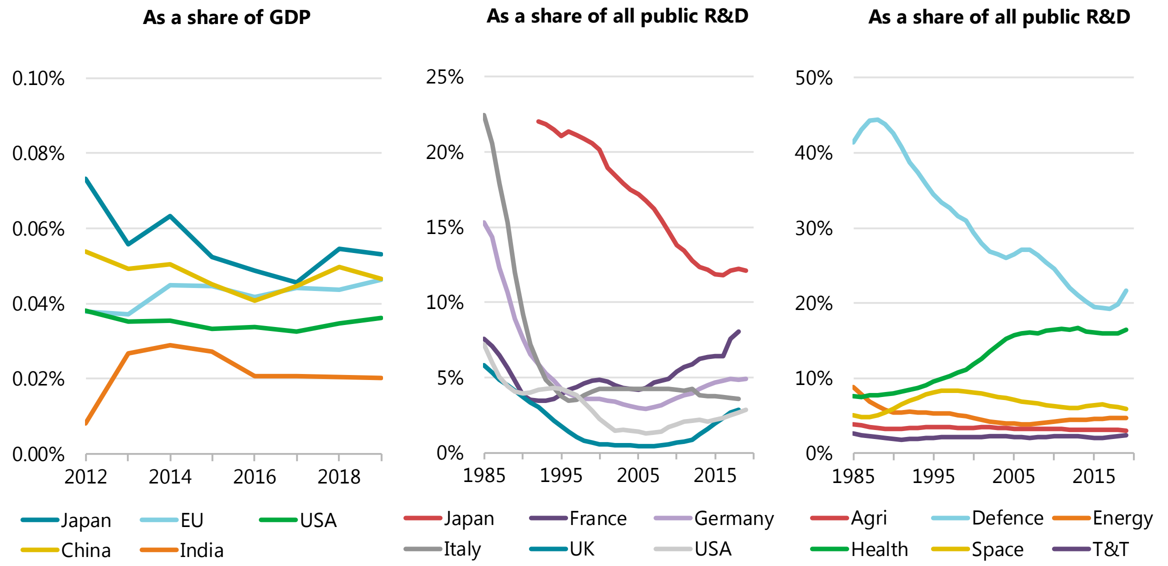
Notes: Peak in 2009 was due to post 2007-08 financial crisis stimulus funding, especially in the United States. CCUS = carbon capture utilisation and storage.
Source: IEA (2020a).

IEA member government R&D spending, which goes mostly to low-carbon technologies, has been broadly flat since 2012 after having doubled over the previous decade or so.

The technology portfolio in public energy R&D is more balanced today than in previous decades, with far more money going to energy efficiency and renewables.[7] Despite this, the portfolio remains strongly oriented towards supply-side technologies, rather than the types of end-use innovations needed for sectors that currently have no commercially available and scalable options for achieving deep emissions reductions. Furthermore, although energy R&D budgets are growing in the aggregate, including for developing low-carbon technologies, they are not growing as a share of GDP, and they account for a shrinking share of total government R&D spending in most cases (Figure 2.2). Energy R&D spending has been losing ground to other public research objectives in recent decades, with health and defence now receiving around five times more R&D funding than energy in OECD member countries. Modest upticks in the share going to energy in some countries since 2005 are nonetheless encouraging (Figure 2.2).

[7] Precise comparisons are difficult due to the rising levels of spending that are not allocated to a particular technology application or are allocated to "cross-cutting" projects, which include research that cannot be allocated to a specific category, such as systems analysis or joint research on the integration of energy sources into networks or end uses.

Figure 2.2 Public energy R&D over GDP and as a share of all public R&D by country and sector



Notes: EU = European Union; USA = United States of America; UK = United Kingdom; China = China (People's Republic of); Agri = agriculture; T&T = transport and telecommunications. EU includes the budget of the European Commission, plus EU member countries as of December 2019 that are also members of the IEA, as well as Norway. Right-hand chart shows shares aggregated across OECD countries for which data are available for each category in each year.

Source: IEA calculations based on IEA (2020b) and OECD (2020a).

Public energy R&D spending has remained fairly constant in terms of overall GDP in major economies since 2012. Since 1985, however, energy has accounted for a diminishing share of government's R&D spending.

Status of major economies' funding programmes

One of the world's largest funding programmes for energy technology demonstration is China's National Major Science and Technology Projects programme. Under this scheme, selected state-owned enterprises are given responsibility and funding for a priority engineering challenge over a multi-year period, for example USD 1 billion over five years. Challenges are designed to attract more co-funding and favourable loans from local governments and enterprises. Large oil and gas, coal bed methane, and nuclear projects were prioritised up to 2020; among the 16 projects announced for 2020-30 are turbines, coal use and smart grids. The bulk of funding from the Ministry of Science and Technology goes to "National Key R&D Projects". Around USD 200 million of this was allocated annually to electric vehicles and smart grids in 2016 and 2017, often for basic research, and around USD 65 million was allocated to renewable energy and hydrogen in 2019. In 2016-17, clean and energy-saving coal received USD 70 million per year.

The European Commission is in the process of finalising its next multiannual R&D funding programme, Horizon Europe, which will run from 2021 to 2027. It foresees an allocation of USD 17 billion for energy, climate and mobility, which represents 16% of the total Horizon Europe budget. Much of this will go to clean energy R&D: funding for fossil fuel extraction and use has been mostly phased out. European Union-funded projects are increasingly open to participation from overseas collaborators, including emerging economies. Horizon Europe will continue the diversification of funding instruments begun under its predecessor to meet innovators' needs, including blended finance options for large-scale demonstration projects, innovation prizes, support for small and medium-sized enterprises, and equity funding for start-ups. As part of this, an "Innovation Fund" is under development with the aim of recycling up to USD 11 billion of revenue from CO_2 trading to first-of-a-kind demonstration projects, integrating lessons learnt from its predecessor, the NER300. Renewed efforts are also being made to further harmonise European Union and member states' research funding through initiatives similar to the "Fuel Cell and Hydrogen Joint Undertaking", which unites public and private funds and co-ordinates expenditure of over USD 200 million per year.

In Japan, a renewed "Environment Innovation Strategy" was published in January 2020, highlighting as many as 39 priority energy technology areas with a higher level of specificity about target applications than in the plans of most other countries. This strategy retains around 25 of the priorities from the 2016 strategy and adds new priorities on nuclear and zero-carbon steel, together with more specificity on renewables, transport and CCUS. The New Energy and Industrial Technology Development Organization, which has a budget of around USD 1.5 billion, and which has funded projects for industrial-scale technology trials in Japan for 40 years, has recently extended its remit to include overseas projects. Japan has a high level of co-ordination between government and large industrial players, enabling long-term projects to be undertaken in partnership: the 2014-18 strategic programme on hydrogen energy carriers is a good example.

The United States' 17 national laboratories, overseen by the Department of Energy, constitute one of the largest scientific research systems in the world, having added responsibilities across most energy areas to their original nuclear and fossil fuel missions from the mid-20th century. Many are run by private companies and have strong ties to local universities. The Advanced Research Projects Agency–Energy programme, established shortly before the 2007-08 financial crisis, has around USD 350 million of annual funding and aims to nurture new strategic energy technologies to achieve rapid deployment of radical technologies with high market potential, including by combining expertise across disciplines to seek spillovers.

Private sector R&D funding

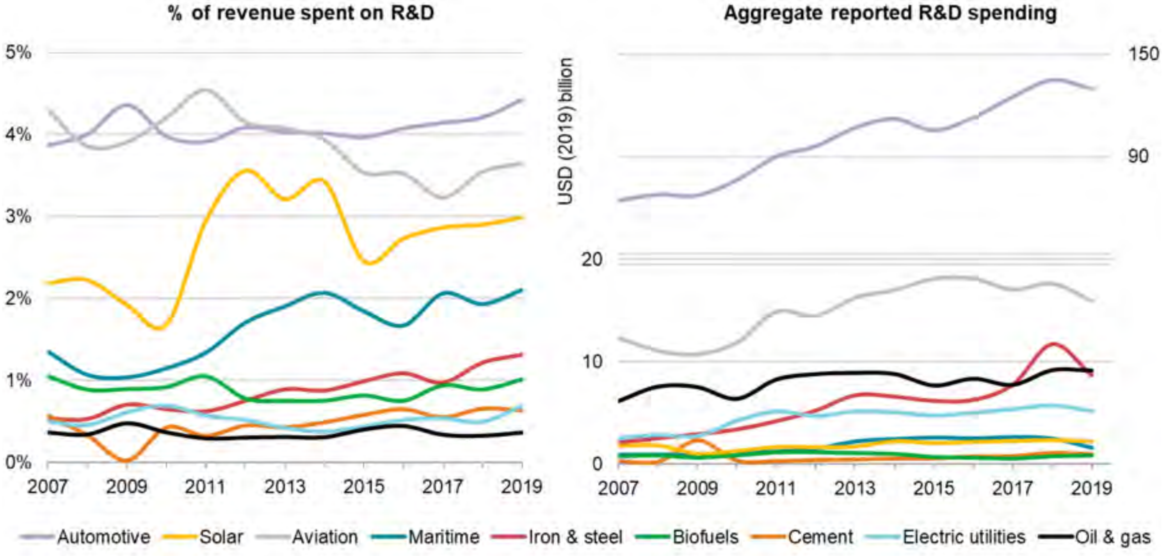
Companies active in energy technology sectors have increased their total annual energy R&D spending by around 40% over the last decade (IEA, 2020b), and their total energy R&D spending reached around USD 90 billion in 2019. In 2019, growth was 3%, lower than the 5% annual growth observed in the two periods 2010-13 and 2015-18, which were preceded by the global financial crisis and divided by the economic impact of the oil price collapse of 2014. The oil price collapse of 2014 caused a 10% drop in the R&D spending of oil and gas companies over two years, and it took four years for spending to recover.

It is worth noting that companies active in renewable energy technologies have increased their R&D spending faster than other energy technology sector companies: they increased their expenditure on R&D by 74% between 2010 and 2019, adding over USD 2.5 billion to efforts to improve their technologies.

The automobile sector spends more on R&D than any other energy-relevant sector (Figure 2.3).[8] Companies have continued to increase their spending in recent years, with government policies and competitive pressures leading them to focus more on energy efficiency and electric vehicles: growth in energy-related R&D seems, however, to have flattened out between 2018 and 2019. New companies, especially those making battery and fuel cell electric vehicles, are meanwhile starting to enter the market and trying to dislodge the major manufacturers. Globally, the number of carmakers selling over 1 million vehicles per year has grown from 15 to 20 since 2005 spurring the emergence of new high-profile start-ups in electric vehicles. All the established carmakers have announced new vehicle designs, battery research coalitions and pilot testing of highly digitalised electric vehicles, and their future success may depend at least in part on their ability to direct sufficient revenue from their current portfolio of products to R&D for low-carbon alternatives. Incumbents in other sectors may face a similar balancing act.

[8] Information and communication technologies (ICT) are increasingly important to energy transitions, and are also enabling productivity gains in fossil technologies, but this sector is not included here as its outputs are not energy-specific.

Figure 2.3 Global corporate R&D spending of selected sectors and as a share of revenue, 2007-19



Notes: Includes companies reporting 50% or more of their revenue in these sectors, per Bloomberg Industrial Classification System (BICS), and for which both reported R&D and revenue data are available in a given year. Total R&D expenditure (not only energy-related R&D) is scaled by the company's revenue share in the reported sector. Automotive is shown on the right-hand axis in the chart of aggregate reported R&D spending. Like other classifications such as ISIC and NACE, BICS provides a structure for analysing data related to different economic activities. It is used here because of the high degree of disaggregation of firm-level data for energy-related sectors.

Source: Bloomberg LLP (2020).

Some sectors for which new technologies will be critical to net-zero emissions typically reinvest a small share of their revenue in R&D, while car companies markedly outspend other sectors.

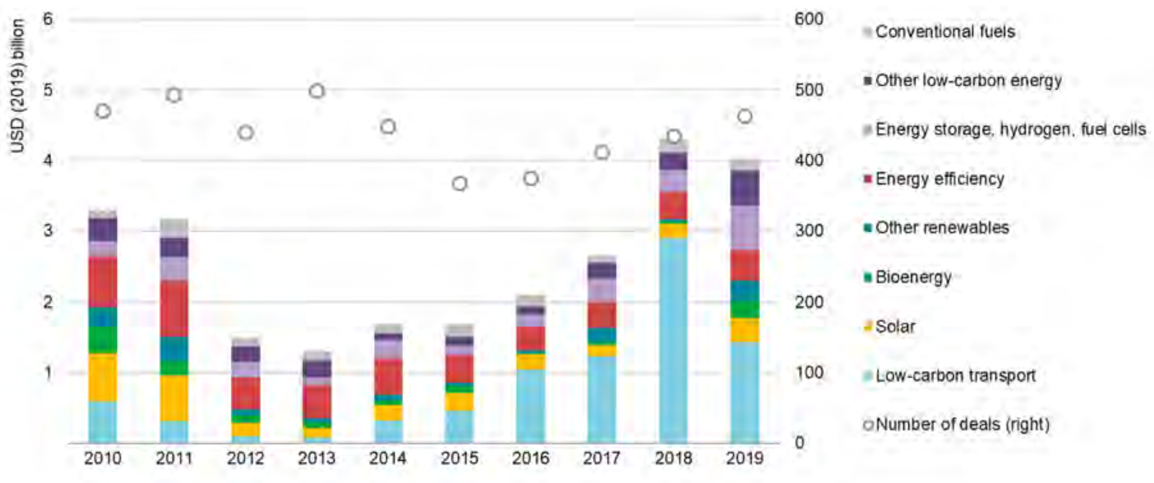
Other sectors – notably cement, biofuels, electric utilities, and iron and steel – invest much less in R&D as a proportion of their revenue. Solar PV manufacturers, the maritime sector and the aviation sector invest rather more than these (though the aviation sector's share has fallen in recent years), but still much less than the automotive sector. This may reflect a view that new technology-driven products are of less importance to their competitiveness than is the case for carmakers. Electric utilities and heavy industrial companies are generally consumers of technology, typically engaging in technology development via partnerships with suppliers. Nonetheless, it is striking that companies in sectors for which new technologies will be critical to achieving net-zero emissions typically invest relatively little in R&D. These sectors will need to test, modify and, in some cases, develop new processes and products for deep decarbonisation.

Some governments have implemented systems to track private sector spending on energy technologies via surveys. While this has yet to be done in a sufficient number of countries to allow international analysis, Canada and Italy are good examples of progress so far.

Venture capital

Total equity investment in energy technology start-ups by all investor types stood at USD 16.5 billion in 2019. Of this, early-stage VC (seed, series A and series B), which supports innovative firms through their highest risk stages, is estimated to account for USD 4 billion (Figure 2.4). These sums are lower than those spent on energy R&D by governments and companies, but this private risk capital plays an important role in helping the most market-ready technologies to create markets and scale-up. The total value of reported deals in 2019 was 7% lower than in 2018, but the figure in both years was well above the average for the decade.

Figure 2.4 Global early-stage venture capital deals for energy technology start-ups



Notes: Includes seed, series A and series B financing deals. Outlier deals of over USD 1 billion that distort the year-on-year trend are excluded; they totalled USD 1.6 billion in 2016, zero in 2017, USD 2.1 billion in 2018 and zero in 2019. Transport includes alternative powertrains and their infrastructure, but does not include shared mobility, logistics or autonomous vehicle technology. “Bioenergy” does not include biochemicals. “Other low-carbon energy” includes CCUS and smart grids. “Conventional fuels” includes fossil fuel extraction and use as well as vehicle fuel economy.
Sources: IEA calculations based on Cleantech Group (2020).

Venture capital investment remained robust in 2019, with more diversification of sectors and countries for clean energy technology start-ups. Storage and hydrogen saw the most growth.

VC fulfils a valuable role by providing finance and imposing the discipline of private capital in cases where its providers see a potential near-term market opportunity and a longer term chance to capture significant market share. VC investors provide risk capital to entrepreneurs in the expectation that the winners in a portfolio of technology and business ideas will scale-up rapidly and profitably enough to pay back their investments in the whole portfolio at around 20% per year over five years. In the energy sector, VC has typically been most effective in supporting start-ups with digital technologies or service offerings that can be quickly prototyped and are not capital intensive (Gaddy, Sivaram and O'Sullivan, 2016; IEA, 2017). Hardware areas like electricity storage, electric vehicles and hydrogen production have, however, recently attracted more VC investment. Most VC investment has taken place in the United States, where financial regulations support VC activity and VC financing is well established, but both Europe and China have recently seen growth in their share of global energy VC activity (IEA, 2020b).

Overall, trends suggest that investors see rising market potential in low-carbon technologies, driven by expectations of more stringent public policy incentives. They also suggest that, in some areas of technology – principally those involving smaller scale technologies and consumer products that are close to market readiness – private risk capital can support and reward the best innovations, and so reduce the need for public sector support. In these areas, VC investors can help technologies make it through the "valley of death" by providing funds for researchers seeking to test an initial idea or for small companies needing to move their idea beyond an initial niche market – ideas that are frequently the products of government-funded early-stage R&D (Breschi et al., 2019). However, the share of clean energy in the total value of global VC deals has fallen from around 10% to around 5% since 2012, indicating that clean energy is becoming less attractive to VC than other technology areas such as biotechnology and information technology.

To boost activity, some governments are exploring direct investment in clean energy start-ups, for example by taking so-called "anchor" equity stakes in riskier start-ups. Breakthrough Energy Ventures Europe, a USD 100 million fund established in 2019, is an example (Breakthrough Energy, 2020). The evidence on government equity stakes in such companies is, however, mixed, and governments generally have to be first to accept losses if the technologies underperform. It is notable that this policy has not been widely used in the United States, where the VC market is well established, despite the appeal of reaping some of the gains from public R&D for taxpayers.

Some countries provide targeted grant support to clean energy start-ups instead. Breakthrough Energy Solutions Canada announced the ten winners of its first round of evaluation in early 2020. In India, the Clean Energy International Incubation Centre was established in 2018 as a partnership between the public sector, which provides grants, and the private sector, which provides infrastructure and equity: it offers equity funding and guidance to start-ups with potential solutions to India's energy challenges. Other countries, including France and Italy, provide tax credits and other benefits to young technology-intensive firms, many of which are spin-offs from academia.

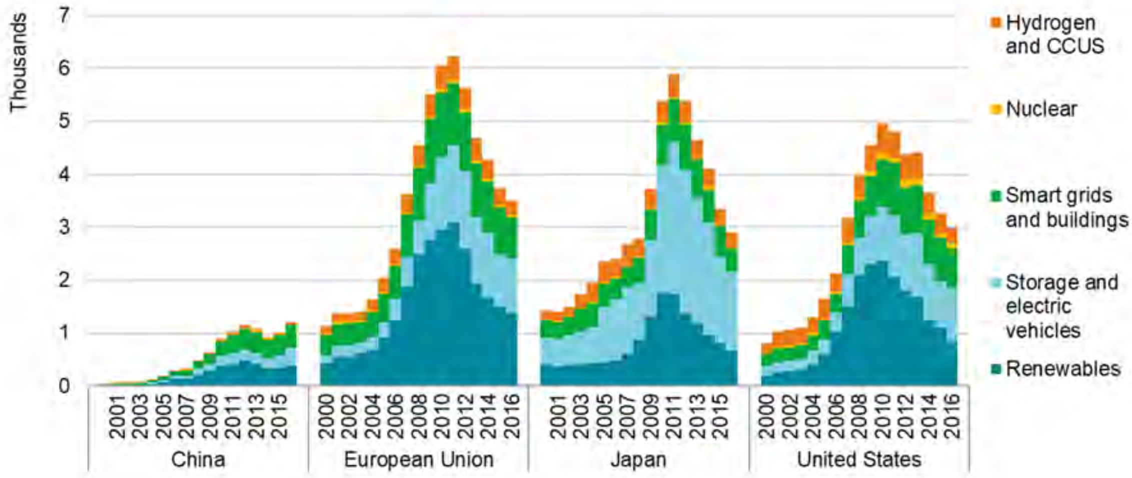
Companies, too, are turning to VC as part of their energy innovation strategies. Faced with regulatory and technological uncertainty, especially in areas dominated by unfamiliar or digital products, corporations are increasingly turning to corporate VC[9] and "open innovation" rather than allocating corporate R&D budgets to developing them in-house (Bennett, 2019). Investments in energy technology start-ups, including those funded by corporate VC and growth equity, reached a new high in 2019 at around USD 5 billion globally. As companies are pushed by net-zero targets to integrate new activities outside their core competences, companies may well increasingly look to corporate VC and the acquisition of start-ups as ways of managing technology uncertainty. Many of the technologies that are expected to contribute to net-zero emissions could be well suited to corporate VC funding, especially if they can be packaged as attractive consumer offerings, because they involve small-unit size technologies and could complement companies existing portfolios: digital controls for energy efficiency and energy storage are a case in point.

Patenting

Following a decade of strong growth in the number of patents filed for low-carbon energy technologies, there has been a marked decline since 2011 (Figure 2.5). Patents provide an insight into the research activities that are generating new knowledge with perceived commercial value: they capture some of the intermediate outputs of R&D, a proportion of which will be translated into commercial products. They do not provide a direct measure of all R&D outputs, not least because they over-represent technologies and jurisdictions for which patenting is more common: in some fast-moving fields, the patenting process can take longer than the opportunity to recoup R&D costs from marketing the technology ahead of the competition, for example, while many digital services based on software and apps are not patentable. Nonetheless, overall trends in patenting provide useful information about the extent and focus of clean energy innovation.

[9] Corporate VC is a subset of VC involving equity investments in start-ups that are developing a new technology or services by companies whose primary business is not venture capital nor other equity investments. In addition to playing the traditional role of a venture capital investor, corporate VC investors often provide support to the start-ups via access to their customer base, R&D laboratories and other corporate resources. Corporate VC in the energy sector has been around since the mid-20th century, when Exxon Enterprises invested in a variety of technologies, including solar, as part of a diversification strategy.

Figure 2.5 Issuance of patents for low-carbon energy technologies in selected countries/regions



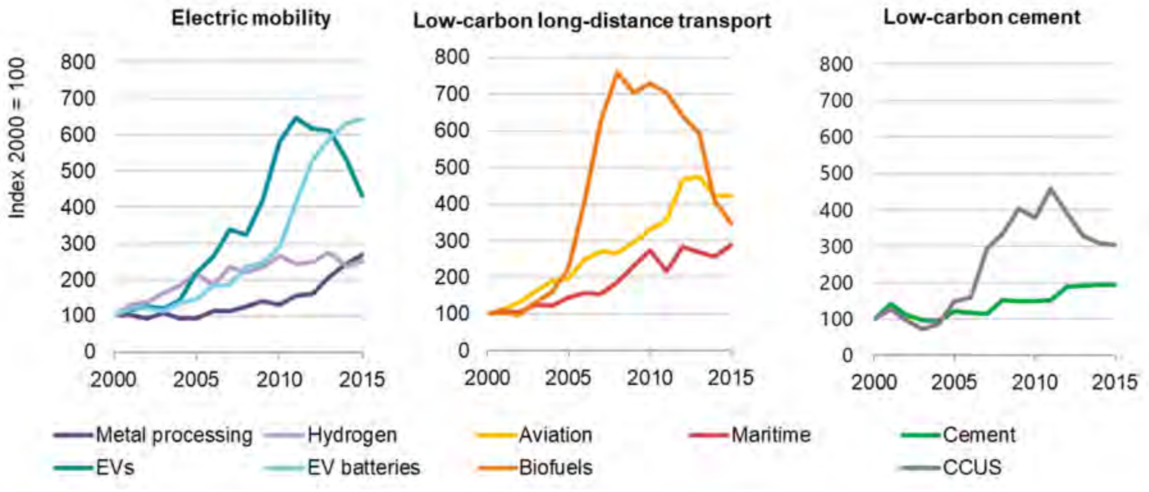
Notes: Patent counts refer to the number of granted international patent families that include at least two geographical offices. Counts are allocated to countries based on the country of the inventor. CCUS = carbon capture utilisation and storage; China = China (People's Republic of).
Source: OECD (2020b).

Following a decade of strong growth in patenting low-carbon energy technologies, there has been an almost uninterrupted slowdown since 2011.

The decline in renewable energy patenting activity since around 2011 may in large part reflect the maturity of some technologies. The dominance of existing solar PV, bioethanol and wind technologies may deter researchers from seeking to improve them and enter the market in Europe, Japan and the United States. Patenting activity for renewable energy remains higher than at any time before around 2007 and patenting for batteries, particularly Li-ion, is a growth area (EPO and IEA, 2020). However, it is still a concern that the decline in patenting since 2011 has so far not been offset by patents in advanced biofuels, novel PV, geothermal, ocean or other renewables.

The adoption of some low-carbon technologies relies on the development of other non-energy technologies in the same value chain. However, patent trends indicate that the level of attention to different technology applications in the same value chain families is not consistent (Figure 2.6). For example, patenting for EV batteries has risen more than two times faster than patenting for metal processing, yet widespread electric mobility depends on new approaches to lightweighting vehicles.

Figure 2.6 Counts of global patents for related applications of low-carbon technologies



Notes: Patent counts refer to the number of granted international patent families that include at least two geographical offices. Counts are allocated to countries based on the country of the inventor. CCUS = carbon capture utilisation and storage; EVs = electric vehicles. For EV batteries, the counts refer to patent applications to the World Intellectual Property Organization. Metal processing refers to the manufacture of bulk metals and its processing to semi-finished and finished metallic products.

Sources: OECD (2020b) and EPO and IEA (2020).

Patenting trends vary widely between low-carbon technologies, including those that would need to be combined to deliver zero emissions in certain applications.

National policy support

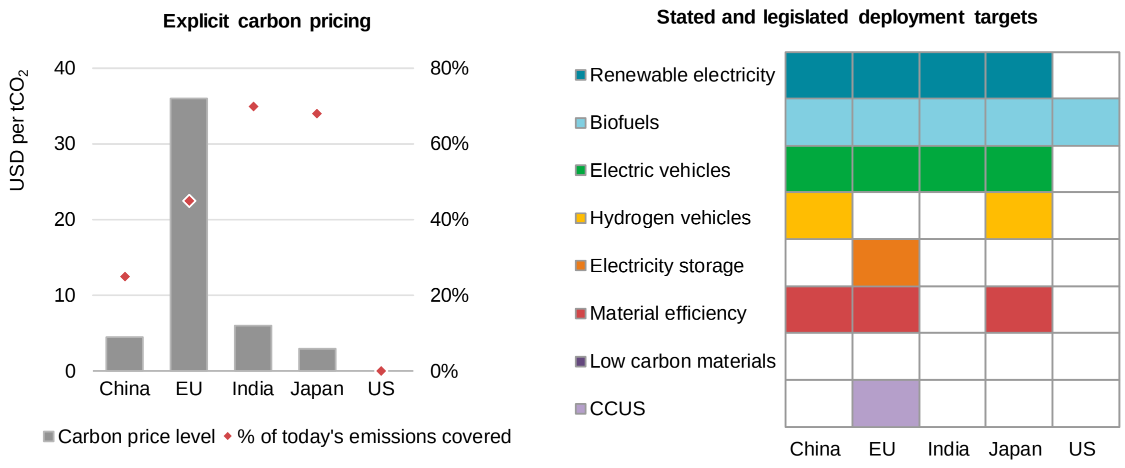
While data are readily available on funding for innovation systems from the public and private sectors as well as for market-led financing such as early-stage VC, this gives only a partial picture. To get a fuller picture, we need also to look at the information that governments regularly provide about the ways in which energy R&D topics are prioritised, knowledge is shared, markets are created and socio-political support is built up. This section provides a brief overview of some relevant developments.

The prioritisation of research topics for clean energy funding programmes and arrangements for the evaluation of those programmes do not follow global standards. Indeed, this is an area that might benefit from some sharing of best practices between practitioners. In Japan, prioritisation and road-mapping are well-documented and provide clear guidance for R&D spending: the process benefits from a high level of co-ordination between government and large industrial players, which enables long-term projects to be undertaken in partnership. China, likewise, has a highly centralised multi-year planning framework that provides clear indications of national innovation priorities; a downside, however, can be a lack of flexibility within these budget periods. One key area that all governments need to consider is how best to exploit synergies between clean energy technology areas: this is an area where Japan and Korea stand out for their promotion of electrochemical technologies across different sectors, from batteries to fuel cells. While many countries have audit processes for programme review, evaluation against overall innovation policy objectives is rarely embedded in policy design (Pless, Hepburn and Farrell, 2020): US programmes, in particular high-level initiatives exposed to political risk, provide some particular examples of good practice.

Governments have begun paying increasing attention in recent years to knowledge sharing. The European Commission now requires recipients of funding to publish results with open access, while technology programmes co-ordinated by the US Department of Energy regularly publish their findings in detail. Certain elements of knowledge generated from European Union-funded large-scale demonstration projects have to be made public, and there is a similar requirement for CCUS projects in Alberta (Canada). In China, the creation of specific zones for the development and deployment of certain technologies, including electric vehicles and hydrogen, facilitates knowledge exchange.

Different economies have different approaches to creating markets that support early-stage commercialisation of clean energy technologies for public policy purposes. The European Union has the highest explicit carbon price and also the most deployment targets for clean energy technologies (Figure 2.7). Across major economies, targets for renewable electricity, biofuels and electric vehicles are common. Public procurement also plays a role in creating niche markets in some countries. In India, it is used to create dependable local markets for new products, such as LEDs, appliances and electric vehicles, while Norway's approach to decarbonisation of maritime transport links R&D and public procurement (DNV-GL, 2019). China's combination of rapid prototyping, public procurement, cheap finance for manufacturing and internal market deployment has proved effective for improving mass-produced products such as electric vehicles and LEDs at an early stage of technology readiness: its relatively high tolerance of trial-and-error is a specific advantage. In Japan, strong standards in energy efficiency and other areas drive market-led innovation, while well-designed requirements for evaluating R&D projects, programmes and planning help to improve them.

Figure 2.7 Levels of explicit carbon pricing and deployment targets that could stimulate innovation in zero-emission technologies



Notes: EU = European Union; US = United States; China = China (People's Republic of). Excludes subnational or EU member state policies, which increase the market-pull incentives for innovation in some regions. Carbon pricing includes explicit climate change-related pricing policies; it does not include other general energy taxes (which effectively price carbon). Targets included set an objective for future deployment in a given technology application and explicitly support the technology referenced in the legend. CCUS = carbon capture utilisation and storage.

The European Union has the highest carbon price; Japan and India's carbon pricing schemes have the widest coverage; most stated and legislated targets for key zero emissions technologies are concentrated in renewable energies.

Potential impact of Covid-19 on clean energy innovation

The complexity of the global clean energy system makes it hard to assess how Covid-19 will affect the speed with which clean energy technologies can be developed and improved. This is compounded by widespread uncertainty about the longer term impacts of the pandemic. However, available data and historical precedent suggest significant cause for concern, given the urgency of the need to compress innovation timelines for clean energy technologies. There are signs that the global clean energy innovation system will be hard hit by spending cutbacks, especially in the private sector, with the largest impact in the near term being a tougher environment for scale-up and commercialisation. In simple terms, there is a risk that the "valley of death" becomes deeper and wider.

Before the pandemic hit, 2020 was expected to be a critical year for several major energy innovation policy initiatives, with keen interest in the details of the European Union's Horizon Europe and Innovation Fund, for example, and in the energy R&D elements of China's 14th Five-Year Plan. These policies, and many others in preparation around the world, are still top priorities, but the immediate focus has shifted to managing revenue losses and economic recovery in most countries. At the same time, many companies are facing severe pressures, and all are having to adjust to a changed and uncertain economic outlook.

While the immediate task of protecting health and livelihoods is understandably occupying all parties in the first half of 2020, measures that directly or indirectly address clean energy innovation have nevertheless already featured in the policy responses of several governments (Table 2.1). Details are still emerging, and other governments are still considering their positions; even so, these policy signals help to give at least an initial idea about how the environment for clean energy technology might evolve between mid-2020 and 2025.

Table 2.1 Selected announcements of relevant measures in economy recovery measures as of early June 2020

Government	Announced measure	Status
European Union	The proposed recovery instrument, Next Generation European Union, includes a Strategic Investment Facility to generate investments of up to EUR 150 billion in strategic sectors, including those linked to the green economy and clean energy transition, with a specific mention for hydrogen energy. Horizon Europe is to be reinforced with additional funds and will have a continued focus on green technologies. The Strategies for Smart Sector Integration and Sustainable and Smart Mobility are proposed as priority areas for immediate investment.	Proposed by the European Commission on 29 May 2020, launching a legislative process that could see implementation from January 2021.
Canada	A non-sector-specific fund of CAD 450 million for universities and health research institutes is aimed at enabling them to retain research staff, and there is also a fund of CAD 20 million to support young entrepreneurs facing challenges due to Covid-19. Quebec has made available targeted grants for businesses at various stages of an innovation project (planning to pre-marketing stage) to help build their capacity for innovation.	National measures announced on 15 May 2020.

Government	Announced measure	Status
France	A non-sector specific fund of EUR 80 million has been established to provide bridge financing to start-ups to help them maintain cash levels between fundraising rounds, together with EUR 1.3 billion to finance cheaper loans and up to EUR 1.5 million in tax breaks for innovative SMEs to weather the crisis. EUR 250 million is available to accelerate the payment of support for innovation projects, together with a EUR 1 billion fund for the modernisation and digitisation of automotive production. A EUR 15 billion support package for the aerospace sector includes a EUR 500 million investment fund for smaller companies and a plan to demonstrate a carbon-neutral intercontinental plane by 2028 using biofuels or hydrogen-based fuels and launch it by 2035. A hybrid electric or hydrogen plane for shorter distances is also targeted.	Funds announced on 25 March 2020. Aerospace details pubzlished on 9 June 2020.
Germany	The stimulus package which has been announced establishes a EUR 50 billion fund for addressing climate change, innovation and digitisation. This is set to include market expansion measures for electric vehicles, R&D funding for energy storage and a EUR 9 billion Hydrogen Strategy to make Germany a "supplier of the world" in electrolysis-related technologies. There is an additional EUR 2 billion non-sector specific fund to expand venture capital financing to start-ups, new technology companies and small businesses.	Announced on 3 June 2020.
Portugal	A National Hydrogen Strategy will be developed to provide a vision and framework for those with hydrogen projects in progress or at an initial phase, aimed at integrating them into a coherent strategy that furnishes the necessary support to unlock public and private investment of EUR 5 billion to EUR 10 billion in the period to 2030.	In public consultation since 22 May 2020.
United Kingdom	A non-sector specific Future Fund with a budget of GBP 500 million was launched to issue convertible loans of up to GBP 5 million to innovative start-ups, together with GBP 750 million to support innovative start-ups via grants, equity and other measures.	Launched on 20 April 2020.

Sources: Breugel (2020); European Commission (2020); HM Treasury (2020); KPMG (2020); MAAC (2020).

Another area of concern is the impact of Covid-19 on global supply chains and how they transmit and develop new knowledge. As described in Chapter 1, the history of performance improvement and cost reduction for solar PV and Li-ion batteries is a global one: new ideas were passed between regions by mobile companies and researchers that responded to the market and funding opportunities in different countries. Global supply chains have been weakened by recent lockdowns and restrictions in response to the Covid-19 pandemic, and it remains unclear how national policy responses will affect their future development.

The overall picture that emerges from the policy announcements and the data presented in this section is that of a seriously weakened innovation system, with demonstration, market entry and learning-by-doing suffering most in the first instance. Additionally, sectors that currently have limited commercially available and scalable low-carbon options and that were already missing concerted efforts to develop suitable zero emissions technologies, could face even longer delays to clean energy innovation. Although emerging economies have yet to publish economic stimulus plans, many of them are likely to be facing particularly significant pressure on their R&D budgets. The evidence so far suggests a systemic challenge: although the risks to basic R&D and prototyping may be lower in the near term, their impact will be diminished if the system as a whole has less capacity to make good use of them. In broad economic terms, if 20% fewer firms are established in a crisis year, which was the case during the 2007-08 financial crisis, then employment could be 0.7% lower overall three years later, and 0.5% lower 14 years later (OECD, 2020c). This issue has not been addressed so far in recovery packages.

Government R&D funding

While it is too early to determine the impact of the Covid-19 pandemic on public energy R&D, the outlook is an uncomfortable one. In many cases, the relevant budgets may be fixed for the next couple of years, and the budgetary pressures may be strongest in the period 2022-25. This seems to be what happened in the years following the 2007-08 financial crisis. In Europe, for example, R&D budgets significantly decreased in 2011-13, three years after the financial crisis, particularly in those countries with the deepest recessions (Izsak et al., 2013). It is worth noting, however, that several major countries turned to R&D policy as a way to reduce reliance on the financial sector after 2008-09 and introduced new types of innovation instruments, such as guarantees, loans and support for VC (see Chapter 5). This is consistent with policies in these countries to pursue counter-cyclical R&D policy, but it is not an option that is available to all governments (OECD, 2009; Pellens et al., 2018).

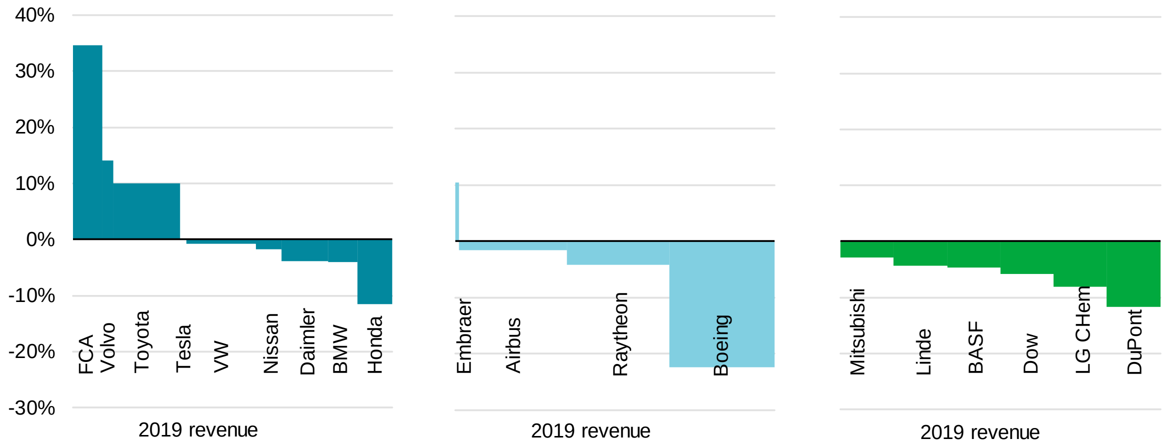
Emerging economies like Brazil and India, which have recently been raising their ambitions to develop indigenous clean energy technologies, may suffer setbacks unless they can tap into additional budget resources. These countries are identifying specific technology needs for their societies and climates that are not being addressed by companies and researchers in other countries. As emerging economies represent most of the projected growth in energy demand in the coming decades, what they decide has important implications for the clean energy transition as a whole. A prolonged downturn in any country would also carry the risk of the loss of highly skilled and highly mobile staff.

Another innovation-related area where government spending is threatened is infrastructure. Governments and regulated entities are typically the primary investors in networks such as electricity grids, district heating, gas grids and communications technologies. Enabling infrastructure that anticipates the needs of new technologies is often critical to the speed of their success. Lower revenues for regulated utilities around the world as a result of Covid-19 pose a challenge to ramping up investments in smart grids, hydrogen-ready pipelines and refuelling, and even CO_2 storage. Where third-party access is guaranteed, the costs of entry for new technology options can, however, be greatly reduced. In the United States, such guaranteed third-party access for CCUS projects as a result of government investment in CO_2 pipelines for the oil industry forms the basis for major CCUS project designs today.

Private sector R&D funding

Corporate R&D is highly likely to be cut or to grow much more slowly in most energy-related sectors as a result of lower revenues in 2020 and beyond. This impact is already evident in company reports for the first quarter of 2020, with companies representing a large share of global revenue in the automotive, aviation and chemicals spending less on R&D than in previous years (Figure 2.8). Reductions were seen in all reporting companies in the chemical sector, with some declines of over 10%. This matches the perceptions of respondents to our survey in May 2020, who anticipate pressure on corporate R&D budgets for key net-zero emissions technology areas for the rest of 2020 and into 2021 (Chapter 1).

Figure 2.8 Changes in R&D spending of automotive, aviation and chemicals firms, Q1 2020–Q1 2019



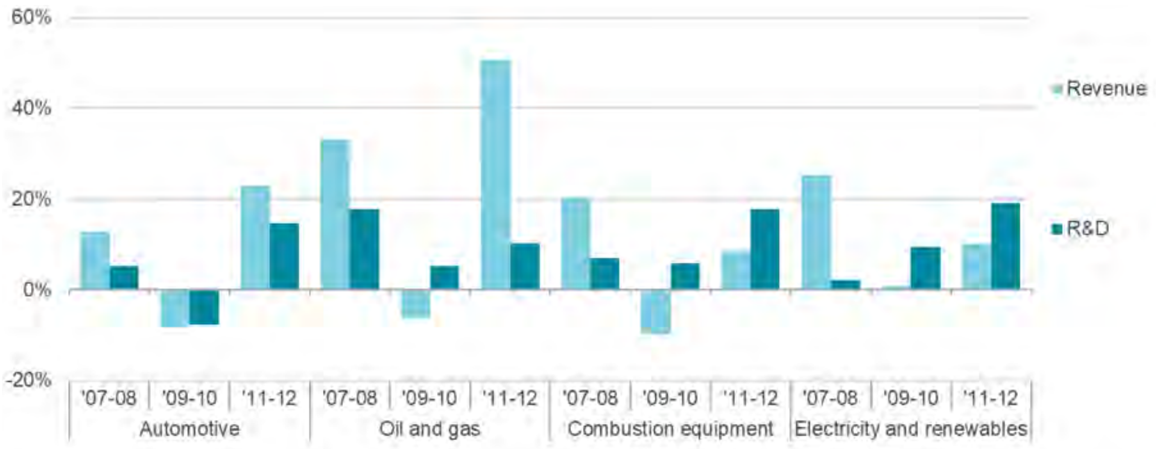
Note: Shows data for the subset of companies that report quarterly R&D spending. Column widths are proportional to revenue in 2019.
Source: IEA calculations based on corporate financial reporting.

Cuts to corporate R&D of 10% or more are evident in company reports of major technology firms for the first quarter of 2020, with sustained lower spending expected through the end of the year.

The financial crisis of 2007-8 and the oil price collapse of 2014 provide some insight into the likely response of companies to the impacts of the Covid-19 pandemic. In 2009-10, the total R&D spending of major energy sectors held up well relative to revenues, with the exception of the automotive sector (Figure 2.9). However, in absolute terms, the electricity supply and renewables sectors were the only energy sectors not to experience slower growth or cuts to R&D budgets in this period. As in 2009, the outcome will be heavily influenced by government policies: for example, the tax incentives and R&D-specific loans being proposed for inclusion in some stimulus packages should be helpful. It is also worth noting that there is some evidence that recessions can create opportunities for companies to reorient to disruptive technologies (Archibugi et al., 2013).

While R&D spending is likely to suffer in the next few years, it can be expected to be much less affected than capital expenditure, as companies seek to retain R&D staff and capabilities and to complete ongoing projects. Furthermore, as underlined by our survey, major companies in several sectors have restated their commitment to a longer term decarbonisation strategy in spite of the challenges ahead. Cuts to capital investment could, however, be more damaging than cuts to R&D for large-scale demonstration of technologies, such as CCUS. Major projects could be postponed and lose vital momentum. Net-zero goals rely on several large-scale, pre-commercial technologies such as CCUS, low-carbon steel processes, large-scale hydrogen supplies, new ships and aircraft concepts (see Chapter 4). A loss of momentum now would be especially bad timing: the past year has seen a number of path-breaking commitments by major industrial players to net-zero goals, which implicitly commit them to the scale-up of technologies in need of demonstration and first-mover investment. A salient example is the integration of low-carbon hydrogen into refineries and gas grids to help meet the ambitious emission targets of several oil and gas companies.[10] Several such projects – including H2.50, H21, HySynergy and NorthH2 in Europe and Sundance Hydrogen in Canada – are currently at the design stage and represent some of the first to be driven largely by private rather than public financial incentives.

Figure 2.9 Growth rates for revenue and R&D for selected sectors, 2007-12



Note: Shows average annual growth rates per pairs of years for the top 20 R&D spenders per sector that reported data in each year.
Source: IEA calculations based on Bloomberg LLP (2020).

In 2009-10, the total R&D spending of key energy sectors grew more slowly than before the 2007-08 financial crisis, with a decline in the automotive sector; electricity and renewables were an exception.

Venture capital

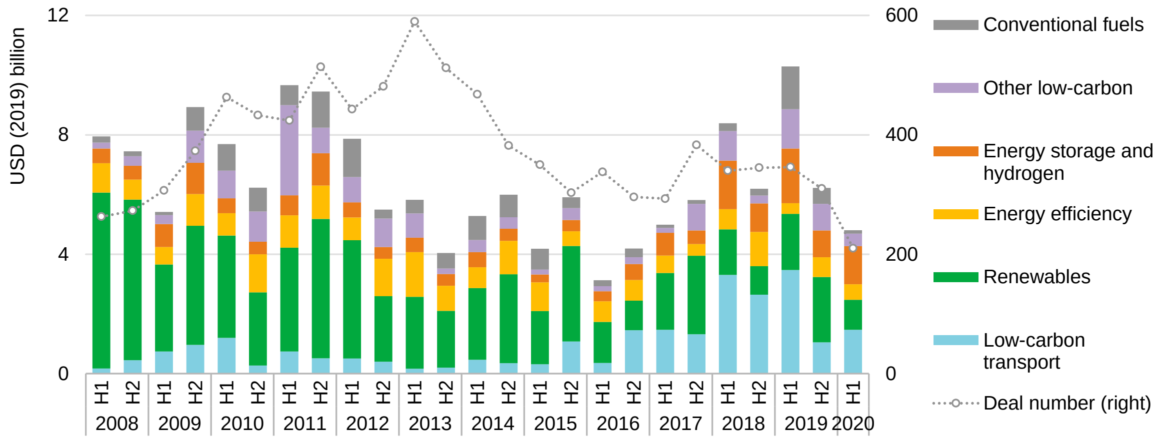
Early-stage energy VC deals decreased by about 30% relative to 2018-19 levels in the first half of 2020, and global declines are expected in the rest of 2020 as a result of

[10] Repsol, Shell, BP and Total all plan to have zero "scope 1 and 2" emissions by 2050 on a net basis. Scope 1 and 2 emissions come directly from the oil and gas industry itself in the production of its products and from the upstream productions of its inputs. Unless offsets are used extensively, these plans necessitate the phase-out of unabated hydrogen production from fossil fuels for refineries.

financial risks, travel, and other restrictions and policy uncertainty. If growth equity is included, a global decline in the first half of 2020 is also visible in the data (Figure 10).

It is widely recognised that many start-ups and innovative SMEs will struggle to stay afloat and will face cash flow and debt challenges, leading to lay-offs and losses of energy technology experts. Other start-ups may have to sell shares in their companies at a low price. Young companies with capital-intensive technologies, such as those needed in many sectors that currently have limited commercially available and scalable low-carbon options, may be less attractive to VC investors if market conditions reduce investors' willingness to wait for financial returns. This could put a brake on financing for innovative entrepreneurs at a time when several major governments are seeking to rely more heavily on VC financing to bring clean energy technologies to market. It could also stimulate a policy discussion about the clean energy technology types that are best suited to VC financing and about other potential models for bringing other types of technologies to market.

Figure 2.10 Value and number of global energy-related venture capital deals (early and late stage) by year and by semester



Note: Includes seed, series A, series B, grants, growth equity, buyout and late-stage private equity, coin/token offering, and private investment in public equity (PIPE) financing deals. Deals reported in the last week of June 2020 are not counted. Outlier deals of over USD 1 billion that distort the year-on-year trend are excluded; they totalled USD 2 billion in 2008, 1.9 in 2009, 1 in 2010, 3.5 in 2011, 4.8 in 2012, 7.9 in 2013, 6.4 in 2014, 1.3 in 2015, 1.6 billion in 2016, 3.9 in 2017, 9.4 in 2018, 1.3 in 2019 and 1.2 in 2020. Transport includes alternative powertrains and their infrastructure, but does not include shared mobility, logistics or autonomous vehicle technology. "Renewables" includes bioenergy but not biochemicals. "Other low-carbon" includes CCUS and smart grids. "Conventional fuels" includes fossil fuel extraction and use as well as vehicle fuel economy.

Sources: IEA calculations based on Cleantech Group (2020).

The first semester of 2020 saw half as much energy-related VC activity (early and late stage) compared with the same period in 2018-19; high-value later-stage fundraising rounds were affected most.

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Chapter 3. Innovation needs in the Sustainable Development Scenario

HIGHLIGHTS

- Innovation is central to the Sustainable Development Scenario. Almost 35% of the cumulative CO_2 emissions reductions seen in the Sustainable Development Scenario by 2070 compared with the current trajectory come from technologies that are currently at the prototype or demonstration phase and that will not become available at scale without further R&D (including commercial demonstrators) and technical improvements. A further 40% of the cumulative emissions reductions rely on technologies that have not yet been commercially deployed in mass-market applications.
- Without strong and targeted R&D efforts in critical technologies, net-zero emissions are not achievable. The main routes for the energy sector to achieve net-zero emissions are well known: electrification of end-use sectors; the use of CO_2 capture, utilisation and storage, including to remove CO_2 from the atmosphere; the use of low-carbon hydrogen and hydrogen-based fuels; and the use of bioenergy. However, each of these routes faces technology challenges to commercialise all steps of its value chain to tackle emissions in sectors that currently have no available scalable low-carbon options.
- Bringing new energy technologies to market can take several decades. Even successful examples in clean energy technology development like solar PV, lithium-ion batteries or LED took between 10 and 30 years from the first prototype to the time of commercialisation. The Sustainable Development Scenario assumes that concerted policy efforts speed up innovation timelines for new energy technologies so that innovation happens at least as fast as it has ever done before. This requires the efficient transmission of knowledge from first-mover countries to those that follow, particularly in the most critical early adoption phase.
- Different technologies have different attributes that can favour or hold back rapid innovation cycles. Technologies that are small and modular are less capital-intensive than large engineering solutions, for example, and this reduces their investment risks in the development phase. They also allow for standardisation and mass production, which in turn encourages innovation through competition and brings improved products to market faster. Synergies between sectors can accelerate further those cycles.
- Knowledge accumulated in one technology area can be of great relevance and value in related technologies. Such "spillovers", often overlooked, are very important because the benefits they bring can be harnessed at relatively low cost and can avoid the need for additional R&D. In the Sustainable Development Scenario, innovation policy stimulates these synergies, and this leads to technology areas with strong spillover potential including electrochemistry for batteries, electrolysers and fuel cells contributing 30% of the cumulative emissions reductions to 2070 compared to the current trajectory.

Introduction

Clean energy technology innovation has a vital role to play in achieving a rapid reduction in emissions of greenhouse gases to zero on a net basis over the coming decades, in line with the United Nations energy-related Sustainable Development Goals (SDGs), including the climate goal of the Paris Agreement.

The Paris Agreement of 2015 set a goal of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels". It also calls for greenhouse gas emissions to peak as soon as possible and for a rapid reduction thereafter in order to achieve a global balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases – net-zero emissions – in the second-half of this century. Net-zero emissions requires that any remaining anthropogenic emissions are entirely offset by negative emissions from changes in land-use systems or the removal of greenhouse gases through bioenergy with carbon capture and storage (BECCS) or the direct capture of CO_2 (DAC) from the air.

The Paris Agreement goal does not correspond to a single pathway for energy sector CO_2 emissions[11] or a specific date for achieving net-zero emissions, both because that goal spans a range of outcomes and because the required trajectory of the energy sector depends on emissions from outside the energy sector, as well as emissions of other greenhouse gases and air pollutants that also have climate effects. The precise timing of the need for overall net-zero greenhouse gas emissions worldwide also depends on how soon the peak in emissions is achieved and the rate at which emissions are subsequently reduced.

In this chapter, we use the IEA's **Sustainable Development Scenario** to assess the contribution needed from clean energy technology innovation for a clean energy transition to net-zero CO_2 emissions by 2070.The Sustainable Development Scenario describes the broad evolution of the energy sector that would be required to reach the key energy-related goals of the United Nations SDGs, including the climate goal of the Paris Agreement (SDG 13), universal access to modern energy by 2030 (SDG 7), and a dramatic reduction in energy-related air pollution and the associated impacts on public health (SDG 3.9).

The Sustainable Development Scenario would limit the global temperature rise to below 1.8°C with a 66% probability if CO_2 emissions remain at net zero after 2070. If CO_2 emissions were to fall below net zero after 2070, then this would increase the

[11] In this report, unless otherwise stated, historical and projected CO_2 emissions from the energy sector include those from fossil fuel combustion as well as from industrial processes, which are often closely linked to energy use.

possibility of reaching 1.5°C by the end of the century: the extent to which it would increase the possibility would depend on the level of carbon removal eventually reached. Reaching such negative emissions is a very common feature of the scenarios assessed by the Intergovernmental Panel on Climate Change in its special report: 88 out of the 90 scenarios in the report assume some level of net negative emissions.[12]

How ready is the energy system for net-zero emissions?

Technological change – the development and diffusion of technology to meet growing demand or displace existing energy assets – drives the clean energy transition in the Sustainable Development Scenario. Most of the capital stock that makes up today's energy system, from supply to end-use, will need to be adapted or transformed to reach the goal of net-zero emissions. To reach net-zero emissions globally in five decades, major reductions in cost and improvements in performance will be needed in a wide range of technologies already in use or in the early stages of development.

Developing a new technology and successfully bringing it to market is typically a long drawn-out process. Technologies go through a journey in which they evolve from a concept to a prototype, are demonstrated at scale and, if successful, are adopted and commercialised more widely. Given that we cannot predict the emergence of technologies that are not known today or which ideas might prove successful, the portfolio of energy technologies in the Sustainable Development Scenario includes those for which at least a large prototype is already proven today and the pathway to commercial scaling-up is understood, which means that that basic information on potential technology performance and costs is available. There are, nonetheless, a variety of factors that could delay or disrupt the clean energy transition in practice, including unexpected future events and the hard-to-predict responses of companies, investors and governments to such events.

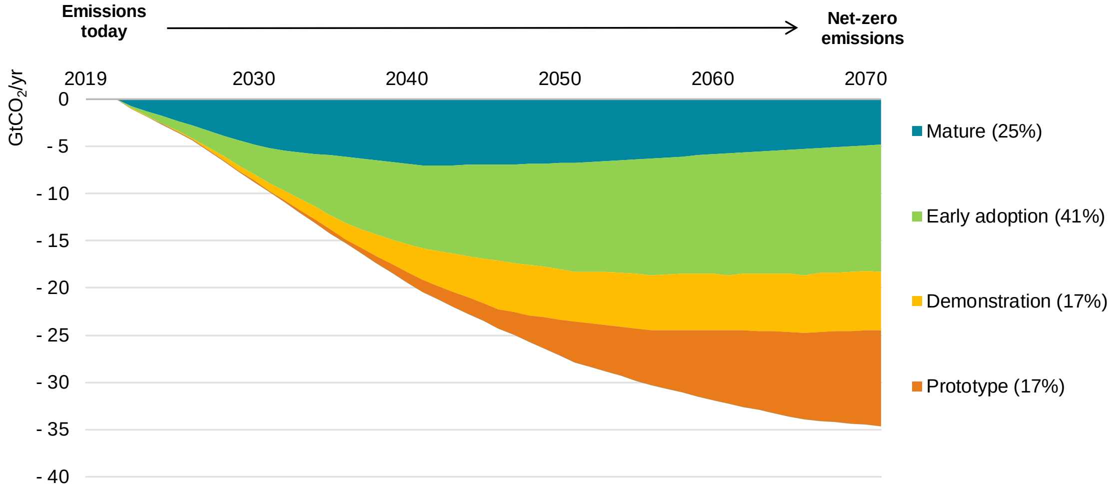
Almost 35% of the cumulative emissions reductions by 2070 in the Sustainable Development Scenario compared with the Stated Policies Scenario[13] hinge on technologies that are currently at large prototype or demonstration phase, and around 40% on technologies that are not yet commercially deployed at a large scale

[12] For further details see IEA (2019).

[13] This scenario serves as a benchmark for the projections of the Sustainable Development Scenario. It assesses the evolution of the global energy system on the assumption that government policies that have already been adopted or announced with respect to energy and the environment, including commitments made in the nationally determined contributions under the Paris Agreement, are implemented.

(Figure 3.1). The contribution of technologies at large prototype or demonstration stage to emissions reductions are even higher in heavy industry and long-distance transport, where no commercially available and scalable options for achieving deep emissions reductions exist today.

Figure 3.1 Global energy sector CO_2 emissions reductions by current technology readiness category in the Sustainable Development Scenario relative to the Stated Policies Scenario



Notes: Percentages refer to cumulative emissions reductions by 2070 between the Sustainable Development Scenario and the Stated Policies Scenario enabled by technologies at a given level of maturity.

Technologies that are only at the large prototype or demonstration stage today contribute almost half of the emissions reductions in 2070 in the Sustainable Development Scenario.

The energy trajectories in the Sustainable Development Scenario are largely determined by how the cost and technical performances of competing technologies evolve through innovation, but are also affected by changing policy priorities and consumer choices. All these factors are interlinked and interact dynamically over time. For example, the pace of decline in the cost of lithium-ion (Li-ion) batteries influences the rate of take-up of electric vehicles, which affects how competitive they are against biofuels as a means of decarbonisation, particularly in light-duty vehicles. Other factors, including battery capacity, efficiency and (dis)charge power, also play a role in determining the attractiveness of electric vehicles, as in determining the economic viability of using Li-ion batteries to provide storage for electricity systems. Deployment is both a cause and effect of cost and performance for each of the technologies that drive the transition to net-zero emissions: the faster their take-up, the greater the economies of scale and learning effects, and the greater the incentives to seek out incremental gains through yet more innovation in a virtuous cycle.

Technological change is a key driver of the clean energy transition in the Sustainable Development Scenario, but not the only one. Consumer behaviour with respect to how much and what type of energy services and commodities are consumed changes considerably in that scenario, both in response to increasing public consciousness about the nefarious environmental and societal impact of current consumption patterns and to changes in price signals. In the Sustainable Development Scenario, there is a fundamental change in how households interact with the energy system as distributed generation and demand-response strategies take root and spread, while the transport system shift towards less emissions-intensive modes of travel, such as public transport, rail and car-sharing. Consumers and producers are active players in material efficiency measures such as the renovation of buildings, the reuse and recycling of goods, and the way products are designed to facilitate sustainable end-of-life management strategies. Strategies that avoid creating the demand for a given service (e.g. shared mobility or plastics recycling) enable 7% (or almost 80 Gt) of cumulative emissions reductions to 2070 in the Sustainable Development Scenario compared to the Stated Policies Scenario.[14]

Box 3.1 The impact of the Covid-19 pandemic on energy use and CO_2 emissions

IEA analysis of the effects of the Covid-19 pandemic on energy use and CO_2 emissions shows that 2020 could see a drop in global energy-related CO_2 emissions of almost 8%. This would be the largest reduction ever over the course of a year, six times larger than the previous record reduction of 0.4 Gt in 2009 due to the financial crisis, and twice as large as the combined total of all previous reductions since the end of World War II.

Based on data for the first four months of 2020, and on the assumption of a gradual recovery in the global economy, the IEA expects total primary energy demand in 2020 to drop in all major regions and to contract globally by around 6%. This includes an 8% decline in oil demand, an 8% reduction in coal demand, a 5% fall in natural gas demand and a 5% drop in electricity demand. As a result, global CO_2 emissions in 2020 are expected to fall by around 2.5 Gt to just under 31 Gt, around 8% lower than in 2019. This would be the lowest level since 2010. However, as nearly all of this decline is due to reductions in economic activity rather than structural changes in the way the world produces and consumes energy, emissions are very likely to rebound

[14] This scenario serves as a benchmark for the projections of the Sustainable Development Scenario. It assesses the evolution of the global energy system on the assumption that government policies that have already been adopted or announced with respect to energy and the environment, including commitments made in the nationally determined contributions under the Paris Agreement, are implemented.

as economies recover, unless there is swift action to bring about such structural changes.

These staggering numbers give a sense of just how radical shifts in technology and consumer behaviour would need to be in order bring about a considerable and permanent reduction in CO_2 emissions while the global economy continues to grow and the global population continues to increase. They underscore the need for a structural transformation in the way energy and goods are produced and consumed, which is realised simultaneously through technological change and radical changes of consumption patterns so as to deliver a clean energy transition that meets both sustainability and economic prosperity objectives.

The critical role of innovation in the Sustainable Development Scenario highlights the need for an efficient innovation cycle to reach net-zero emissions in the most cost-effective manner. This means making sure that researchers are funded to come up with potentially powerful new ideas, that strong links are in place between R&D institutions and industrialists, that today's prototypes are given the best possible chance of reaching their full potential and that the scaling-up of technologies as they enter the market is accompanied by continual improvements. Achieving net-zero emissions smoothly and quickly calls for any bottlenecks in innovation – such as insufficient flows of capital, knowledge or funding – to be avoided by learning from past experiences.

The speed at which energy-producing and energy-consuming equipment would have to be replaced and new technologies introduced in the Sustainable Development Scenario is as fast as has ever been seen in the history of energy. For those technologies at an early stage of development today, diffusion time would need to be reduced by several decades compared with historical averages. But just because this transformation would be unprecedented does not make it impossible. Many of the technologies needed in the Sustainable Development Scenario rely on digitalisation, for example, making them unlike energy technologies of the past, and on rapid adoption by consumers, who are operating in a world in which information spreads faster than ever before. Other technologies require extensive new infrastructure and reduced efficiencies (e.g. integrating carbon capture), but are backed by strong social and regulatory pressure for change.

The projections in the Sustainable Development Scenario are underpinned by an extensive body of analysis of the interaction of energy innovation and deployment, informed by case studies of how key technologies have emerged in the past. The rest of this chapter looks at the timescales involved in taking emerging technologies from the laboratory to the market, how learning-by-researching and learning-by-doing affect cost reductions, and the specific technology attributes that are known to influence the pace and success of innovation over time. It also explains how all these factors are incorporated into the Sustainable Development Scenario.

Box 3.2 Assessing technology readiness: The ETP Clean Energy Technology Guide

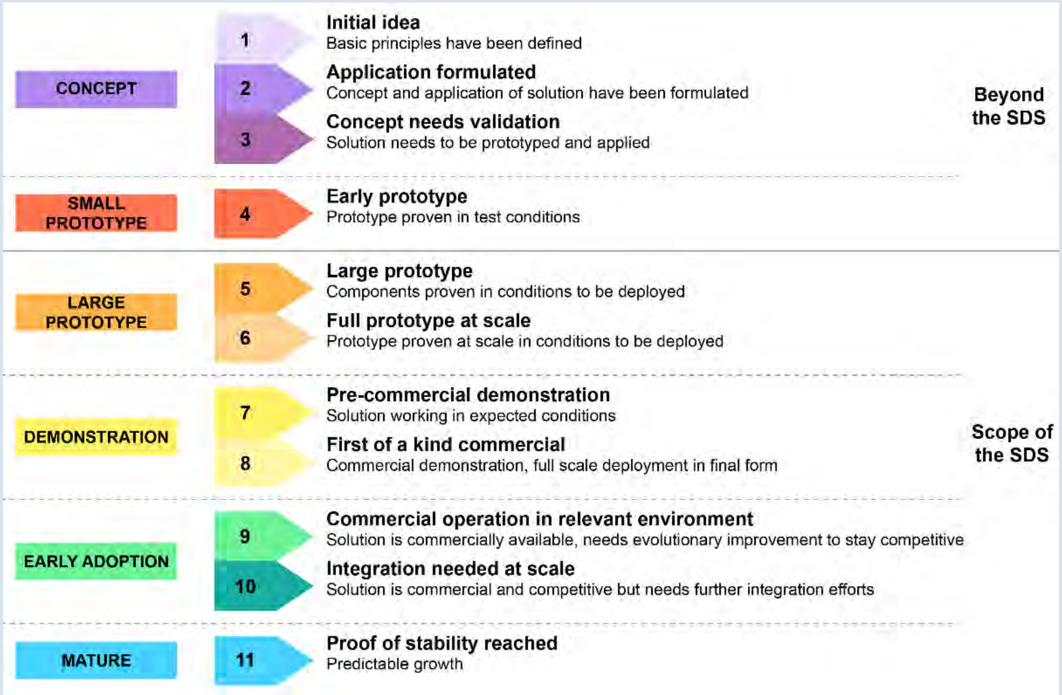
One way to assess where a technology is on its journey from initial idea to market is to use the technology readiness level (TRL) scale. Originally developed by the National Aeronautics and Space Administration (NASA) in the United States in the 1970s and used in many US government agencies since the 1990s, the TRL provides a snapshot in time of the level of maturity of a given technology within a defined scale (Mankins, 1995). The US Department of Defence has been using the TRL scale since the early 2000s for procurement, while the European Space Agency adopted it in 2008. In 2014, the TRL was applied for the first time outside the aerospace industry to assess EU funded projects as part of the Horizon 2020 framework programme. It is now widely used by research institutions and technology developers around the world to set research priorities and design innovation support programmes.

The scale provides a common framework that can be applied consistently to any technology to assess and compare the maturity of technologies across sectors. The technology journey begins from the point at which its basic principles are defined (TRL 1). As the concept and area of application develop, the technology moves into TRL 2, reaching TRL 3 when an experiment has been carried out that proves the concept. The technology now enters the phase where the concept itself needs to be validated, starting from a prototype developed in a laboratory environment (TRL 4), through to testing in the conditions it which it will be deployed (TRL 6). The technology then moves to the demonstration phase, where it is tested in real-world environments (TRL 7), eventually reaching a first-of-a-kind commercial demonstration (TRL 8) on its way towards full commercial operation in the relevant environment (TRL 9).

Arriving at a stage where a technology can be considered commercially available (TRL 9) is not sufficient to describe its readiness to meet energy policy objectives, for which scale is often crucial. Beyond the TRL 9 stage, technologies need to be further developed to be integrated within existing systems or otherwise evolve to be able to reach scale; other supporting technologies may need to be developed, or supply chains set up, which in turn might require further development of the technology itself. For this reason, the IEA has extended the TRL scale used in this report to incorporate two additional levels of readiness: one where the technology is commercial and competitive but needs further innovation efforts for the technology to be integrated into energy systems and value chains when deployed at scale (TRL 10), and a final one where the technology has achieved predictable growth (TRL 11).

As technologies pass through each stage, the level of risk associated with technology performance is reduced, but the level of overall risk rises as capital expenditure requirements grow. However, innovation is rarely a linear progression. Not all technology designs make it to market or get deployed at scale. Stages of development can accelerate or slow down depending on technical or cost factors, and a given technology can be at different stages in different markets and applications. As the development of a technology generates new ideas for improvements, alternative configurations and potentially better components can appear even once a given technology configuration has become competitive. Stages overlap and run concurrently, feeding on one another.

Technology readiness level scale applied by the IEA



Notes: SDS = Sustainable Development Scenario.

To inform this analysis, we have analysed the technology readiness of almost 400 individual technology designs and components, and have structured them hierarchically alongside others delivering the same service in what we refer to as the

ETP Clean Energy Technology Guide[15]. This is an interactive framework that includes information on the level of maturity of different technology designs and components, as well as a compilation of cost and performance improvement targets and leading players in the field. 60% of the technology designs and components analysed are not commercially available today, and 35% are at the early adoption phase, meaning that they are still significantly dependent on innovation to improve performance and reduce costs. Of the mature technology designs assessed, 65% relate to the buildings and power generation sectors: a higher proportion of the technologies in industry, transport and fuels transformation have lower TRLs.

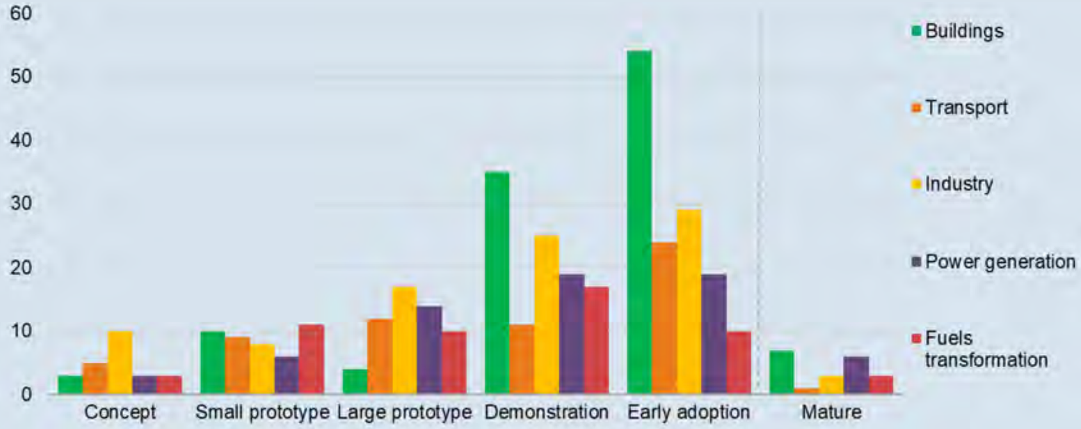
In this report we refer to four broader readiness categories, each of which comprises different ranges of specific readiness levels from the full TRL scale: mature, early adoption, demonstration and prototype. Each technology type is assigned to one of these higher level categories based on the granular levels of maturity of individual technology designs or components today associated with that technology.

- “Mature” for commercial technology types that have reached sizeable deployment and for which only incremental innovations are expected. Technology types in this category have all designs and underlying components at TRL 11. Hydropower and electric trains are examples.
- “Early adoption” for technology types for which some designs have reached markets and policy support is required for scale-up. But there are competing designs being validated at demonstration and prototype phase. Technology types in this category have at least an underlying design at TRL ≥ 9 and others at lower TRLs. Offshore, wind, electric batteries and heat pumps are examples.
- “Demonstration” for technology types for which designs are at demonstration stage or below, meaning no underlying design at TRL ≥ 9, but at least a design at TRL 7 or 8. Carbon capture in cement kilns, electrolytic hydrogen-based ammonia and methanol, and large long-distance battery-electric ships are examples.
- “Large prototype” for technology types for which designs are at prototype stage of a certain scale, meaning no underlying design at TRL 7 or 8 but with at least one design at TRL 5. Ammonia powered vessels, electrolytic hydrogen-based steel production and direct air capture are examples.
- “Small prototype” for technology types for which designs are at early prototype stage, meaning no underlying design at TRL 5, but with at least one design at TRL 4. Battery-electric aircrafts and direct electrification of primary steelmaking are examples.

[15] For more information please visit: www.iea.org/articles/etp-clean-energy-technology-guide.

- "Concept" for applications that have just been formulated but that need to be validated. Lithium-air batteries and electrifying a steam cracker for olefins production are examples.

Number of clean energy technology designs and components analysed in the ETP Clean Energy Technology Guide

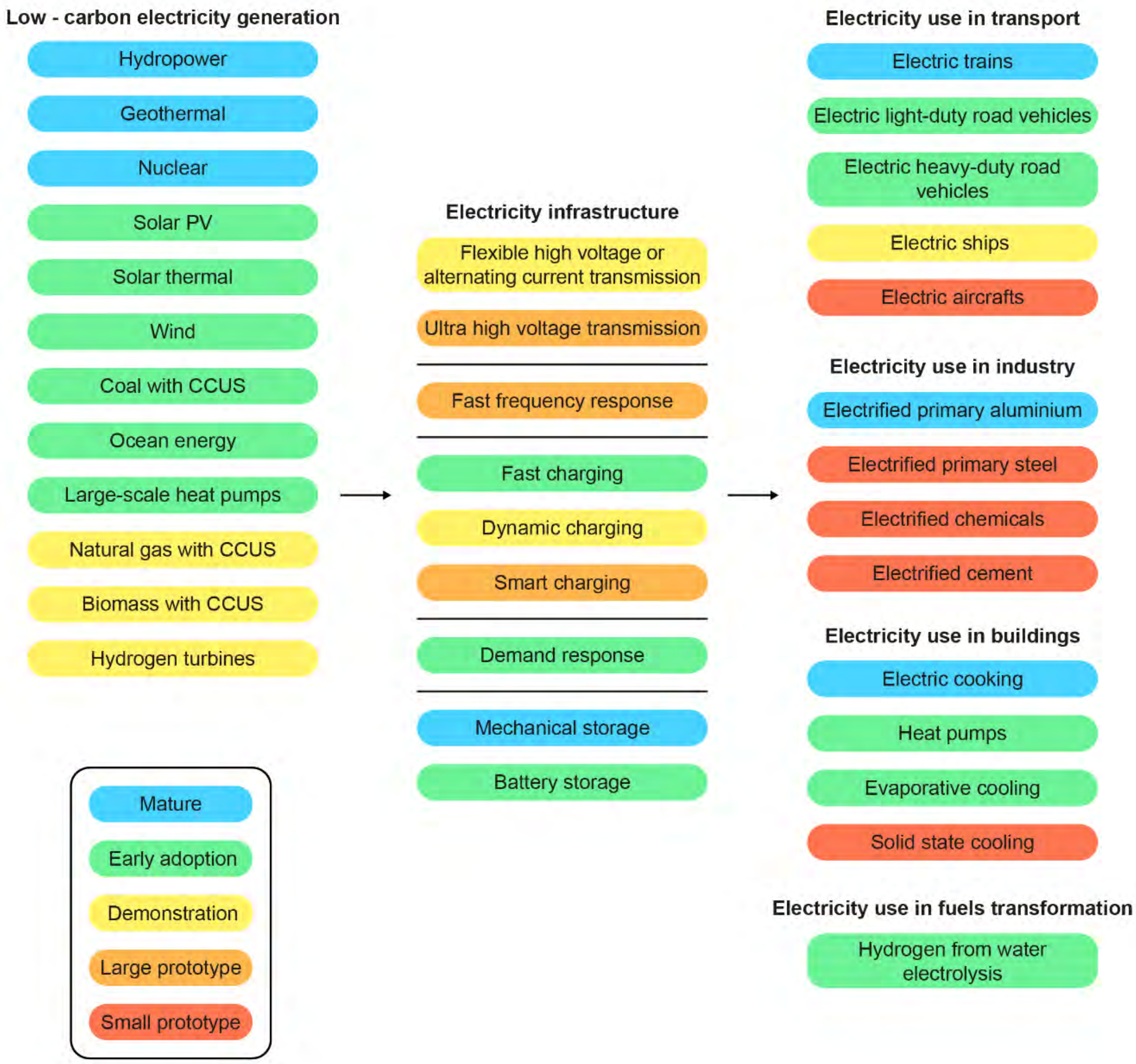


Readiness of critical low-carbon value chains

The Sustainable Development Scenario identifies key decarbonisation strategies. The electrification of the transport, industry and buildings sectors combined with the deployment of renewables in power generation accounts for about 40% of the cumulative reduction in emissions by 2070 in the Sustainable Development Scenario, relative to the Stated Policies Scenario. The shift towards more sustainable alternative fuels and feedstock such as bioenergy, hydrogen and hydrogen-derived synthetic fuels (using low-carbon hydrogen and sustainable carbon sources) accounts for around 20%. The deployment of carbon capture utilisation and storage (CCUS) systems, including those allowing for negative emissions and for low-carbon hydrogen production, accounts for almost 15% more. For these decarbonisation strategies to be rolled out, innovation is needed to bring new technologies to market and to improve emerging ones along all the different steps of the involved value chains.

In the **low-carbon electricity value chain**, several technologies have reached maturity, but there is still a long way to go for others (Figure 3.2). This is particularly true in demand areas such as heavy industry and long-distance transport that are proving difficult to electrify: some key technologies in these areas are today still at small prototype stage or below. The same point applies in other areas too. Innovation to develop effective integration measures that provide greater flexibility to lower carbon electricity grids is becoming increasingly important: relevant technologies today are, however, generally between the early adoption and large prototype stages. In end-use sectors, some technologies such as electric vehicles and heat pumps are commercially available, but innovation remains an important issue: their ability to expand their markets depends on further technology innovation to improve performance and reduce costs.

Figure 3.2 Technology readiness level of technologies along the low-carbon electricity value chain



Notes: Each technology is assigned the highest technology readiness level of the underlying technology designs. CCUS = carbon capture utilisation and storage. For more detailed information on individual technology designs for each of these technologies, and designs at small prototype stage or below, please visit: www.iea.org/articles/etp-clean-energy-technology-guide.

Not all parts of the low-carbon electricity value chain are at commercial scale today; some technologies in end-use sectors and in electricity infrastructure are at demonstration or large prototype stage.

The **capture, transport and utilisation or storage of CO_2 emissions** as a successful decarbonisation strategy hinges on the commercial availability of technologies at each stage of the process as well as on the development and expansion of CO_2 transport and storage networks at a sizeable scale.

Capture: While CO_2 has been captured for decades in certain industrial and fuel transformation processes such as ammonia production and natural gas processing, it has just commercially emerged or is still being demonstrated at a large scale in many of the other possible applications (Figure 3.3). In each of these potential new applications, which range from power generation and fuels transformation to cement and iron and steel production, a wide range of CO_2 separation techniques needs to be tailored to the particular conditions of each individual process. Chemical absorption is the CO_2 separation technique for which there is the most operational experience, and it is currently used in commercial capture facilities and embedded in demonstration plants for most applications across different sectors. Chemical absorption is therefore the CO_2 separation technique the most widely used over the next two decades in the Sustainable Development Scenario.

Use: CO_2 is used commercially today in a few industries; it is, for instance, used in the production of urea (the main precursor of nitrogen-based fertilisers) and of carbonated drinks. In both applications, CO_2 is only stored temporarily and is ultimately released to the atmosphere. Other potential uses of CO_2 are emerging: they include building materials (which would provide long-term but not permanent CO_2 storage) and feedstock for synthetic fuels (which would prevent the CO_2 from being released into the atmosphere only temporarily).[16]

Storage: CO_2 has been used for enhanced-oil recovery for more than five decades; this counts as a form of storage because the vast majority of the CO_2 is retained in the reservoir over the life of the project. Most of the CO_2 used is sourced from natural reservoirs, but an increasing amount comes from CO_2 captured from industrial sources. However, there is relatively limited experience in operating at scale other geological storage options. There are 5 large-scale facilities currently storing more than 7 $MtCO_2$/year in saline formations, one of which has been operating since 1995 (the Sleipner CCS project). CO_2 storage in depleted oil and gas wells has been limited to pilot demonstrations, but there are plans to develop commercial facilities.

Negative emissions: Biomass-based CO_2 emissions capture and storage and direct air capture (DAC) both have the ability to yield negative emissions, and therefore have considerable potential long-term importance. With a few exceptions, however,

[16] Even if released again, the use of fossil CO_2 can contribute to CO_2 reduction as, in principle, each carbon molecule is being used twice: the carbon contained in a fossil fuel is used to produce energy or in an industrial production process; then the resulting CO_2 is used in combination with hydrogen to produce a synthetic hydrocarbon fuel.

neither technology has yet reached markets at a large scale.[17] Some demonstration plants and pilots have been completed, and in some cases they have been maintained in operation, particularly when a suitable commercial use for the captured CO_2 was found nearby. Several small pilot-scale DAC plants are currently operating around the world: they incorporate commercial facilities that sell the captured CO_2.

Figure 3.3 Technology readiness level of technologies along the CO_2 value chain

Notes: Technologies included are at large prototype or at a more advanced stage. Each technology is assigned the highest technology readiness level of the underlying technology designs. CCUS = carbon capture utilisation and storage. For more detailed information on individual technology designs for each of these technologies, and designs at small prototype stage or below, please visit: www.iea.org/articles/etp-clean-energy-technology-guide.

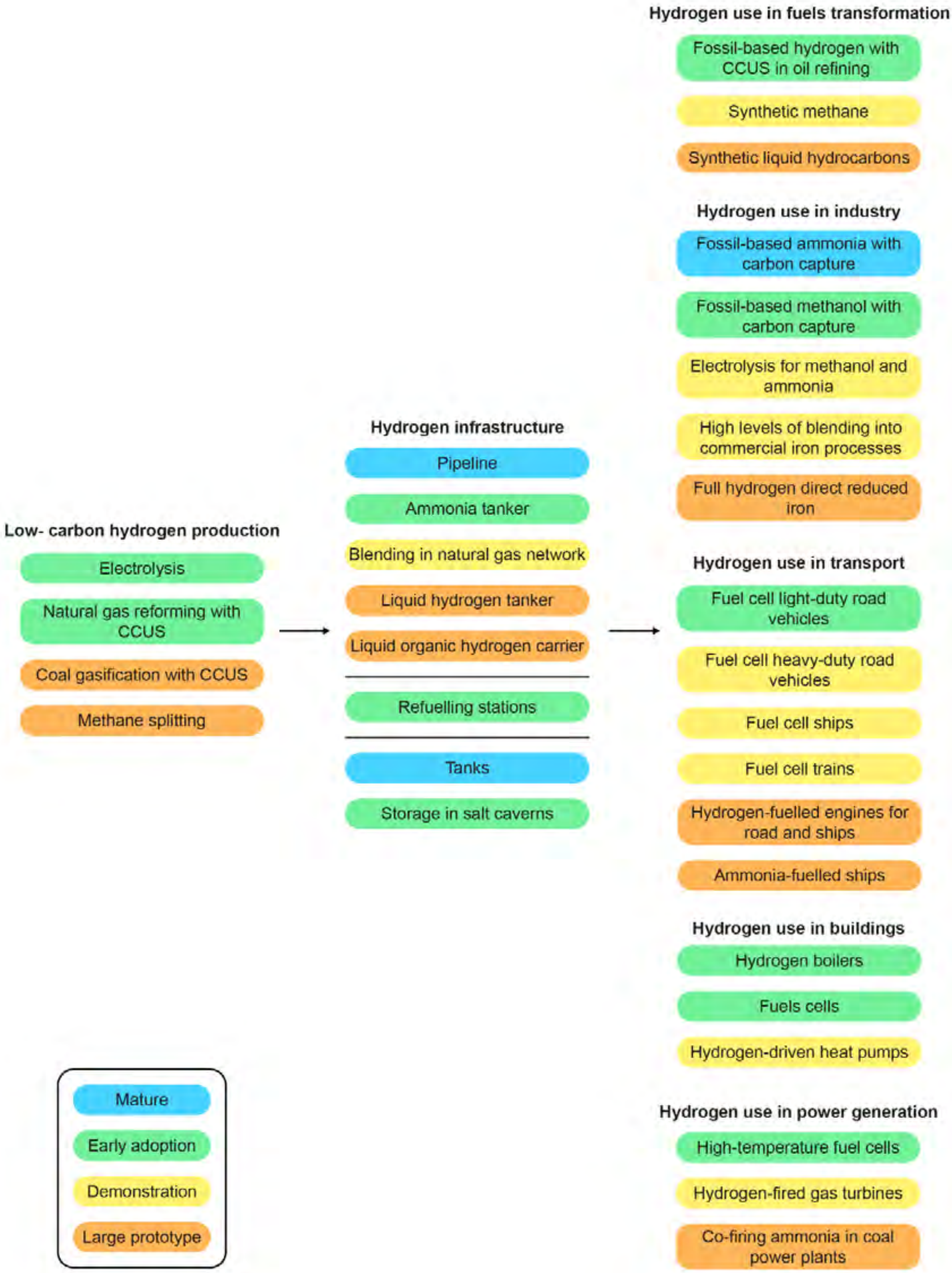
Not all parts of the CO_2 value chain are operating at commercial scale today: many of the relevant technologies are still at the demonstration and the large prototype stage.

[17] A bioethanol plant in Illinois (United States) captures and stores 1 Mt of CO_2 per year.

The **value chain for low-carbon hydrogen** is not completely developed at commercial scale today. It comprises many technologies that are necessary to produce, transport, store and consume low-carbon hydrogen, each of them at a different stage of maturity and facing specific technical challenges (Figure 3.4). Among the low-carbon hydrogen production routes that are commercially available today, the use of electrolytic hydrogen in heavy industrial processes is less advanced (i.e. just at the demonstration stage) than that of natural gas with CCUS with facilities in operation. Setting to one side its long-standing use in oil refining and chemical production, hydrogen use today is limited by current commercially viable technologies to light-duty vehicles, space heating, and electricity generation in buildings and distributed electricity systems.[18] Large portions of the full potential demand for hydrogen will remain untapped until technologies are developed to use hydrogen in iron and steel and heavy-duty transport, and until fuels derived from low-carbon hydrogen (for example synthetic hydrocarbon fuels and ammonia), are demonstrated at commercial scale and then deployed.

[18] Stationary fuel cells deployed today mostly rely on natural gas as fuel, although they are capable of using hydrogen.

Figure 3.4 Technology readiness level of technologies along the low-carbon hydrogen value chain



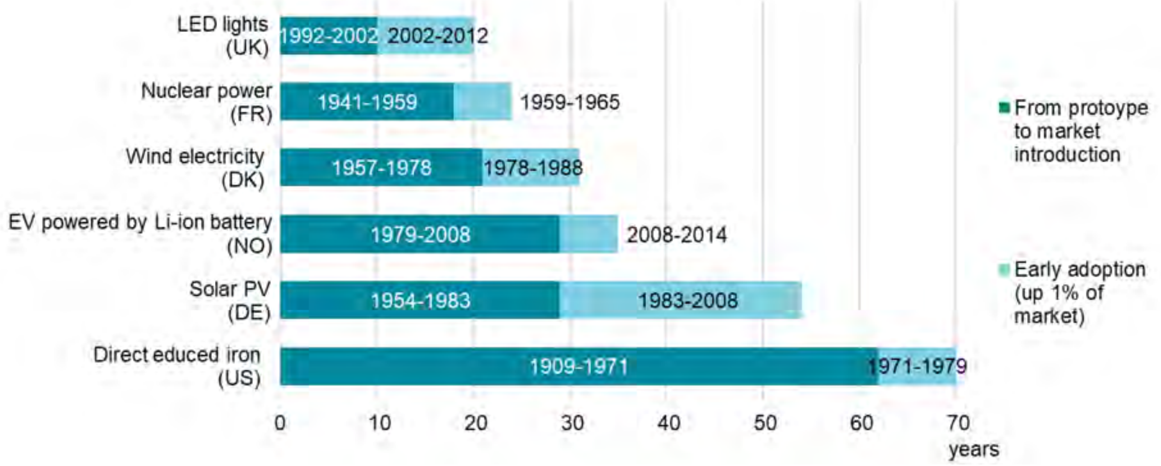
Notes: Technologies included are at large prototype or at a more advanced stage. CCUS = carbon capture utilisation and storage. For more detailed information on individual technology designs for each of these technologies, and designs at small prototype stage or below, please visit: www.iea.org/articles/etp-clean-energy-technology-guide.

Not all steps of the low-carbon hydrogen value chain are operating at commercial scale today; the majority of demand technologies are only at the demonstration or prototype stage.

Timescales in taking technologies from the laboratory to market

History shows that it can take between 20 and almost 70 years for new energy technologies to go from first prototype to materiality (that is, to reach 1% of a national market) (Gross, 2018; Bento, Wilson and Anadon, 2018). Even recent success stories in clean energy technology development – such as solar photovoltaic (PV) and Li-ion batteries to power electric vehicles – took around 30 years years from their first prototype to the time of commercialisation (Figure 3.5). Having achieved market introduction, it took a further 25 years for solar PV to achieve a 1% share of a national electricity supply market for the first time (in Spain, closely followed by Germany), while it took just 6 years for Li-ion battery-powered electric vehicles to achieve the same national market share for the first time (in Norway). The time from prototype to market introduction for direct reduced iron technology was around 60 years – from prototypes in Sweden to the first commercial-scale MIDREX plant in South Carolina in the United States – due in part to the dominance of large blast furnaces over batch processes for a prolonged period.

Figure 3.5 Prototype to market introduction and early adoption periods for selected energy technologies



Notes: FR = France; DK = Denmark; UK = United Kingdom; DE = Germany; NO = Norway. PV = photovoltaics; EV = electric vehicles. Country designation applies to early adoption phase and refers to first countries reaching materiality for the technologies analysed. Country designation applies to early adoption phase. Market definitions: lighting equipment stock in buildings for LEDs; generation of electricity for nuclear; generation of electricity for wind electricity; light-duty vehicle stock for electric vehicles; generation of electricity for PV; total steel production for direct reduced iron.

Sources: IEA data; Gross (2018); UK National Statistics (2019); Worldsteel Association (2020).

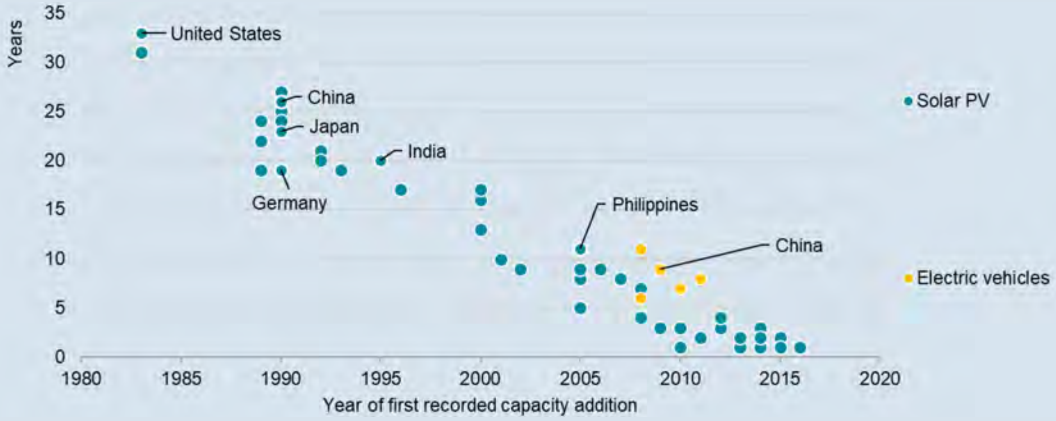
Bringing major new energy technologies to market on a large scale after the first prototype took between 20 and almost 70 years.

Among leading energy technologies, LED lighting for buildings achieved materiality in the shortest amount of time, being introduced in the United Kingdom just 10 years after the initial prototype was developed, while nuclear power was introduced in France just 18 years after the initial prototype. In both cases, government intervention accelerated innovation. While white LED lights were largely the product of private sector research funding, building on knowledge from the semiconductor industry, their early adoption was very heavily dependent on government standards and regulations for lighting efficiency. The large-scale deployment of nuclear power was driven by a combination of government-funded basic science and applied R&D in several countries and public procurement of the first large-scale plants in France.

Box 3.3 Technology diffusion across borders

While Germany took about 20 years to meet 1% of national electricity demand from solar PV in 2008, Philippines, for instance, took only around 10 years to reach the same milestone in 2015. In the case of Li-ion batteries for light-duty electric vehicles, it took just 6 years in Norway to reach the milestone of 1% of the national market for light-duty electric vehicles, building on nearly two decades of effort to deploy EVs with other battery chemistries and the 12 years it took for electric vehicles to reach 1% market share in the United States.[19]

Years to materiality for solar PV and electric vehicles powered by Li-ion batteries by country



Notes: China = China (People's Republic of). Market share is defined here as the share of service provision in the country. For solar PV, the share of total electricity generation is used. For Li-ion in electric vehicles, the share of the total vehicle stock is used as a proxy.

[19] Plug-in hybrid electric vehicles and battery-electric vehicles combined.

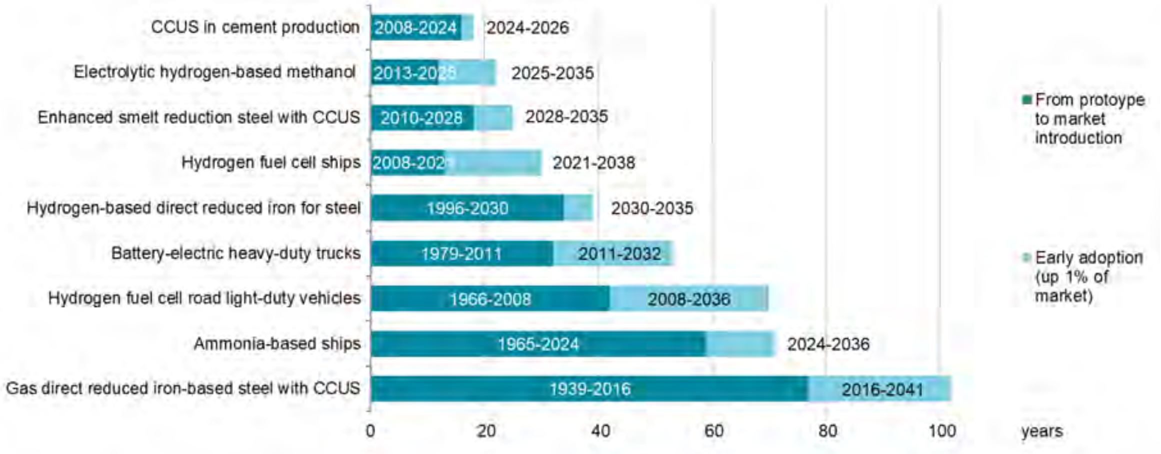
These trends illustrate both the lower costs encountered by later adopters and the institutional and societal learning that takes place between countries, their governments and companies. However, this should not be seen as an argument for governments to play wait-and-see and try to take advantage of the efforts of others. Early adoption can bring benefits in terms of market leadership. Companies in Germany and Japan became market leaders in producing solar PV panels and Li-ion batteries respectively, for example, and in selling expertise in developing supply chains.

The international deployment pattern is an argument in favour of maximising knowledge exchange between countries to accelerate deployment, learning-by-doing and economies of scale. While level playing fields are central to fair global trade, globally integrated markets favour innovation. In the Sustainable Development Scenario, cost reductions generated from experience in one market are assumed to be transferred to the next market to adopt the technology, so that the technology enters each successive market better able to compete against incumbent technologies and their corporate backers.

The assumptions in the Sustainable Development Scenario about the time periods for emerging technologies to reach commercial readiness take account of historical trends and the underlying factors behind them. The time for each technology type to develop from early prototype to first-of-a-kind commercial installation is particularly crucial: this can be a decade or more, even with strong policy support. In practice, industrial dynamics, investment and technical learning place limits on how fast some technologies – especially large unit size technologies – can reach the market.

In general, the Sustainable Development Scenario assumes somewhat shorter development periods than those observed in the past, since policy support is assumed to be much stronger, and to lead to more efficient exchange of technical knowledge and greater exploitation of synergies between sectors. Factors that have in the past led to discontinuous learning, including a lack of financial resources, fossil fuel price risk and political instability, are assumed not to affect innovation in the future.

Figure 3.6 Times to materiality for selected technologies in the Sustainable Development Scenario



Notes: Period from market introduction to materiality relate to global deployment projections in the Sustainable Development Scenario. Pace of deployment of a given technology depends not only on observed historical patterns for analogous examples, but also on how competitive it is on cost and performance compared with alternative available low-carbon technologies delivering an equivalent service, as well as the effectiveness of policies to stimulate uptake.

Sources: Matsunaga, Tatsuya and Kuniaki (2009); Zemships (2008), Molino et al. (2018); European Cement Research Academy (2012); Brohi (2014); TATA Steel (2017); Kohl and Nielse (1997); Ballard (2019); Kraftwerk Forchung (2013), Nuber, Eichberger and Rollinger (2006).

Bringing new clean energy technologies to market on a large scale after the first prototype takes from around 20 years to more than 80 years in the Sustainable Development Scenario, depending on the technology.

For large, non-modular, site-tailored technologies still at a pilot stage today, a six to eight year period from first large prototype to full-scale demonstration is assumed in the Sustainable Development Scenario, followed by a seven to ten year period to first commercial introduction under prevailing market conditions. In some cases, up to five full-scale major demonstration projects operating for five to ten years in commercial environments around the world may be required to generate investor and regulator confidence, with knowledge transferred between them. On the other hand, small and/or modular technologies like engines, batteries and electrolysers are assumed to reach markets no later than 12-14 years from early prototype in the Sustainable Development Scenario[20]. As a result, the various technology designs that become increasingly competitive and are adopted in the Sustainable Development

[20] This consideration applies only to the projected period, and excludes instances in which technologies may have taken already a longer period from first prototype to reach current status of development prior to 2020.

Scenario enter early adoption at different times (Figure 3.6 above). These timescales apply to the first country adopting a technology; the timeframe is generally much shorter for other countries (Box 3.3 above).

Moving down the learning curve

When learning-by-researching, learning-by-doing, standardisation, collaboration across the industry and economies of scale collectively result in cost and price reductions that continue over a decade or more, empirical "learning curves" (or experience curves) can be constructed to inform future expectations for similar technologies. The typical approach is to correlate the percentage cost reduction with the time it takes to double the cumulative installed capacity, which is a proxy for the level of experience and scale acquired by the industry.

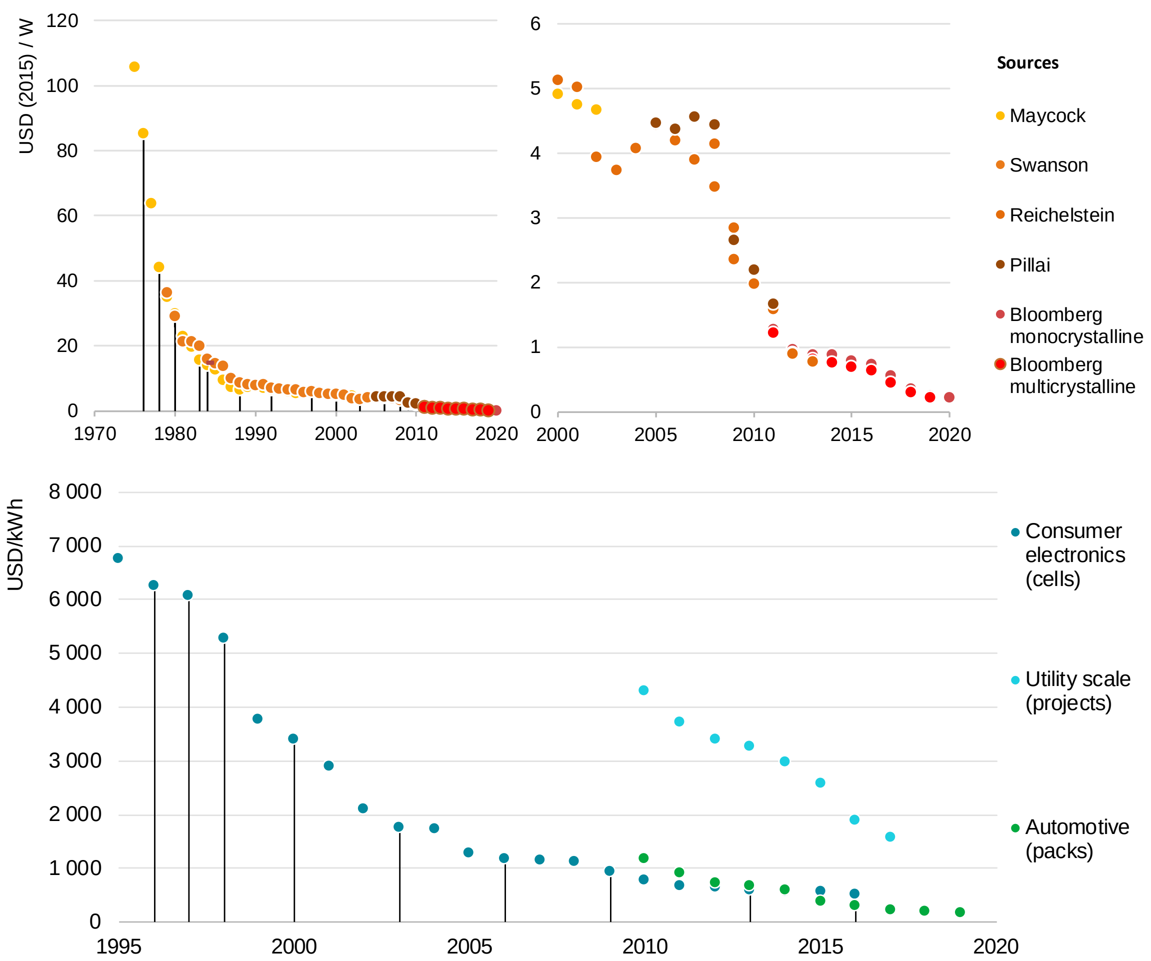
Solar PV and Li-ion batteries are good examples of such learning curves. Each time the cumulative amount of capacity has doubled worldwide, unit costs for PV have fallen since the 1970s by 24%: in recent years, the fall in unit costs associated with each doubling of capacity (the learning rate) has increased to more than 30%. The equivalent learning rate for Li-on has been around 20% (Figure 3.7). For both technologies, these learning rates have led to an exponential decline in prices. Future cost declines are expected as capacity expands further, novel technology configurations are likely to be needed for such a decline to continue.

Both technologies built on many decades of relevant scientific and engineering R&D, and neither technology was developed to serve the energy sector. The first PV panel was demonstrated in 1954 and the first Li-ion battery was prototyped in 1979. The first application of solar panels was to power satellites and their first commercial applications were in wristwatches and pocket calculators.[21] Li-ion batteries were first used in handheld video cameras and then smartphones. The military were early users of both technologies: early individual users tended to be wealthy individuals willing to pay for the unique attributes of the panels or devices. Subsequent niche markets for PV included light meters, flashlights, electric fences, off-grid holiday homes and lighthouses. For Li-ion they included medical implants, portable music players, mobile telephones, laptop computers, power tools and aviation applications. During the first decades of manufacturing, it was not clear in either case which configuration would become dominant: many changes were made by different researchers and firms to the types of silicon wafers, electronics and electrodes that were used. Grid-

[21] The small solar cells used in consumer products in the late 1970s initially had near-zero costs for electronics companies as the market could be satisfied from unusable offcuts from larger modules produced for unprofitable off-grid applications.

connected electricity generation only became the primary market for PV in the 1990s, and electric vehicles only became the primary market for Li-ion in 2015.

Figure 3.7 Evolution of solar PV module cost (top) and Li-ion battery price (bottom)



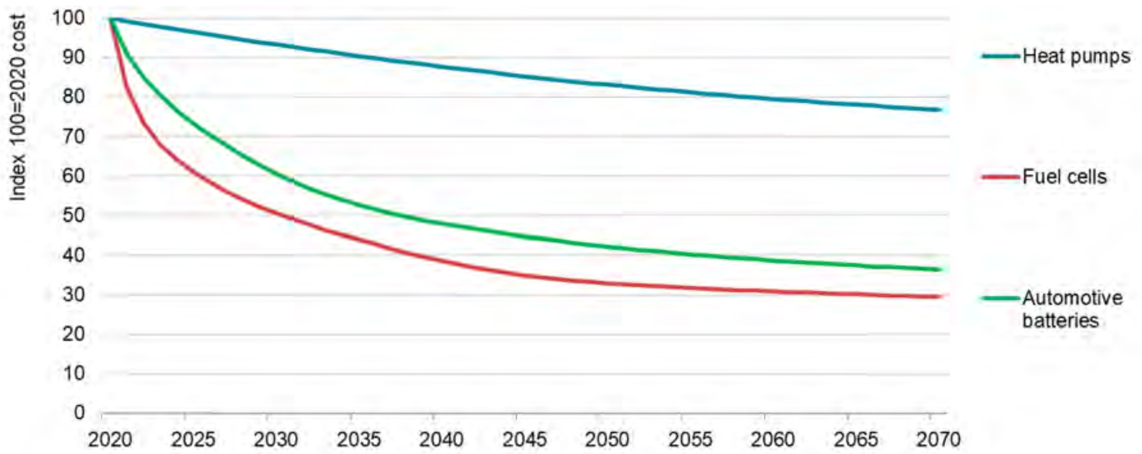
Notes: Vertical lines show each doubling of cumulative capacity installed. These technologies are not directly comparable since they refer respectively to battery, cell and system level prices. Colours in the PV chart represent different data sources.
Sources: Kavlak, McNerney and Trancik (2018); Bloomberg LLP (2020); Kittner et al. (2020).

The costs of both solar PV and Li-ion batteries have declined exponentially as cumulative installed capacity has doubled every two to three years.

The learning rates for these two technologies are applied as appropriate in the Sustainable Development Scenario to other small, simple, modular and adaptable designs. For example, electrolysers and fuel cells, which have been manufactured in only limited volumes to date, see rapid adoption in the next decade that drives down costs and spurs mainstream diffusion (Figure 3.8). In some cases, the learning rates applied are lower, reflecting a more mature stage of development of a given technology. For example, heat pumps, for which significant learning experience has already been gained, follow a slower cost-reduction trajectory.

It is clear that not all technologies will follow the same journey, and learning rates in the Sustainable Development Scenario are adjusted in line with those seen for analogous technology scales and manufacturing methods. For example, energy technologies like refineries and turbines, which benefit from strong economies of scale in materials and throughput as well as in manufacturing, tend to experience periods of very rapid increases in unit scale and associated discontinuous patterns of cost reduction (Wilson, 2009). Occasionally the journey even involves going backwards: nuclear fission, a complex, large-scale technology, actually experienced “negative learning” in the 1970s and 1990s in France, partly due to the difficulties of standardising supply chains for successive projects (Grubler, 2010)

Figure 3.8 Unit cost reductions for selected technologies in the Sustainable Development Scenario



Notes: Cost reductions are calculated as a function of cumulative installed capacity in 2018, projected capacity additions from the model and component-specific learning rates. Learning rates for heat pumps, automotive battery cells and fuel cells stacks: 10%. Learning rates for battery packaging and fuel cell balance of plant: 5%.

Cost of technologies decline in the Sustainable Development Scenario but at different rates as a result of their different scale and technology attributes.

Technology attributes for faster innovation

Understanding the innovation dynamics of different technology designs is vitally important for governments and investors alike. Various types of technology have attributes that benefit from different means of innovation support and attributes that can favour (or disfavour) rapid innovation cycles (Bennett, 2019). Knowing how these attributes affect innovation can help governments determine whether they should take a leading role at any given stage of the innovation value chain or whether the private sector might reasonably be expected to take on much of the innovation risk.

There are a number of attributes that influence the rates of learning and technology adoption in the Sustainable Development Scenario (Table 3.1). They include small unit size and modularity – both of which favoured mass production, standardisation and continuous learning for PV and Li-ion, as described above – as well as spillovers. One of them, the use of digital solutions, has the potential to reduce significantly the time it takes to bring a technology to market for a wide variety of energy technologies types that are not digital in nature. These attributes can give a better chance of success, but do not guarantee it: the history of energy is littered with examples of failed or stalled technological developments. In some cases, resources were allocated to solve a problem, such as perceived oil shortages, that did not persist and so the business case for the R&D strategy unravelled as a result (Grubbler and Wilson, 2014).

Table 3.1 Energy technology attributes that can favour more rapid innovation cycles or faster learning

Attribute	Description	Past examples	Examples in the Sustainable Development Scenario
Small enough unit size to be mass produced	Small units can be prototyped and tested quickly before factories are built. As a result, global demand can support many factories and industrial competition can lead to faster turnover of products. New generations of these technologies hit the market every few years, with associated innovative improvements. In some cases, mismatched investment and consumption cycles can, however, lead to oversupply and intensive competition for market share.	• PV • Li-ion batteries	• Heat pumps • Fuel cells
Modularity	Modularity confers many of the same benefits as small unit size, but can also apply to larger units that cannot be mass produced but can be readily standardised and added sequentially to a facility. One of the main benefits is lower capital requirements for each stepwise addition, reducing the risks associated with scaling-up and enabling the pace of deployment to match that of other elements in the value chain.	• PV • Aluminium smelting	• Solid sorbent-based direct air capture • Electrolytic hydrogen routes for chemicals production • Small modular nuclear reactors • Standardised building retrofits
Offers services valued by consumers	Technologies need to be first taken up in niche markets where a small number of consumers are willing to pay a premium for their specific benefits. End-users, especially early adopters, will often pay a premium for a product that offers convenience, fun and reputational benefits. While many low-carbon technologies offer limited performance or economic advantages, low-carbon products could offer reputational and other benefits that consumers want, helping them to enter a virtuous cycle of adoption, learning, network effects and expansion to new applications.	• Passenger cars • Smart thermostats • LEDs • Micromobility • Smartphones (which replace up to 18 other devices)	• Autonomous, connected, electric and shared vehicles • Connected appliances • Building-integrated PV • Decentralised energy trading • Electrochromic fenestration
Spillovers (strong synergies with technology advances elsewhere)	shared between researchers and engineers from different sectors, reducing the need for dedicated energy R&D. This is because the advances needed to make a technology commercial in one application are simultaneously beneficial in another unrelated application. Electric vehicles are an example of a technology that was promoted for decades without uptake until spillovers from consumer electronics batteries, hybrid vehicles, lightweighting and motors helped it to take off.	• Combined cycle gas turbines (from jet turbines) • PV (from semiconductors) • Li-ion for EVs (from Li-ion for consumer products) • LEDs for lighting (from LEDs for electronics) • Offshore wind and geothermal (from oil and gas)	• CCUS (from oil and gas exploration, chemical catalysis and gas separation) • Batteries, fuel cells and electrolysers (from each other and other electrochemical technologies) • Biofuels (from health and agriculture) • Smart, connected energy technologies (from sensors and data communication)

Attribute	Description	Past examples	Examples in the Sustainable Development Scenario
Can be used as a drop-in replacement or bolt-on device	A new technology can be adopted more quickly if it requires no changes to associated equipment or infrastructure. A "drop-in" replacement is a substitute that is fully compatible with the dominant existing means of providing an energy service. A "bolt-on" device is fully compatible with existing processes, but leaves them intact and adds an additional function, such as emissions capture. CO_2 capture has the potential to be a "bolt-on" device, but usually requires significant changes to associated infrastructure (e.g. CO2 storage).	• Certain biofuels, e.g. hydrotreated vegetable oil • Biomethane • Catalytic converter • Desulphurisation	• Hydrogen-based synthetic fuels • Electric vehicles using existing road and electricity infrastructure • Biojet fuel
Replaces hardware or labour with digital solutions	Many recent energy sector innovations have replaced manual or analogue processes with digital ones. Innovation in digital technologies requires limited capital and allows continuous experimentation and cheap upgrading in situ. In addition, many digital products generate data that have commercial value, meaning that the risk of investment is shared between the energy-related and data-related value streams.	• Seismic geological exploration • Power grid management	• Autonomous, connected, electric and shared vehicles • Passive demand response • Digital twin O&M • 3D printing
Minimal dependence on improvements in other technologies in the value chain	hydrogen storage all depend on improvements not just in themselves, but also in the others. Likewise, the success of CO_2 capture depends in large part on simultaneous developments in CO_2 transport and storage. Though it is less of a bottleneck than for hydrogen and CCUS, the same factor has affected variable renewable power generation, which often relies on improvements to the grid or storage solutions. These dependencies raise the risks of R&D in each coupled element of the value chain and can significantly slow the pace of innovation.	• Biomass power generation • Nuclear • LEDs • Coal gasification	• Renewables plus storage • Enhanced smelt reduction-based steel
Minimal need for adaptation to local conditions	Some technologies, such as batteries, may need to be adapted to local climatic conditions when they are deployed in a new region. Temperature extremes, temperature swings or frequent storms are examples of local conditions that can dramatically change performance. Variations in fuel supply, for example for biomass gasification, can also make it harder to standardise a technology for a global market. In some cases, end-use products need to be adapted to local consumer preferences, regulations and expectations. Technologies that do not encounter these problems can reach wider markets faster.	• Internal combustion engines • Turbines	• Novel battery electrolytes • Fuel cells

Note: CCUS = carbon capture utilisation and storage; O&M = operation and maintenance

Focus on spillovers as an important attribute for faster innovation

The history of energy technology development is rich with examples of spillovers that changed the course of investment and industrial competition. Knowledge accumulated in one technology area has been a powerful driver for innovation in other related technologies. This factor, often overlooked, is of vital importance to technology policy because the benefits of spillovers can be harnessed at relatively low cost and can avoid or reduce the need for additional R&D. In the Sustainable Development Scenario, spillovers play a significant role in the transition towards net-zero emissions.

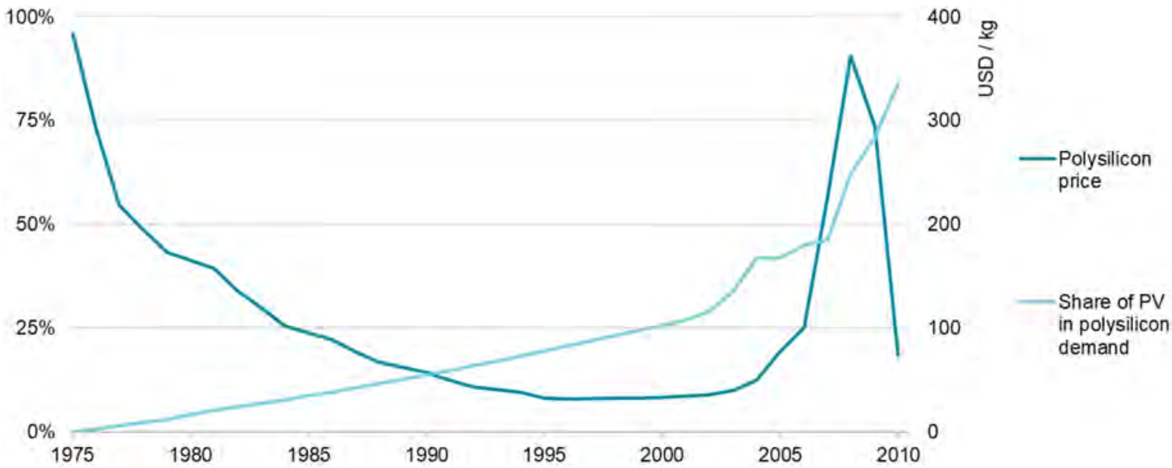
Spillovers can refer to knowledge transferring across technology areas (knowledge spillovers) or knowledge obtained by implementing a technology across different applications (application spillovers), though the boundaries between the two are sometimes blurred. Knowledge spillovers across different domains can occur if two technology designs share a common scientific base, similar manufacturing techniques, or common installation and operation skills. Application spillovers can occur when a technology design or technology component (such as an input material) that is optimised for one application becomes suitable for a different purpose. They are more likely to occur if the technology can be adapted to a large number of uses. The most potent cases of application spillovers have been termed "general-purpose technologies". These technologies can drive productivity growth right across the economy if they bring radical efficiency gains in multiple sectors. Archetypal examples include steam engines, electric power and information technology (Bresnahan and Trajtenberg, 1995; Ruttan, 2008). Public investment in the science underpinning these types of technologies can have particularly large paybacks.

The knowledge transferred via spillovers can be transmitted through researchers, engineers, consultants and plant operators. Geographical proximity can enhance spillovers, as can professional societies and conferences. An important part is played by companies that provide services to different sectors, such as engineering, procurement, and construction contractors and technical consultancies (Hoppmann, 2018).

Many critical spillovers that have benefited specific energy technologies have come from outside the energy sector. The development of combined cycle gas turbines, which now play an integral role in electricity generation systems, was initiated by the aerospace sector. The first gas turbine jet engine was developed in 1939 following government-funded military R&D in the United Kingdom. These gas turbines were initially rejected by electricity utilities for being low powered and inefficient compared with steam turbines, but a number of blackouts in industrialised countries in the 1960s led utilities to install gas turbines designed for aircrafts for emergency backup. In response to power sector requirements, gas turbine power output and efficiency were increased (Watson, 2001). Additional demand then led to further improvements in materials and design.

Another example is provided by the cost-competitive mass production of solar PV panels, which was enabled by knowledge spillovers from parallel developments in the production of silicon for microprocessors. Adoption of semiconductor manufacturing processes by the PV sector and sharing of silicon production between the two sectors were vital factors in cutting PV costs, resulting in the share of PV in total polysilicon demand growing very rapidly after 2000, by which time polysilicon prices had fallen to less than 10% of their 1975 level (Figure 3.9). Likewise, the development of the carbon anode used in Li-ion batteries benefited from knowledge and techniques developed by the petrochemical sector: the first functioning carbon anode was developed by a petrochemical company.

Figure 3.9 Share of PV in polysilicon demand (left) and polysilicon price (right), 1975-2010



Note: The 2008 price spike was due to shortage of supply after spike in demand for PV panels that rebalanced after the global financial crisis.
Sources: Mehta (2014); Ferber, Costogue and Pellin (1982).

The share of PV in total polysilicon demand grew very rapidly after 2000, by which time polysilicon prices had fallen below 10% of their 1975 level.

Box 3.4 Could biofuel technology developments benefit through spillovers from the race for a Covid-19 vaccine?

R&D in biotechnology is attracting increased interest as the race continues to produce an effective Covid-19 vaccine. Applying biotechnology in the form of genetic engineering[22] to certain plants and microalgae could help scale-up the production of any vaccine when it becomes available, while also potentially creating synergies with the production of biofuels.

Typically, vaccines are produced within bacterial or mammalian cells. Developing these cell lines can take months, and scaling them up in a stable way can take at least a year or two. Growing and harvesting genetically modified plants and microalgae, on the other hand, takes only a matter of weeks, and no additional scale-up protocol is required, allowing full production to be ready in months. This could deliver vaccines faster while reducing production costs and potentially also avoiding the need for expensive refrigeration of the vaccine (Balfour, 2020; Capell et al., 2020).

Development of genetically engineered plants (also known as transgenic plants) for the production of vaccines is not a new concept, but has yet to be commercialised. There are, however, several plant-based vaccines now undergoing clinical trials, such as ZMapp, a combination of antibodies produced in transgenic tobacco plants that was used to fight the Ebola virus in 2015 (Xu, Towler and Weathers, 2016). Several companies and research institutes are actively pursuing both genetically engineering plants and microalgae to develop a suite of tools to control the Covid-19 pandemic, including proteins for vaccines, antivirals and testing kits (ISAAA, 2020).

There are two key techniques in the biotechnology domain that, if further developed and commercialised, could help overcome barriers to the commercialisation of advanced biofuels production:

- **Genetic engineering** could increase the content of biomass materials that can be used as feedstocks for energy purposes (e.g. sugars, oil and lignocellulosic material in plants) or produce enzymes that break down lignocellulosic material, thus facilitating its further processing to produce biofuel.
- **Advanced extraction techniques** could allow multiple bioproducts (e.g. oil, proteins, sugars) to be recovered efficiently at high purity, lower energy requirement and low cost (Kumar et al., 2020; CRAG, 2020a).

Biorefineries provide an ideal platform to exploit potential synergies because they are able to create multiple products from a single biomass feedstock in much the same way as petroleum refineries produce multiple products from crude oil. This offers the

[22] In this form, genetic engineering involves manipulating the metabolic pathways within organisms to produce desired bioproducts so that plants and microalgae become a type of plant factory.

prospect of diversified revenue streams that reduce the production cost of each individual bioproduct (whether for pharmaceuticals, nutrition, biofuels) and help to insulate the producer from the economic impacts of market fluctuations within different sectors. Depending on the feedstock selected, two approaches that hold promise are:

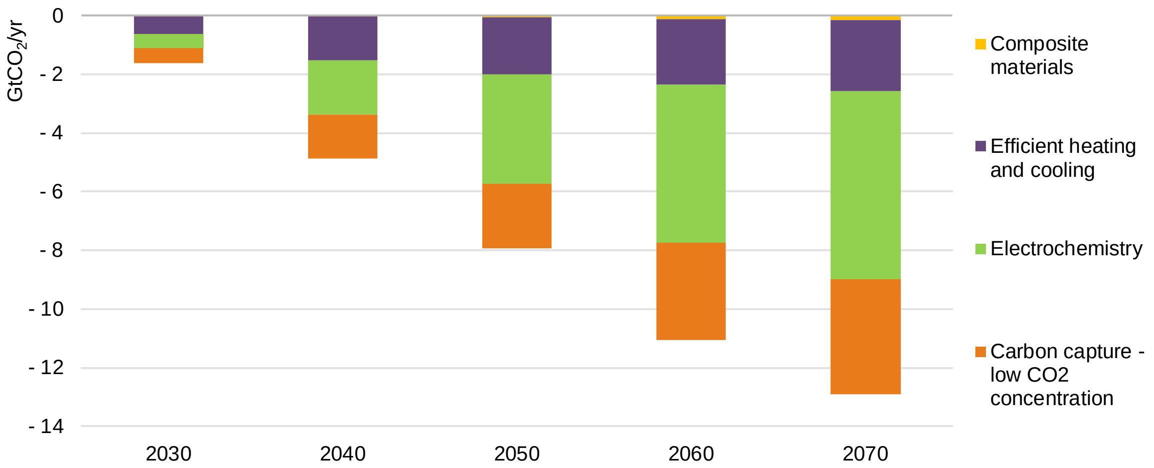
- **Genetic modification of microalgae** to produce increased oil, sugar, proteins or other compounds that can be extracted and then refined for use in myriad of sectors, including biofuels and pharmaceuticals
- **Use of transgenic plants** (e.g. tobacco) and residual biomass (biomass that remains after extracting the proteins or enzymes of interest for medical purposes) to produce bioethanol or biogas.

Governments, research institutions and companies can stimulate this spillover effect by harnessing transgenic plants and microalgae research for both pharmaceutical and biofuels applications. The Centre for Research in Agricultural Genomics in Spain is an example of how this might be approached: it is pursuing research to find a vaccine for Covid-19 alongside research on how best to use lignocellulosic material to produce bioethanol (CRAG, 2020a; 2020b).

Spillovers in the Sustainable Development Scenario

Spillovers play a particularly important role in the Sustainable Development Scenario. This section discusses how spillovers accelerate progress in four selected technology areas: electrochemistry, carbon capture in low CO_2 concentration applications, composite materials for lightweighting, and vapour compression cycles for cooling and heating. These four technologies together account for 30% of the additional cumulative emissions reductions through to 2070 in the Sustainable Development Scenario compared with the Stated Policies Scenario, with electrochemistry accounting for around 45% of these reductions (Figure 3.10).

Figure 3.10 Emissions reductions between the Sustainable Development Scenario and the Stated Policies Scenario enabled through selected technology synergic areas



A quarter of cumulative emissions reductions in the Sustainable Development Scenario are related to technology families benefiting from knowledge spillovers.

Box 3.5 Quantifying the impact of spillovers on accelerating technology cost reductions

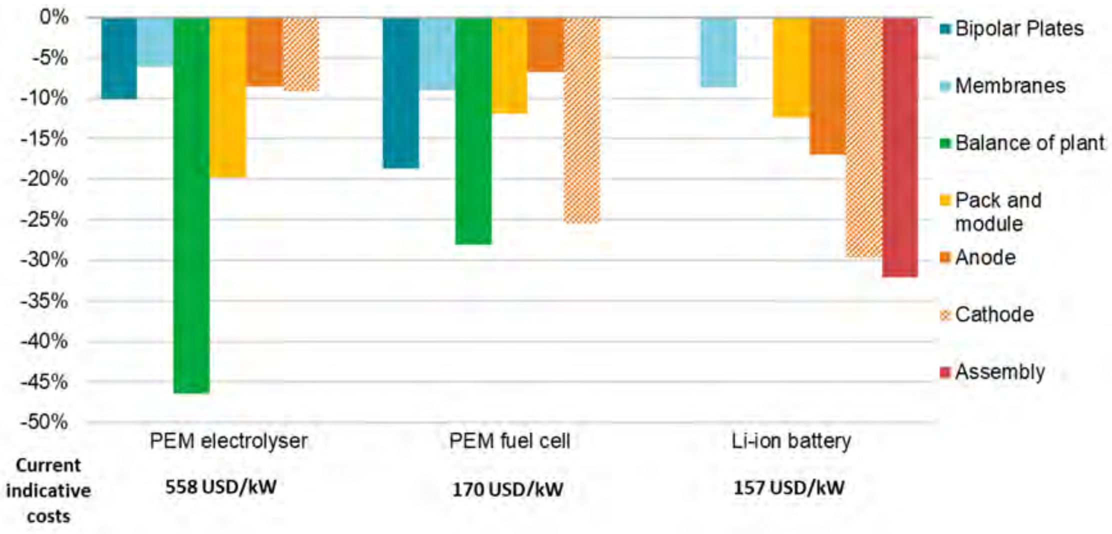
There is no consensus today on how to quantify the impact of spillover effects. The impact of knowledge spillovers cannot be easily quantified because of the complexity of the interactions between those working on different technologies that use the same scientific principles. The impact of application spillovers in technology cost can, however, be quantified by making use of learning curves. As discussed earlier in this chapter, learning curves relate the cost reductions for a given technology to its cumulative installed capacity, which is a proxy for the level of experience and scale acquired by the industry. We develop learning curves that aggregate the projected cumulative installed capacity resulting from implementing that technology in different applications, so that the projections reflect the accumulation of learning from multiple sources. Then we develop alternative learning curves based only on the deployment in each individual application, and we use that as a counterfactual to isolate the effect of spillover in cost reductions in the Sustainable Development Scenario.

Electrochemistry: Spillovers between batteries, fuel cells and electrolysers

Electrochemical devices convert electrical energy into chemical energy (and vice versa). Because chemical energy is easier to store in large quantities than electrical energy, these devices have an important role to play in the electrification of transport and the provision of short- and long-term storage (through hydrogen synthesis) for variable renewables. Batteries, fuel cells and water electrolysers are all electrochemical devices, and together they are responsible for 15% of the projected cumulative emissions reductions to 2070 in the Sustainable Development Scenario compared to the Stated Policies Scenario These technologies share scientific principles, component design, and materials and manufacturing techniques, which means that developments in one kind of device are likely to directly or indirectly benefit advances in others. These synergies are most likely to be exploited by organisations involved in the development of more than one of these technologies. Examples include automotive companies developing fuel cell and battery-electric vehicles in parallel, manufacturers using decades of knowledge about chlorine electrolysis for alkaline water electrolysers, and chemical companies developing components for batteries, fuel cells and electrolysers.

A way to illustrate the potential of strengthening such spillovers across these three electrochemical devices is to explore the cost-reduction potential of specific common component families: electrodes, membranes and electrolytes, cell and stack assembly, and balance of plant components (Figure 3.11). Analysis suggests that advanced materials and manufacturing techniques for electrodes (i.e. cathodes and anodes) could unlock between around 20% and 45% of the cost-reduction potential for polymer electrolyte membrane (PEM) electrolysers, fuel cells and Li-ion batteries in the Sustainable Development Scenario (Figure 3.11), while sharing learning on improving the balance of plant between PEM electrolysers and fuel cells could deliver 45% and 25% cost reductions in these two technologies respectively.

Figure 3.11 Breakdown of cost-reduction potential for electrochemical devices by component category



Notes: PEM = polymer electrolyte membrane. Cost-reduction potentials by component are obtained from technological bottom-up studies of each device. Assembly refers to stack assembly for PEM devices and to cell assembly for batteries. Anode and cathode categories involve related materials and manufacturing for batteries, as well as gas diffusion layer (anode) and catalyst layer (cathode). Membranes refers to membranes and electrolyte for batteries, and polymer membranes for PEMs. Bipolar plates are components exclusively found in electrolysers and fuel cells, while package and module costs are exclusive to batteries.

Sources: Thompson (2018); Mayyas et al. (2019); IEA analysis based on BatPac; Argonne National Laboratory (2020).

Cost reductions in all the key components of electrochemical devices have the potential to spill over from one kind of device to another

In the Sustainable Development Scenario, the deployment of batteries in electric vehicles and in grid storage applications brings spillover benefits. Fuel cells and electrolysers benefit more from learnings in batteries development and manufacturing than the other way around because they have less advanced value chains and there is less experience of mass manufacturing them in large numbers: this helps to accelerate the deployment of fuel cells and electrolysers, which become more competitive against alternatives as a result of their spillover gains.

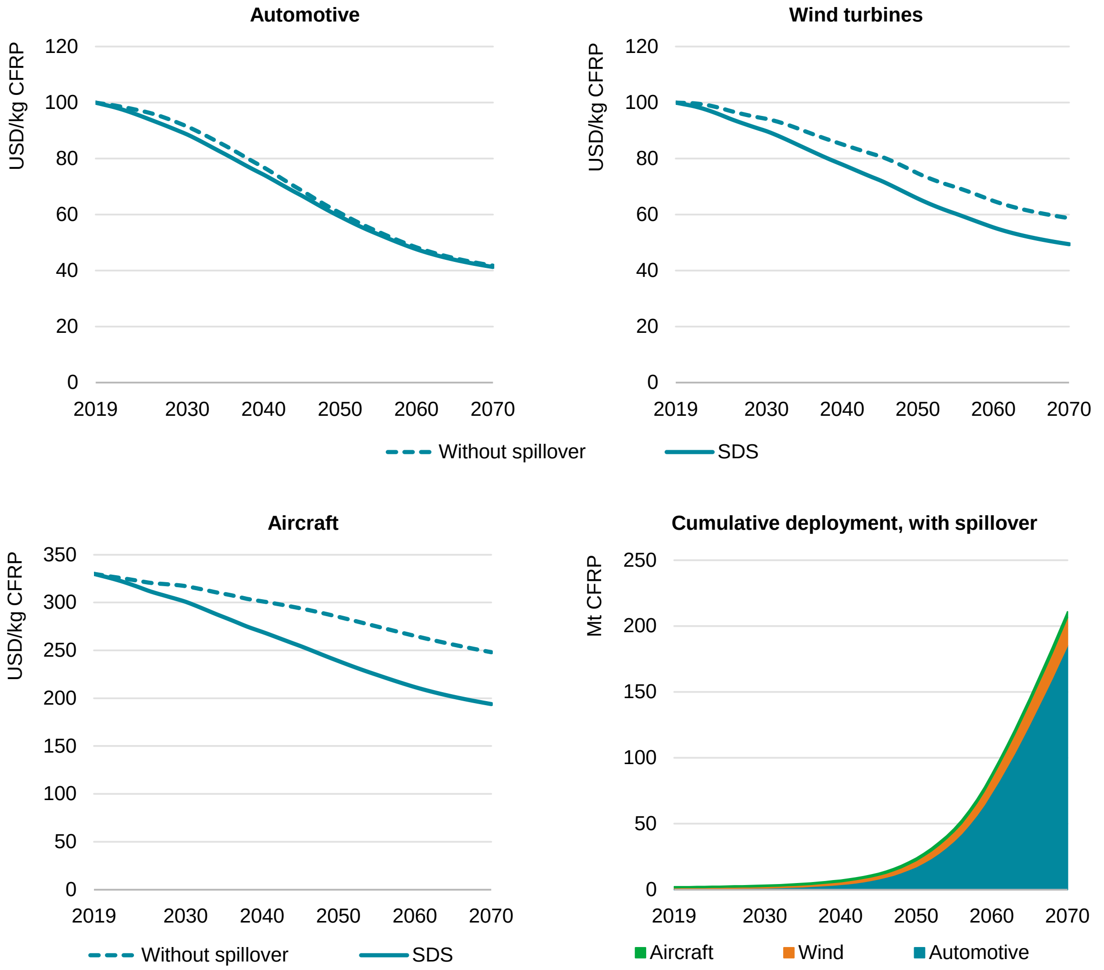
The Sustainable Development Scenario also sees spillover benefits from deploying the same electrochemical device across different applications. For example, synergies between batteries developed for the automotive sectors and those for grid-scale applications lead to lower cost batteries for grid storage. Grid storage costs in the Sustainable Development Scenario would be 20% higher by 2070 without these spillover gains.

Composite materials: Spillovers between lightweight wind turbines, road vehicles and aircraft

The increased use of light materials such as carbon fibre-reinforced plastics (CFRP) offers scope for fuel savings in road vehicles and aircraft, and for higher capacity factors in wind turbines. Today, the use of CFRP in these three areas is still at a relatively early stage. In road vehicles, it is estimated to account for less than 1% of the average vehicle weight in most cases. In aircraft, by contrast, composite plastic use is relatively common, although not yet ubiquitous: CFRP makes up on average about 10% of structural weight in small and medium aircraft, and about 25% in larger aircraft: nearly fully CFRP designs are in the demonstration phase (Air Transportation Analytics Ltd. And Ellondee Ltd., 2018; NASA, 2010; Coppinger, 2019). In wind power applications, roughly 25% of turbines are manufactured with carbon fibre components in their blades (Composites, World, 2020).

These applications are all linked through a common material (carbon fibre) and a common manufacturing base, which means that there is scope for accelerated innovation through spillovers as the use of carbon fibre-reinforced plastic increases. In particular, use of carbon fibre in the road transport fleet provides scope for spillover gains for the relatively smaller sectors of wind energy and aviation (Figure 3.12).

Figure 3.12 Carbon fibre-reinforced plastic costs and cumulative deployment in selected applications in the Sustainable Development Scenario



Notes: SDS = Sustainable Development Scenario; CFRP = carbon fibre-reinforced plastic. Combined learning (spillover effect) across different applications is applied to the share of total price of each application associated to carbon fibre production. Solid line for technology costs represents the cost trajectory in the Sustainable Development Scenario while the "no spillover" case is a counterfactual that shows the slower price decline that would be observed if the technology could not benefit from experience gathered in different applications. Base year cost assumptions from Das et al. (2016).

The use of carbon fibre-reinforced plastic in aviation and wind turbine applications benefits from learnings gained from its use in the automotive market.

In aviation-related applications, spillover effects result in a 20% reduction in the cost of CFRP in 2070 in the Sustainable Development Scenario relative to a case without spillover: this cost reduction leads to greater use of CFRP in aircraft, which reduces fuel costs and speeds up performance improvements.

In wind turbines, composite plastic materials bring a number of improvements, mainly by making larger turbine diameters available earlier. Turbines with larger swept areas provide higher and more reliable electricity output: steadier output is easier to integrate and increases the value of wind power in electricity markets. Higher capacity factor wind turbines also open up low-wind areas for wind farm development that would have otherwise been considered unattractive, thus increasing the exploitable wind resource.

The combined spillovers from these wide-ranging applications also trigger innovation activity along the whole CFRP supply chain, resulting in cost, energy and emission reductions through multiple avenues both in carbon fibre production – including using alternative precursors, recycled fibres and alternative production processes – and in the conversion of carbon fibre into CFRP – including though rapid cure and automated processes that speed production. The supply chain innovations impacting the CO_2 intensity of CFRP production alone enable 1.5 $MtCO_2$ additional emissions savings in 2070 from the integration of CFRP compared to a hypothetical case in which each application was developed in isolation.

At present, it is challenging to recycle CFRP, since many current recycling technologies damage the carbon fibres, making them unsuitable for many applications and so reducing their value. Current recycling options also tend to be expensive or require toxic chemicals. Further innovation is needed so that this lack of recyclability can be overcome: this would promote greater use of CFRP, and would also reduce energy consumption by cutting down on the need for virgin CFRP production. Several methods are currently under exploration, including one that uses non-toxic solvents and another that melts the polymers into a new CFRP.

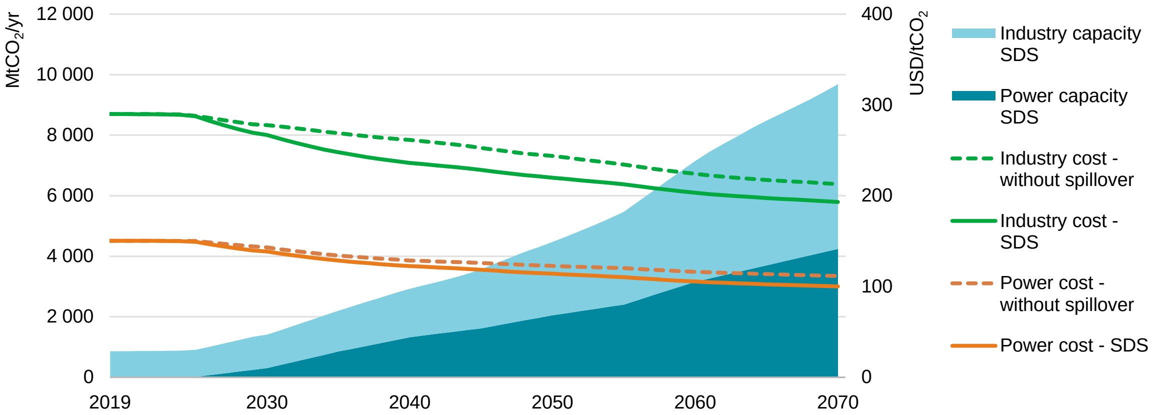
Carbon capture: Spillovers between low CO_2 concentration applications

By 2070, the use of CCUS is responsible for more than 10% of the additional cumulative emissions reductions in the Sustainable Development Scenario compared with the Stated Policies Scenario. Achieving the deployment levels necessary to achieve this requires developing and scaling-up a suite of different CO_2 capture technologies that can be adapted to different CO_2 sources. CO_2 separation techniques range from chemical absorption and membrane separation (already used by industry for other gases) to those that require more disruptive innovations, such as oxy-fuel and calcium looping.

Chemical absorption is the most advanced carbon capture technique. It was developed in the 1930s and has been applied commercially over several decades to separate out CO_2 from gases with a wide range of CO_2 concentrations. Cumulative installed capture capacity is estimated today at around 860 $MtCO_2$/year.

Despite accumulated experience to date, there is scope for further cost reductions from sharing the knowledge gained about the use of chemical absorption in different processes. There is also scope to reduce capital costs, for example through the standardisation of capture units, economies of scale and learning-by-doing from large-scale deployment. In the Sustainable Development Scenario, the learning gained from applications of chemical absorption in industry and power generation mean that the cost of deploying this technology is around 10% cheaper in the Sustainable Development Scenario by 2070 than in a hypothetical case where there is no learning from other applications of this technology (Figure 3.13).

Figure 3.13 Cumulative capacity (left) and capital cost learning curve (right) chemical absorption in industrial and power applications in the Sustainable Development Scenario



Notes: SDS = Sustainable Development Scenario. Solid line for technology costs represents the cost trajectory in the Sustainable Development Scenario while the "no spillover" case is a counterfactual that shows the slower price decline that would be observed if the technology could not benefit from experience gathered in different applications.

Cost reductions in deploying chemical absorption accelerates in the Sustainable Development Scenario as a result of sharing learnings gained from different applications.

Box 3.6 Potential knowledge spillovers from electrochemistry to carbon capture

Typically, carbon capture techniques rely on changes in temperature or pressure in order to absorb and release CO_2 captured from gas streams. However, novel devices are now making use of electrochemical reactions to trap and liberate CO_2. These reactions have the potential to capture CO_2 even when its concentration is as low as 0.04%, i.e. the proportion of CO_2 in air.

One such device, called electro-swing adsorption (ESA), is similar to a large battery. It adsorbs CO_2 if a CO_2-containing gas passes across the electrodes at the same time as electricity charges it. The discharge cycle releases pure CO_2. ESA has been demonstrated at laboratory scale using quinone sorbents in solution and has recently been adapted by tethering the solvents to a solid surface. Researchers are currently planning a prototype device.

As this design is compact, modular and relies solely on electricity, it would have the flexibility to operate with variable electricity supplies. Furthermore, with an electricity requirement of up to 2.5 GJ per tonne CO_2 captured, it is expected to need around four times less energy than solid sorbent-based DAC, which currently needs around 7 GJ of low-temperature thermal energy and 1-2 GJ of electricity. However, before ESA can become a competitive alternative, it will need to increase the sorption time in order to minimise the number of cells required, and this will involve capital costs (Wilcox, 2020). Fewer cells will also help to manage the land area required: it has been estimated that a 1 $MtCO_2$/yr ESA DAC plant would require tens of thousands of square metres for the capture equipment alone. This is lower than the estimates for solid-sorbent DAC designs, but still represents a significant challenge to deployment.

Another way in which electrochemical processes can be harnessed for carbon capture is through carbonate fuel cells. These cells generate electricity from carbon-containing inputs, such as natural gas, while converting all the carbon to a stream of CO_2 and hydrogen by-product: CO_2 can then be easily separated from other flue gases. If the flue gas containing CO_2 is fed into the fuel cell, then the fuel cell separates both the CO_2 from the electricity generation process and the CO_2 from the flue gas input and allows them to be captured together. Molten carbonate fuel cells have been tested since the 1960s and have operated in commercial conditions since the early 1990s: over 300 MW of capacity has been installed to date (Weidner, Ortiz Cebolla and Davies, 2019).

All electrochemical approaches to CO_2 capture will continue to benefit from knowledge spillovers from more mature electrochemical devices, like batteries, including their experience in mass production and electrochemical plate design.

Efficient heating and cooling: Spillovers between air conditioners and heat pumps

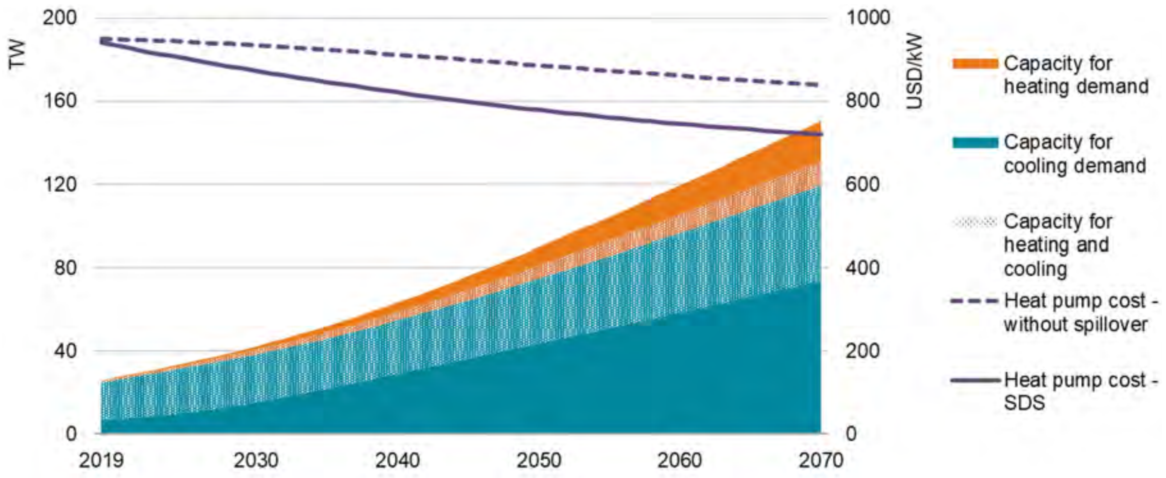
Heat pumps and efficient air conditioners are a cornerstone of buildings sector decarbonisation, enabling almost a quarter of the cumulative additional CO_2 emissions reductions through to 2070 in the Sustainable Development Scenario compared to the Stated Policies Scenario. Both devices are generally based on the vapour compression cycle, which transfers heat energy from one source to another (air-to-air, air-to-water, water-to-water) to provide end-use services (space cooling, space heating, water heating). Air conditioners are optimised cooling applications, whereas heat pumps are optimised heating applications. When reversible, a vapour compression cycle provides both heating and cooling comfort. While learning has been accumulated for decades from designing, manufacturing and installing these devices, spillovers between these two applications still have the potential to stimulate further innovation and to speed up incremental cost reductions and efficiency improvements.

Historically, the development of heat pumps and air conditioners has been driven by a combination of reducing upfront costs, improving reliability and increasing efficiency of thermal energy delivered or removed per unit of electricity consumed. For air conditioners, efficiency has improved thanks to a combination of market forces and regulations (e.g. minimum energy performance standards for products and buildings codes), while costs have continuously decreased, so that more efficient products such as inverter air conditioners have increasingly replaced less efficient products (Groff, 2014; Desroches, L. B. et al., 2013). Performance improvement and cost reduction have, however, slowed down in recent years. Heat pump performance and cost metrics have also improved, mainly as a result of policy incentives, while growing demand for heat pumps has opened the way for innovative market schemes in which, for instance, operators of distribution systems act as service providers and/or heat pump operators.

Globally, the growth of cooling needs is the main demand-pull mechanism for current and future improvements in vapour compression technologies. Current global space cooling installed capacity is more than 10 times larger than that of heat pumps. In the Sustainable Development Scenario, despite rapid heat pump growth, space cooling installed capacity remains almost four times larger than that of heat pumps for primary heating use in 2070. Synergies between air conditioners and heat pumps mean that heat pumps achieve an additional 15% cost reduction thanks to spillovers from cooling applications in 2070 in the Sustainable Development Scenario (Figure 3.4).

These improvements in cost and performance would result in heat pumps gaining half of the heating market share globally, mainly in countries like the Russian Federation and the People's Republic of China (hereafter "China"), where the incumbent heating technology is direct or district use of natural gas or coal. They are likely to require a special focus on balance-of-system components and soft costs, which are expected to account for a growing share of total future costs. In the longer term, they are also likely to require alternative designs to reduce what are currently considered the minimum costs which are technically achievable: this might involve the use of innovations such as vapour compression cycles based on optimised low global warming potential refrigerants.

Figure 3.14 Cumulative capacity (left) and capital cost learning curve (right) for vapour compression applications in the Sustainable Development Scenario



Notes: SDS = Sustainable Development Scenario. Solid line for technology costs represents the cost trajectory in the Sustainable Development Scenario while the "no spillover" case is a counterfactual that shows the slower price decline that would be observed if the technology could not benefit from experience gathered in different applications. The cost excludes geothermal applications and is referred to heat-pumps unitary cost excluding additional components needed for the system and eventual ductwork. This cost trajectory is representative for units of less than 20 kW capacity.

Estimated capacity additions for vapour compression technologies are dominated by cooling applications: the synergy between heating and cooling results in around 15% lower cost for heating equipment.

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Chapter 4. Clean energy innovation needs faster progress

HIGHLIGHTS

- The Covid-19 crisis represents both an opportunity and a risk for clean energy technology innovation. It offers a once-in-a-generation opportunity for governments to reprioritise and boost innovation, including R&D, as part of stimulus efforts with a view to achieving a long-term transition to net-zero emissions. But it could also result in tighter government and corporate budgets that lead reduce the pace of clean energy innovation.
- We explore two variants of the Sustainable Development Scenario to illustrate the potential impacts. In a Faster Innovation Case, we examine what would be needed in terms of even faster progress in clean energy technology innovation to deliver net-zero emissions globally by 2050, including from technologies that are currently only in the laboratory or at the stage of small prototypes. In a Reduced Innovation Case, we examine what the effects would be if demonstration projects currently in the pipeline were to be delayed by five years and if deployment rates for technologies at the critical early adoption stage were to be slowed down.
- In the Faster Innovation Case, CO_2 savings from technologies currently at the prototype or demonstration stage would be more than 75% higher in 2050 than in the Sustainable Development Scenario, and 45% of all emissions savings in 2050 would come from technologies that have not yet reached the market. Such rapid deployment would require successful innovation cycles that are more rapid than any seen in recent energy technology history. Key clean energy technologies at demonstration or large prototype stage today would need to reach markets in six years from now at the latest, which is twice as fast as in the Sustainable Development Scenario. Robust market deployment of current prototypes would need to start right after the completion of only one single commercial-scale demonstration, which is not common practice.
- In the Faster Innovation Case, advanced high-energy density battery chemistries would enable electrification of transport to be more widespread, and large-scale high-temperature industrial electric heating is widely deployed in sectors such as chemicals (both technologies are at concept and early prototype stage today). Demand for hydrogen and hydrogen-based fuels would grow by almost 25% in 2050 over the Sustainable Development Scenario, requiring, for example, almost two new hydrogen-based steel plants (today at prototype stage) to be installed each month from now to 2050. CO_2 capture would increase by 50% to around 7.5 $GtCO_2$ per year in 2050, while almost 90 new bioenergy plants equipped with CO_2 capture and storage would be needed each year, nearly three times as much as the capacity projected in the Sustainable Development Scenario.
- In the Reduced Innovation Case, the rate of technology development would be much slower than in the Sustainable Development Scenario as a result of the Covid-19 pandemic, and emissions would be higher. The capital costs of critical technologies such as hydrogen electrolysers would rise by almost 10% by 2030 relative to the Sustainable Development Scenario, increasing the investment challenge and cost of finance, undermining the ability of the industry to scale-up production at the required pace, and requiring governments to provide additional financial support for longer until the technology becomes competitive.

Introduction

A clean energy transition of the global energy sector to net-zero emissions in the long term requires radical changes to the way we produce and consume energy. It requires us, in particular, to move away from the production and use of fossil fuels without carbon capture utilisation and storage (CCUS) and to use low-carbon and more efficient energy technologies. The Sustainable Development Scenario, presented in Chapter 3 of this *ETP Special Report*, describes such a low-carbon transition. It is designed to meet UN energy-related Sustainable Development Goals, including the goal of the Paris Agreement, and the transition it sets out is unprecedented in scope, depth and speed. The technology turnover and innovation needs that it details are significant, and show how much more there is to do: almost 35% of the cumulative emissions reductions by 2070 in the Sustainable Development Scenario compared with the Stated Policies Scenario hinge on technologies that are currently only at large prototype or demonstration phase, and around 40% on technologies that are not yet commercially deployed at a large scale. In other words, technologies currently available to the market at scale will not be sufficient to effect a global clean energy transition to net-zero emissions, and a continued and strong focus on RD&D is essential to the transition.

Against this background, it is clearly of paramount importance to ensure that government and corporate RD&D portfolios and priorities are aligned with a transition to net-zero emissions. There is much to do, and the challenges are formidable. As discussed in Chapters 2 and 3, technology innovation is a time-consuming non-linear process in which some ideas get abandoned while new ones are being generated. History shows that bringing new energy technologies to sizeable deployment after the first prototype can take between 20 and almost 70 years: the journey took around 30 years even for recent highly successful clean energy technologies, such as solar photovoltaic (PV) and lithium-ion (Li-ion) batteries to power electric vehicles. The impact of the Covid-19 pandemic has greatly affected economic activity, including in the energy sector, thus adding to the challenges. In response, governments are now increasingly looking at economic stimulus packages: these offer an important opportunity for action that helps to ensure continued security of energy supplies while supporting clean energy transitions, including the technology innovation that they depend on.

In this chapter, we complement the Sustainable Development Scenario by analysing two additional variants that serve to illustrate the importance of prioritising clean energy innovation in stimulus packages and more widely:

- We analyse a **Faster Innovation Case** that explores just how much more clean energy technology innovation would be needed to bring forward the time at which the Sustainable Development Scenario reaches net-zero emissions from 2070 to 2050. This case serves to underline the importance of governments grasping the opportunity provided by stimulus packages in the context of Covid-19 to review their RD&D portfolios and priorities and align them with their long-term clean energy transition objectives.

- We then analyse a **Reduced Innovation Case** that explores the risks associated with a potential slowdown in innovation activities arising from delays in demonstration projects or a slow uptake of technologies currently at an early stage of adoption. This brings out the likely consequences if governments fail to prioritise clean energy technology innovation in stimulus packages and more widely.

Box 4.1 Is clean energy technology innovation at risk following the Covid-19 crisis?

With the global economic crisis unfolding after the pandemic, there is a risk that the innovation efforts of governments and companies could be deprioritised and that the development and deployment of key clean energy technologies could be delayed as a result. Early signs are generally encouraging, however, indicating that governments and companies understand the importance for clean energy transitions of a continuing strong focus on RD&D.

The Covid-19 outbreak has affected critical electricity-based technologies. Heat pumps sales reported for 2020 suggest a temporary levelling off or decrease in some markets. Air-source heat pump sales increased by 5% in the United States from January to March 2020 relative to 2019, but decreased 15% year-on-year in April (AHRI, 2020). The Japanese producer Daikin projects an almost 9% drop in sales for 2020 (Daikin, 2020), while the European Heat Pump Association estimates that the European market could register a decline of up to 10%. However, manufacturers seem confident in a bright future for heat pumps. As of June 2020, heat pump manufacturing outputs returned to pre-pandemic levels in China and Europe, although a number of factories were still closed in India. Daikin (accounting for an estimated third of the global heat pump market) also plans to maintain its R&D spending in 2020 relative to 2019, and the company is strengthening R&D capacity in Germany (Daikin, 2020a; 2020b). Governments are seizing the opportunity to include heat pumping technology in Covid-19 stimulus packages: for example, the Italian "Super Eco-bonus" provides a 110% fiscal incentive (up to EUR 30 000) for A-class heating and cooling systems, on top of other renovation measures (Gazzetta Ufficiale, 2020).

In transport, the outbreak of the Covid-19 pandemic brought about a dramatic decline in electric car sales in some regions. In China, the decline was largest in February, with electric car sales falling by around 60% from the same month in 2019: sales rebounded strongly in April, however, reaching around 80% of the level they were at a year earlier. In the United States, electric car sales in April more than halved from a year earlier. In the largest European car markets combined (France, Germany, Italy and the United Kingdom), however, sales of electric cars in the first four months of 2020 reached more than 145 000 electric cars, about 90% higher than in the same period last year, as a result of recently revitalised supportive policy schemes.

For carbon capture utilisation and storage (CCUS), short-term uncertainty has been tempered by recent project and funding announcements. In March 2020, the United Kingdom confirmed its pledge to invest GBP 800 million (USD 995 million) in CCUS infrastructure: its plans involve establishing CCUS in at least two locations. In Europe, the EUR 10-billion Innovation Fund will be available to support CCUS projects (and other clean energy technologies) from 2020, while in May the Australian government announced plans to make CCUS eligible for existing funding programmes. Direct air capture research also received a boost in March 2020 when the US Department of Energy earmarked USD 22 million in research and development grants (US DoE, 2020). Recent industry commitments to CCUS include an announcement by the Oil and Gas Climate Initiative in April 2020 to invest in a natural gas CCUS power plant in the United States, and a commitment in May 2020 by Equinor, Shell and Total to invest more than USD 700 million in the Northern Lights offshore CO_2 storage project. In addition, Climeworks announced in June 2020 that it had by then raised CHF 73 million (USD 75 million), the largest private investment to date for direct air capture (Climeworks, 2020).

Some delays have been announced to hydrogen projects, for instance in Sweden, where a project aiming to develop several commercial-scale demonstrators for methanol based on electrolytic hydrogen has delayed the detailed engineering phase, although only by a matter of months (Liquid Wind, 2020). Other projects may face delays as well: Hydrogen Europe estimates that up to EUR 130 billion of investments in low-carbon hydrogen production projects may be at risk in Europe (Hydrogen Europe, 2020). But there have also been plenty of confirmations of pre-Covid development plans for hydrogen technologies. Several governments, such as Germany and Norway, announced in early June their hydrogen development strategies with firm commitments (EUR 9 billion to support hydrogen technologies in the case of Germany, which is 7% of its national total recovery fund). In addition, the consortium behind the development of iron ore reduction for steelmaking based fully on electrolytic hydrogen confirmed in June 2020 its commitment to proceed with the project as planned. This means that construction of an industrial scale demonstration plant will commence in 2023 with the objective of producing commercial fossil-free steel as early as 2026 (Hybrit, 2020).

New initiatives that promote innovation in hydrogen-related technologies have also emerged over recent months. Australia is committing AUD 300 million funding to support hydrogen-powered projects (Department of Industry, Science, Energy and Resources, Australia, 2020). The Next Generation EU plan could see investments in hydrogen technologies as a tool to support the economic recovery from the Covid-19 crisis (EC, 2020). In the People's Republic of China (hereafter "China"), the capital city released in June 2020 its municipal "New Infrastructure Action Plan (2020-2022)" to become the demonstration city in China for hydrogen fuel cell vehicles, including establishing national-leading manufacturing centres for hydrogen technologies (Beijing Municipality, 2020). Also in China, State Power Investment Corp disclosed in May 2020 plans to construct an industrial hub in Zhuzhou City (Hunan Province) that integrates hydrogen supply with renewables, storage, refuelling infrastructure and fuel cell manufacturing, with a total investment of JPY 3.6 billion (USD 0.5 billion) (21SPV, 2020). In the private sector, there is a strong focus on sectors that currently have limited commercially available scalable low-carbon options. For instance, six Danish companies from the energy and transport sectors have announced a joint effort to develop hydrogen-based fuels for long-distance transport and heavy industry, with the first projects starting operations in 2023 (Financial Times, 2020). In April 2020, several automakers announced plans to start production of fuel cells for heavy-duty road vehicles, beginning as early as 2020 in some cases (Green Car Congress, 2020; Daimler, 2020), while some equipment manufacturers have announced an agreement to join forces in developing mega-watt scale fuel cell systems suitable for ocean-going vessels (ABB, 2020).

The Faster Innovation Case – just how far could innovation take us?

The Sustainable Development Scenario reaches net-zero emissions from the energy sector within five decades on the back of ambitious technological change and optimised innovation systems comparable to the fastest and most successful clean energy technology innovation success stories in history. In this section we explore just how much more clean energy technology innovation would be needed to bring forward net-zero emissions to 2050, a milestone year of clean energy transitions work that has gained much prominence through the public debate that followed the release of the Intergovernmental Panel on Climate Change's Special Report on Global Warming of 1.5°C.

The Faster Innovation Case is a special case of the Sustainable Development Scenario that focuses on stretching underlying innovation drivers. It is not designed to be an ideal pathway to net-zero emissions by 2050; the complexity of this question goes well beyond technology innovation alone, and is likely to require much more fundamental changes to our lifestyles.[23] Rather, it is designed to explore how much shorter development cycles would need to be than in the Sustainable Development Scenario, and how much more ambitious technology diffusion rates would need to be in order to deliver net-zero emissions globally by 2050. There are three key changes that distinguish the Faster Innovation Case from the Sustainable Development Scenario:

- In the Sustainable Development Scenario, technologies that are still in the laboratory or early prototype stage today are not considered because of the high level of uncertainty about their performance and possible future commercialisation. To explore their potential contribution to reach net-zero emissions earlier, we include in the Faster Innovation Case those technologies at low technology readiness level (TRL) that are modular and small enough to be mass produced and that have the potential for high spillovers from and to other net-zero emissions technologies. We also include those technologies that have a lot of potential to unlock supply constraints and shift the supply curve towards lower cost resources.
- For technologies currently at prototype stage, we assume a further significant shortening of the period to market introduction, well below what has been achieved in recent success stories of clean energy technology development. We also assume that robust market deployment starts right after the completion of only one single commercial-scale demonstration, which is not common practice.
- For new and emerging clean energy technologies, we further raise adoption rates to a level that risks additional market bottlenecks and resource constraints along the supply chain if co-ordination fails when expanding rapidly.

There is little or no precedent for the required pace of innovation in the Faster Innovation Case and it does not leave any room for any delays or unexpected operational problems during demonstration or at any other stage. These are, of course, bound to happen in practice. Nonetheless, while it can take several decades for a technology to move from the laboratory to mainstream diffusion (as discussed in earlier parts of this report), the 50-year projection horizon of this report is certainly long enough to throw in some surprises. Mission-oriented approaches that support clean energy innovation in technology areas with attributes conducive to fast innovation cycles could speed up the pace of progress, particularly if they are

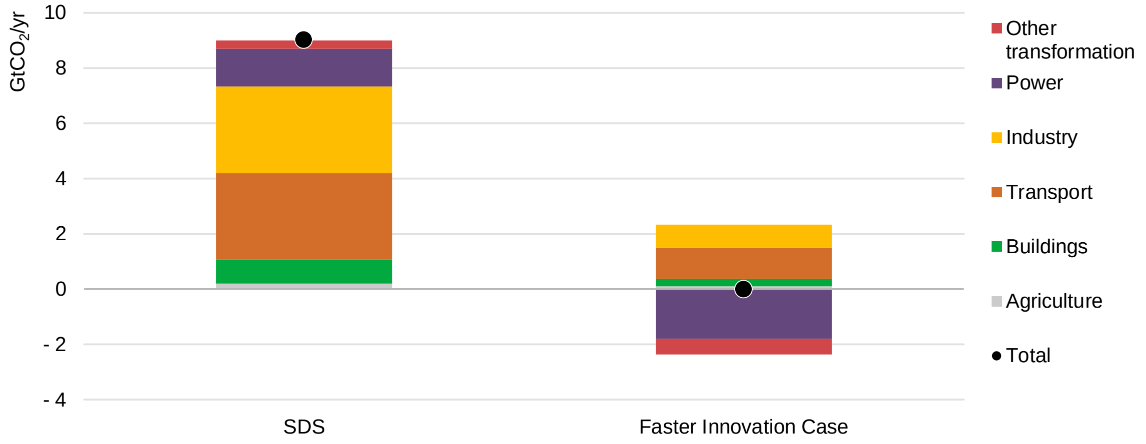
[23] See the World Energy Outlook 2019 for a discussion of changes required for a 1.5°C pathway (IEA, 2019).

coupled with a once-in-a-generation investment opportunity as a result of recovery plans in response to the Covid-19 crisis. Some technologies currently in the laboratory or at the level of small prototype that are outside the scope of the Sustainable Development Scenario might progress fast enough to be able to contribute to the transition to net-zero emissions in that timeframe. While the true potential and potential ease of scale-up for technologies at such early stages of maturity is highly uncertain, it is reasonable to consider what the impact might be if R&D is successful in bringing some of them to market within that period. This is what the Faster Innovation Case aims to do.

Emissions savings in the Faster Innovation Case

In the Faster Innovation Case, enhanced clean energy technology innovation would need to enable 9 $GtCO_2$ of additional net emissions savings compared to the Sustainable Development Scenario in 2050, which is the equivalent of almost 30% of today's energy sector emissions (Figure 4.1). The result is that emissions in end-use sectors would be significantly lower by 2050 in the Faster Innovation Case; by 2050, remaining transport-related emissions would be down to 1.1 Gt (mainly in heavy-duty trucks, aviation and shipping). In industry, they would be down to 0.8 Gt (mainly steel, cement and chemicals production); and in buildings, down to almost 0.3 $GtCO_2$. To put this into perspective, the additional emissions reductions reached in the Faster Innovation Case through innovative technologies in passenger transport, for instance, would be equivalent to a drop of almost 60% in what the level of passenger activity is otherwise across different modes in the Sustainable Development Scenario in 2050. Similarly, materials production from heavy industrial sectors would need to drop on average to around a quarter of the level reached in the Sustainable Development Scenario in 2050 in the absence of additional technological change to reach an equivalent level of emissions reductions as in the Faster Innovation Case.

Figure 4.1 Global energy sector CO_2 emissions in 2050 by sector

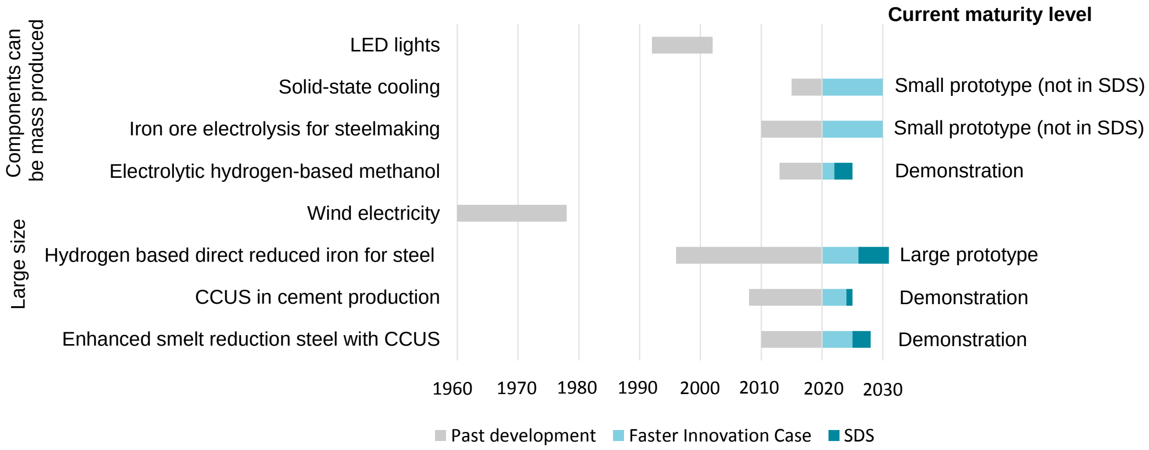


Notes: SDS = Sustainable Development Scenario. Emissions include those from fossil fuel combustion and those released in industrial processes from carbon contained in the raw materials used.

Despite the additional innovation push to reduce CO_2 emissions in the Faster Innovation Case, there would still be CO_2 emissions in 2050 that would need to be offset by negative emissions.

Achieving such transformation of the energy landscape globally in just three decades would require innovation cycles much faster than those achieved in recent success stories of clean energy technology development. Key clean energy technologies at demonstration or large prototype stage today, such as hydrogen-based steel production, electrolytic hydrogen-based ammonia to fuel vessels or carbon capture in cement production, amongst others, are assumed to reach markets in six years from now at the latest. This is about twice as fast as in the Sustainable Development Scenario, which assumes that deployment starts after several demonstrators have been successfully completed, in line with normal innovation practices (Figure 4.2). Technologies at laboratory or small prototype stage are commercialised in ten years from now on average in the Faster Innovation Case, which is the minimum time required from the first prototype to market introduction observed across all technologies explored for this report: the only case for which there is historical evidence of such rapid progress is that of LEDs, which are small enough to be mass produced and to require a relatively low level of capital expenditure during the prototyping and demonstration phase.

Figure 4.2 Period from first prototype to market introduction for selected technologies, including the quickest examples in recent clean energy technology development



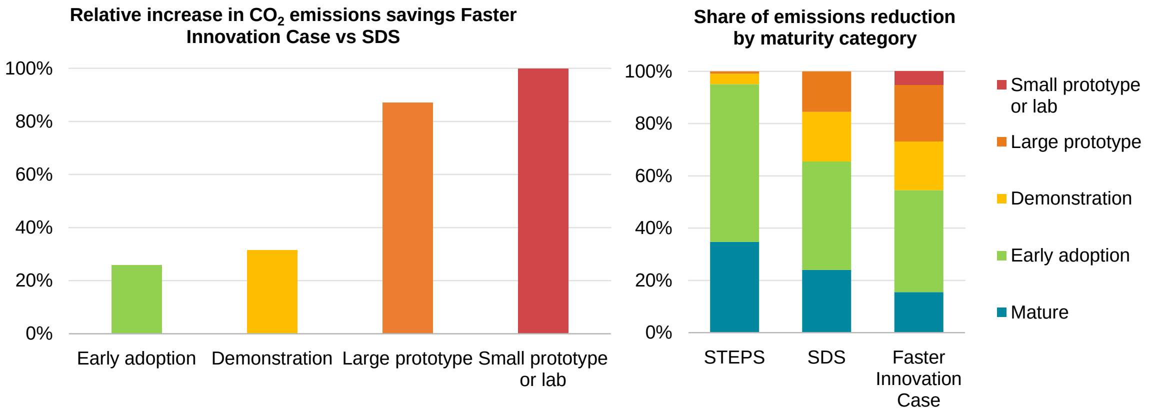
Notes: SDS = Sustainable Development Scenario;CCUS = carbon capture utilisation and storage. The classification between large process technologies and those dependent on components able to be mass produced is based on the characteristics of the equipment or process steps within the technologies analysed that are not commercially available today.

Source: Historic year from different technologies based on Gross (2018) , European Cement Research Academy (2012); Brohi (2014); TATA Steel (2017) and Nuber, Eichberger and Rollinger (2006).

The time to market introduction for pre-commercial technologies would be reduced by almost 40% on average in the Faster Innovation Case compared to the Sustainable Development Scenario, on the basis that a single commercial demonstrator would be enough to allow a move to vigorous market deployment.

In the Faster Innovation Case, the pace of adoption of new technologies following their commercialisation increases by about two-fold on average compared to the Sustainable Development Scenario, and up to almost three-fold for technologies that can be mass produced and that have strong synergies with technology advances elsewhere. In 2050, the share of emissions reductions achieved by deploying technologies that have not reached markets today would be 75% greater in the Faster Innovation Case than in the Sustainable Development Scenario (equivalent to 17 $GtCO_2$ or energy-related emissions from China, the United States and the European Union combined in 2018) (Figure 4.3). Technologies now at prototype stage would enable the largest increase in emissions reductions, partly as a result of assumed actions to stimulate technologies in the laboratory and at small prototype stage that go beyond the scope of the Sustainable Development Scenario. Both the Sustainable Development Scenario and the Faster Innovation Case see a major role for technologies that are not commercially available today; in the Stated Policies Scenario, which takes into account only existing and announced policies which generally focus on technologies that are either mature or are currently at early stage of adoption, such pre-commercial technologies enable just 5% of emissions reductions in 2050, relative to today.

Figure 4.3 Global energy sector annual CO_2 emissions reductions by current technology readiness in 2050



Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. In the right-hand graph, emissions reductions in 2050 in the Stated Policies Scenario are calculated as relative to today's technology performance levels; in the Sustainable Development Scenario and the Faster Innovation Case, emissions reductions are additional to those in the Stated Policies Scenario.

Annual emissions reductions from technologies at the prototype or demonstration stage today would grow by more than 75% in the Faster Innovation Case in 2050 relative to the Sustainable Development Scenario.

The main decarbonisation strategies in the Faster Innovation Case are not radically different from those in the Sustainable Development Scenario: new and emerging technologies would target the displacement of fossil fuels by electricity or alternative clean energy fuels such as hydrogen, hydrogen-derived fuels and bioenergy, or they would target the capture of CO_2 emissions for use and storage (CCUS). What is different is the step change in speed of innovation assumed in the Faster Innovation Case in all sectors.

As in the Sustainable Development Scenario, **electrification** would be a key strategy in the Faster Innovation Case, which would see the share of electricity in total final energy demand grow by around one-quarter relative to the Sustainable Development Scenario and reach about 45% of total final energy in 2050 compared to nearly 20% today.[24] Transport and industry would be responsible for almost 95% of the additional

[24] Electricity demand reported here refers to direct use of electricity only, and exclude indirect uses such as for the production of electrolytic hydrogen.

electricity demand in the Faster Innovation Case in 2050 compared to the Sustainable Development Scenario, with the electrification of road transport accounting for more than 40% of the total increase. Faster learning in battery manufacturing and in smart charging infrastructure would be central to the Faster Innovation Case: so would be the development and demonstration of advanced battery chemistries, particularly for heavy-duty vehicles. Without advances in alternative chemistries to Li-ion, the use of batteries for transport will have difficulties to move beyond road vehicles and very short-distance shipping and aviation routes. In the Faster Innovation Case, the gravimetric energy densities (at cell level) would nearly triple from current levels in 2050 compared to a (still very rapid) growth of 70% it the Sustainable Development Scenario. At least two alternative battery chemistries – lithium-sulphur (Li-S) and lithium-air (Li-air) – have the potential to provide such advances: they are at small prototype and concept stage today, respectively. These developments would lead to more rapid uptake of electric vehicles: almost 80% and around 60% of light- and heavy-duty vehicles on the roads in 2050 would be battery-electric in the Faster Innovation Case. In the case of heavy-duty vehicles, nearly 3.5 times more battery-electric vehicles would be deployed than in the Sustainable Development Scenario.

To satisfy demand for electric vehicles in the Faster Innovation Case, about 17 TWh of battery manufacturing capacity would be required by 2050, meaning that around one battery manufacturing plant of the size of the Tesla Gigafactory would need to come online each month from today to 2050. The Faster Innovation Case also would require the rapid deployment of charging infrastructure, and in particular of fast-charging stations capable of charging high battery capacities for electric trucks and buses through conductive or inductive dynamic charging on road and highways: such fast-charging stations are today still at prototype stage. In the Faster Innovation Case, the number of fast chargers for electric heavy-duty vehicles would reach 19 million globally in 2050, more than twice the number in the Sustainable Development Scenario.

While the rapid battery developments envisioned in the Faster Innovation Case would transform road transport, and especially long-distance heavy-duty road operations, their impacts would be more muted in shipping and aviation. Due to the requirements for high energy density fuels in shipping and aviation, battery-electric powertrains only substitute for very short-range operations – the total weight of the battery restricts the range due to mass-compounding effects. Even by 2050, battery-electric powertrains would account for only around 3% of freight movements in shipping and of passenger activity in aviation.

Half of the additional electricity demand in the Faster Innovation Case in 2050 compared to the Sustainable Development Scenario would come from industry.

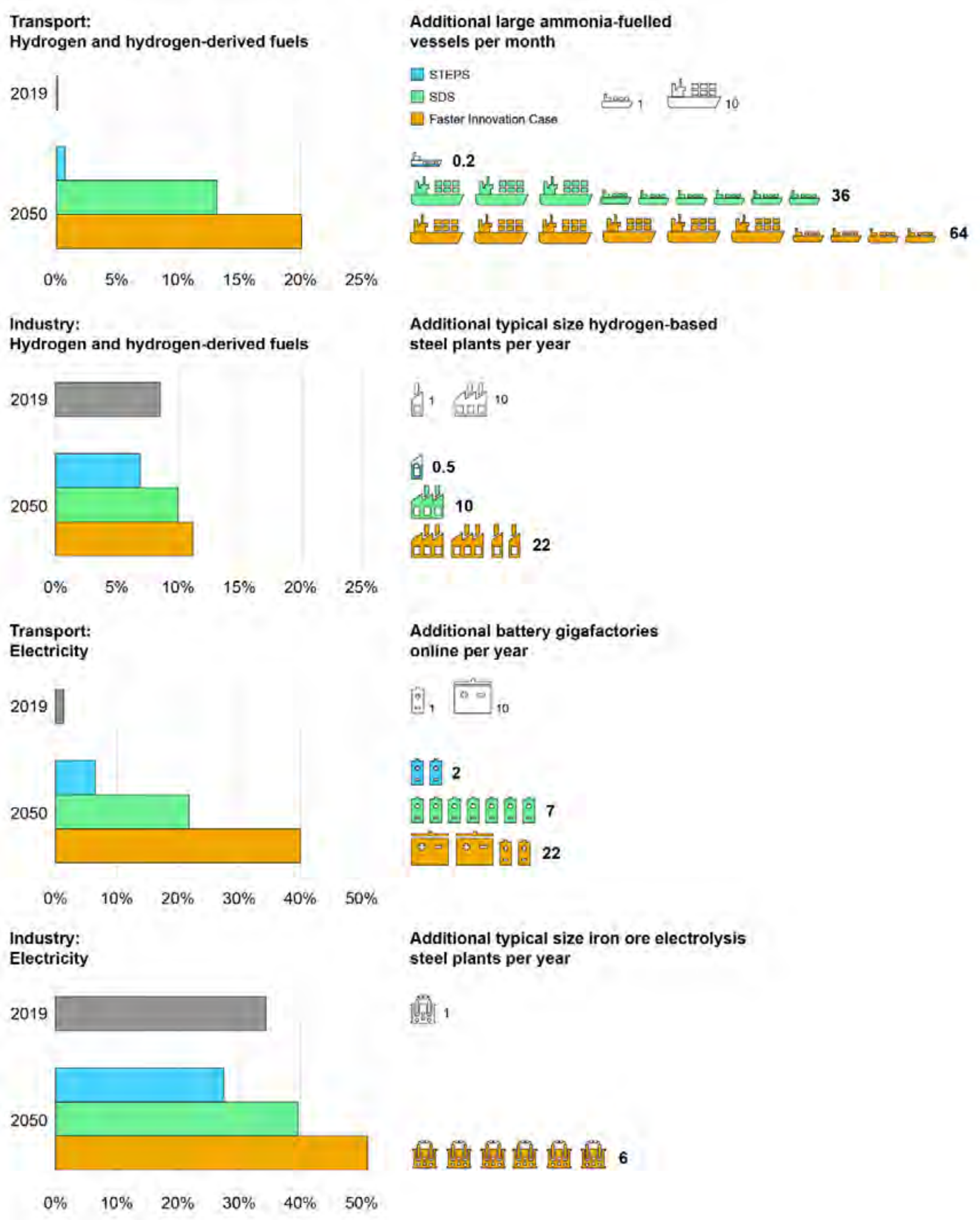
Large-scale electric heating would penetrate far more deeply into the industrial sector in the Faster Innovation Case than in the Sustainable Development Scenario. Rapid advances in the demonstration of large-scale high-temperature electric heating[25] for industrial processes that do not involve electricity-conducive materials would be required to enable such sizeable deployment levels in the Faster Innovation Case. Most of these technologies (e.g. electromagnetic) are at the concept validation stage today, but they would reach markets by no later than ten years from now in the Faster Innovation Case.

The commercialisation of direct electrification of energy-intensive industrial processes such as primary steelmaking through iron ore electrolysis (currently at small prototype stage and thus outside the scope of the Sustainable Development Scenario) would also open up new avenues for electrification in the Faster Innovation Case. This is based on the assumption that the time from small prototype to market for iron ore electrolysis is completed in record time (just below ten years), and that average deployment thereafter is maintained at a new 1 Mt installation (equivalent to half the capacity of a conventional integrated steel mill) every two months in the period to 2050. In the buildings sector, around 30 GW thermal capacity from integrated heat pump systems for heating and cooling (including storage systems) are installed every month on average in the period to 2050 in the Faster Innovation Case compared to just over 15 GW per month on average in the Sustainable Development Scenario.

Demand for **hydrogen and hydrogen-derived synthetic fuels** (including ammonia) would also grow by almost 25% in the Faster Innovation Case in 2050, relative to the Sustainable Development Scenario, with most of the demand coming from the industry and transport sectors. In industry, this increase would translate, for instance, into almost two new 1 Mt steel plants based on full hydrogen reduction being installed every month on average from today to 2050 in the Faster Innovation Case, a pace of adoption that is more than twice as fast as in the Sustainable Development Scenario. Adoption at such a rapid pace necessarily means radical changes to the existing stock of steelmaking capacity; without such changes, around 40% of current global primary steelmaking assets would still be in operation in 2050. In transport, more than 60 ammonia-fuelled large vessels are put into service every month on average until 2050 in the Faster Innovation Case, almost twice the deployment rate in the Sustainable Development Scenario, in the context of a projected monthly market requirement of just over 80 large new vessels a month.

[25] High-temperature heating refers to heat delivered at 450°C or above, with some of the specific applications targeted requiring a temperature above 1 000°C.

Figure 4.4 World share of hydrogen and electricity in final energy demand by end-use sector (left) and selected adoption metrics of hydrogen technologies (right)



Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. Final energy demand includes energy use for blast furnaces and coke ovens. Hydrogen includes direct demand of hydrogen and hydrogen-derived fuels for transport and buildings, and final energy demand required to produce hydrogen on-site for industrial processes. Typical size of steel plant considered at 1 Mt crude steel per year capacity. Typical maximum capacity for a large vessel considered is 50 kt of dead weight tonnage. Adoption rates show area average values for the period to 2050. Battery gigafactory capacity considered at 35 GWh/year.

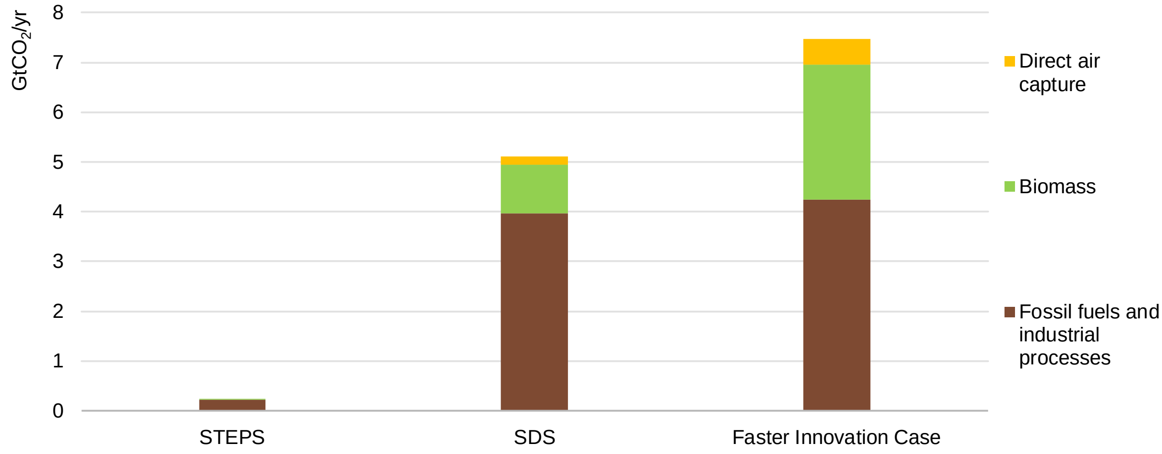
Electricity, hydrogen and other renewables see the greatest growth in final energy demand in the Faster Innovation Case relative to the Sustainable Development Scenario in 2050: this comes at the expense of fossil fuels.

The share of **bioenergy** in total final energy demand would increase by around 25% in 2050 in the Faster Innovation Case relative to the Sustainable Development Scenario, mainly driven by industrial and transport-related applications. Such an increase would not present a technical challenge on the demand side, as biofuels are drop-in fuels for most applications, but it would put additional stress on biomass supply chains. Rapid innovation developments in biofuel conversion technologies and agricultural practices would be essential to unlock additional biomass sources and open new conversion routes to ensure the sustainability of supplies. Algae-based biofuels, which are currently only at small prototype stage today for most conversion routes, would be deployed at scale by 2050, but are not deployed in the Sustainable Development Scenario. The Faster Innovation Case would also require the rapid demonstration at scale of advanced biofuels production technologies such as biodiesel and bio-jet through gasification and Fischer-Tropsch, the aggregated production capacity of which would increase at an average rate around 40% faster than in the Sustainable Development Scenario through to 2050.

The overall level of **captured CO_2 emissions** is almost 50% higher in the Faster Innovation Case in 2050 than in the Sustainable Development Scenario (at around 7.5 $GtCO_2$ per year, with the amount of CO_2 stored almost 200 times greater than today) (Figure 4.5). Negative emissions technologies, such as direct air capture (DAC) and bioenergy carbon capture and storage, would account for the bulk of this. Both technologies would become even more critical in offsetting residual emissions from long-distance transport and heavy industry than in the Sustainable Development Scenario: emissions captured through these techniques in 2050 would almost triple relative to the Sustainable Development Scenario. Almost 16 DAC facilities of 1 Mt capture capacity would need to be commissioned every year on average from today to 2050 in the Faster Innovation Case compared with around 5 such facilities per year in the Sustainable Development Scenario. The largest DAC plant currently being designed is of 1 Mt capture capacity; only pilot-scale units of 0.4% that size have been operated so far. For bioenergy carbon capture and storage, almost 90 plants of 1 Mt capture capacity would be needed each year, almost three times as much as the capacity projected in the Sustainable Development Scenario.[26] Accelerated innovation in CCUS would also enable direct emissions reduction in heavy industry: for example, the Faster Innovation Case would see more than five carbon capture facilities of 1 Mt capacity each month in the cement sector through to 2050, compared to around four in the Sustainable Development Scenario.

[26] 1 Mt capture capacity is equivalent to the largest biofuel plant with CO_2 capture in operation today, which was commissioned in 2017 in the United States to produce bioethanol.

Figure 4.5 Global captured CO_2 emissions by source, 2050



Notes: SDS = Sustainable Development Scenario; STEPS = Stated Policies Scenario. Captured emissions include those from fuel combustion and those from emissions released in industrial processes from carbon contained in the raw materials used.

Total CO_2 capture volumes would increase by 50% in 2050 in the Faster Innovation Case, with the increase driven by almost a tripling in negative emissions technologies deployment compared to the Sustainable Development Scenario.

Focus on the key opportunities among technologies at laboratory or small prototype stage today

It is evident from the Faster Innovation Case that some technologies are likely to play a particularly crucial part in achieving net-zero emissions by 2050. For policy makers who are seeking to support technologies currently at laboratory or small prototype stage through stimulus packages, and who are looking to identify those technologies that will have maximum impact, two kinds of technology are likely to be particularly relevant. The first are those technologies that are modular and small enough to be mass produced and have potential for high spillovers from and to other net-zero emissions technologies; the second are those technologies that have a high potential to unlock supply constraints (such as those affecting bioenergy and rare or increasingly demanded materials) and that can shift the supply curve towards lower cost resources. Several such technologies are particularly important in the Faster Innovation Case: advanced battery chemistries and battery recycling technologies; innovative practices to boost biomass resources; and iron ore electrolysis for making steel and advanced cooling.

Advanced battery chemistries and recycling techniques

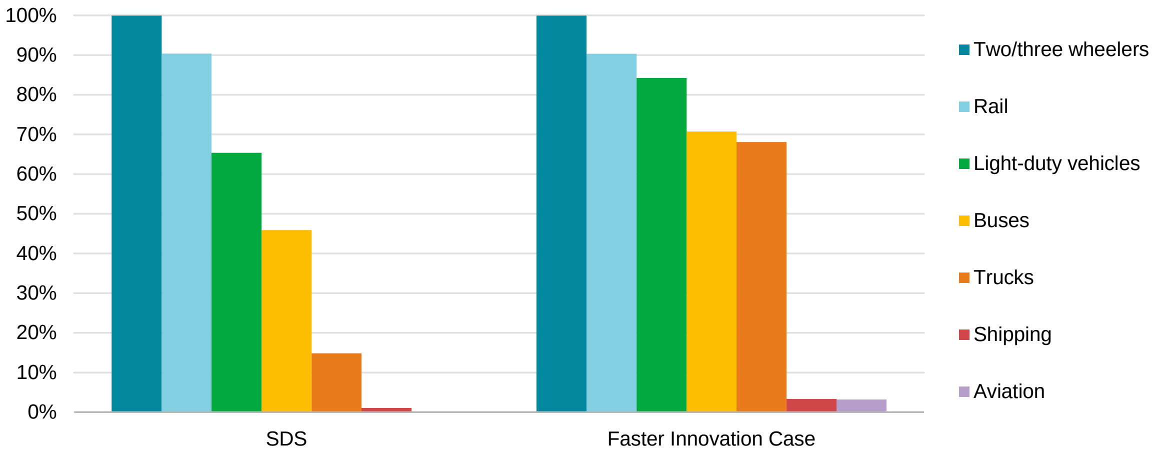
The increased use of batteries across a broad range of applications plays a critical role in facilitating CO_2 emissions reductions. Decarbonising transport relies heavily on electromobility: installed battery capacity for electromobility applications increases 500-fold in the Sustainable Development Scenario by 2070. In grid-scale applications, the capacity of the battery fleet increases 260-fold from today over the same period, providing a range of services from facilitating the integration of variable renewables to facilitating the electrification of end uses. These levels of deployment assume ambitious innovation efforts to maintain cost and performance trajectories: by 2070, the cost of the average battery drops by 68% in the Sustainable Development Scenario, while gravimetric energy densities at cell level increase by 160% compared with current levels.

Despite these improvements, the use of batteries for transport remains largely confined in the Sustainable Development Scenario to road vehicles and to short-distance shipping and aviation routes (the latter with a very marginal impact on total aviation fuel demand). Electric aircraft of the size and range needed for commercial passenger aviation are still not practical on a significant scale in 2070 in the Sustainable Development Scenario, mainly due to the high power density required during take-off. With current battery technology, an Airbus 380 would need batteries with an overall weight 30 times greater than its current fuel intake, making lift-off impossible. Early concepts for ten-seaters and electric taxis, including electrical vertical take-off and landing aircraft, have been developed by Rolls Royce, Uber and a number of start-ups. An all-electric passenger commercial aircraft capable of operating over ranges of 750-1 100 km would, however, require battery cells with densities of 800 Wh/kg, more than three times the current performance of Li-ion batteries (Schafer et al., 2019).

Accelerated innovation could reduce the gap between the theoretical and current performance of batteries, and enable the use of batteries even in aviation and shipping. It could also strengthen the competitiveness of electric powertrains and make them a more competitive option for road freight. There are at least two alternative battery chemistries that could theoretically reach the necessary density through technological advancements: lithium-sulphur and lithium-air, which are at small prototype and concept stage today, respectively (Thackeray, Wolverton and Isaacs, 2012). And advancements are coming fast: for instance, a recent cathode design for lithium-sulphur chemistry shows a significant improvement in the battery cycle life while retaining energy density advantages compared to Li-ion (Lee et al., 2020). Ultra-high density batteries could in time make electric aircraft possible. They could also make battery-electric trucks the most compelling zero-emission powertrain even for regional and long-haul operations, thereby accelerating and extending the electrification of heavy-duty road freight. Finally, better performing batteries could provide vessels with the high volumes of energy that must be stored on-board to cover medium-distance ranges without the need for frequent recharging: with such extended range, purely electric ships could cover a larger number of routes.

Reaching the performance goal of 800 Wh/kg (cell level) by 2050 as assumed in the Faster Innovation Case (a level 60% higher than in the Sustainable Development Scenario) would boost the share of electricity in heavy-duty road freight from 15% in the Sustainable Development Scenario to almost 70% by that year, with battery-electric trucks dominating the vehicle fleet (Figure 4.6). In aviation, commercial electric aircraft would begin to penetrate the market in the early 2040s, displacing about 3% of fuel use in that sector by 2050. In shipping, the higher energy density would make possible longer journeys of up to 1 000 km. This increased level of electrification across all transport modes in turn would ease constraints on alternative clean high energy density fuels, delivering more than one additional gigatonne of total CO_2 emissions savings in 2050 compared to the Sustainable Development Scenario: this is equivalent to 15% of the annual emissions from all modes of transport in 2019.

Figure 4.6 Global share of vehicle activity electrified in the Faster Innovation Case compared with the Sustainable Development Scenario by mode, 2050



Note: SDS = Sustainable Development Scenario.

Advanced batteries chemistries would enable an almost fivefold increase in the share of battery-electric heavy-duty trucks in 2050 in the Faster Innovation Case compared to the Sustainable Development Scenario, and would open the way to electrifying short-range shipping and aircraft operations.

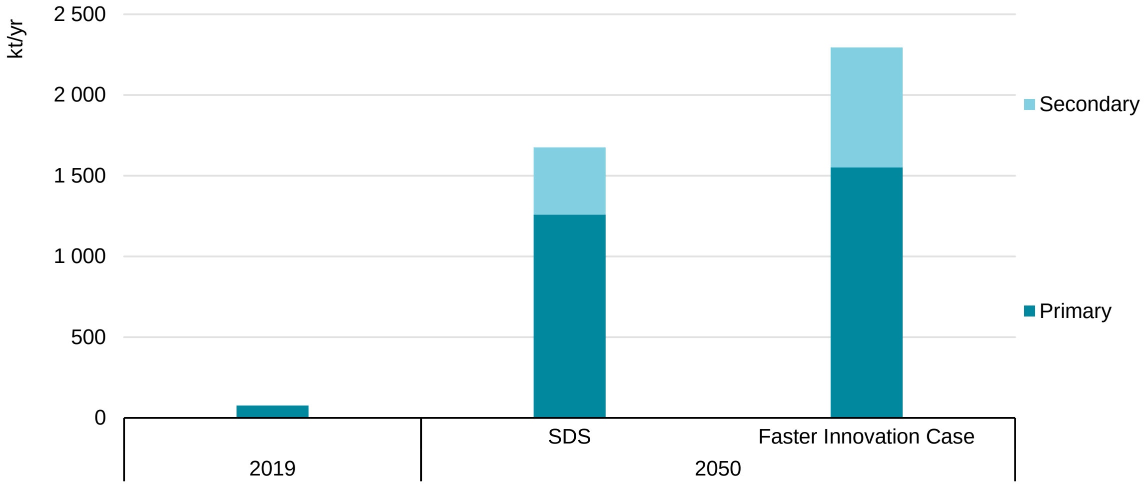
The demand-pull from the large-scale deployment of lithium-based batteries in the Sustainable Development Scenario brings with it important implications upstream. In 2011, less than 1% of lithium supply was related to mobility or grid storage applications whereas by 2019 that share increased to around 20%. In 2070, lithium production in the Sustainable Development Scenario is roughly thirty-fold larger than levels today, with batteries taking 90% of total supply. In the Faster Innovation Case, the same level would be reached by 2040. Demand for lithium is currently small relative to other metals, totalling around 75 kt per year – two orders of magnitude smaller than that of copper.

All stages of the lithium supply chain from exploration and mineral extraction to metal processing have to expand quickly and evolve in order to ensure the reliable provision of a critical commodity. Demand for lithium is projected to continue to grow beyond 2030 since most battery chemistries currently at prototype stage use it. Measures such as recycling that can prevent potential supply chain bottlenecks for lithium are important in this context. Battery recycling technologies today are mainly focused on high-value metals like cobalt and nickel: lithium is rarely recycled, not least because of limited demand for it. This changes in the Sustainable Development Scenario: lithium recycling reaches almost 780 kt by 2070, meeting 35% of all lithium demand in that year, based on recycling technologies either available now or already at the demonstration phase. Technologies now at early stages of development could enhance the efficiency of recycling, and thus reduce the energy consumption of the lithium supply chain.

There are a number of technologies at low technology readiness level along the battery recycling value chain that could provide a step change in current performance. Collaborative human-robot sorting and disassembling of batteries could greatly reduce costs, for example, while ultrasonic assisted separation offers a novel way to accelerate the separation of the layered components of a battery, and could greatly increase efficiency in combination with conventional agitation. Bioleaching applies microorganisms to help in the recovery of metals: it is already used in the mining industry, but is at an early stage of development for battery recycling. Research so far shows that it could offer a more efficient way of recovering metals than other methods. The ability to handle different battery chemistries will be key to innovative recycling technologies becoming competitive: by the time such technologies are commercially available, the batteries they process are likely to be based on current chemistries, but battery chemistries already entering markets are rapidly evolving, and it is just a matter of time before they reach recycling markets too.

The Faster Innovation Case assumes that innovative battery recycling would be commercialised over the next decade, reducing demand for primary lithium below the level it would otherwise have reached, and accelerating the electrification of the transport sector by lowering costs. The main markets for repurposed batteries are in light-duty vehicles, urban mobility and utility-scale power storage, as these uses are less affected than others by the lower performance and reduced capacities of repurposed batteries, which inevitably lag behind best available technologies at any given moment. Secondary lithium production would be almost 80% higher in 2050 in the Faster Innovation Case than in the Sustainable Development Scenario, and this would push down the CO_2 footprint of lithium production (Figure 4.7). This downward effect on emissions is offset, however, by the increase in lithium demand in the Faster Innovation Case as a result of faster electrification: the Faster Innovation Case would require more lithium than the Sustainable Development Scenario from primary as well as from secondary routes.

Figure 4.7 Global production of lithium by route, scenario and case



Note: SDS = Sustainable Development Scenario.

The share of secondary lithium production in 2050 would be almost 80% higher in the Faster Innovation Case than in the Sustainable Development Scenario thanks to advanced battery recycling.

Innovative techniques to expand sustainable biomass supply

Primary demand for bioenergy worldwide grows from 1 470 Mtoe (62 EJ/year) in 2019 to 2 870 Mtoe (120 EJ/year) in 2070 in the Sustainable Development Scenario. As a result, its share of total primary energy demand increases more than 80% to almost one-fifth, making it the second largest energy source. It plays an important role in the transition to net-zero emissions in the Sustainable Development Scenario: it is used in sectors that are difficult to electrify, and it provides feedstock for the production of transport biofuels. In shipping and aviation combined, the share of biofuels grows from a negligible level today to about 30% by 2070. This scaling-up of the consumption of biomass resources needs to be undertaken sustainably to deliver real lifecycle emissions reductions and wider environmental and social benefits.

Scientific studies have yielded a wide range of estimates of the availability of sustainable biomass for energy purposes, but there appears to be a broad consensus that up to 2 400 Mtoe (100 EJ/year) could be produced sustainably without serious difficulties, while the long-term potential could be as high as 5 000 Mtoe (200 EJ/year). In the Faster Innovation Case, 3 220 Mtoe (135 EJ/year) of primary bioenergy is supplied sustainably by 2050, which is 12% more than in the Sustainable Development Scenario by 2070. This expansion and acceleration of bioenergy consumption in the Faster Innovation Case is made sustainable by a set of innovative technologies and practices:

- Using crops with higher yields, which allows the production of additional energy without a requirement for more land. An example is “energy cane”, a variety of cane that creates more bagasse residues without compromising sugar content. Some trials in Brazil for this crop have shown increases of up to threefold in production yields compared with standard cane varieties (IEA, 2017). The additional bagasse can be used as fuel for co-generation of electricity and heat or for cellulosic ethanol production.
- Developing new biomass resources such as algae and aquatic biomass for the production of liquid biofuels, biogas or high-value chemicals. These technologies are today at the early prototype stage of development, and face high production and harvesting costs, but there are promising near-term opportunities to co-produce fuels and chemicals in biorefineries (IEA, 2017).
- Maximising the potential of agricultural land by applying "double-cropping" on a more widespread basis. Where soil and climatic conditions make it appropriate, a secondary energy crop could be harvested on the same land after the principal food crop, providing additional biomass resource and diversifying the incomes of farmers. For example, *brassica carinata* is an oil-yielding crop that can be cultivated in winter and used as a feedstock for biofuel production, complementing conventional food crops grown in other seasons (Todo el Campo, 2018).
- Developing advanced waste management systems on a much larger scale, enabling a step increase in collection and segregation together with the rapid development of supply chains and the implementation of advanced waste-to-energy systems. With the commercialisation of thermochemical biomass technologies, the waste produced could be utilised as a feedstock for transport biofuel production.

Enhancing the availability of sustainable biomass resources enables bioenergy to play an even bigger role in the Faster Innovation Case than in the Sustainable

Development Scenario, particularly after 2040: by 2050, the share of bioenergy in final energy demand in the Faster Innovation Case would be 25% higher than in the Sustainable Development Scenario. In industry, larger amounts of bioenergy would be directed in the Faster Innovation Case towards medium- and high-temperature heating applications that do not require significant equipment retrofits for its use. Cement kilns are good examples of this. The result of increasing bioenergy shares in the fuel mix of cement kilns that are equipped with CCUS is that more than four times as much negative emissions would be achieved in 2050 in cement production than in the Sustainable Development Scenario: this helps to bring forward the achievement of net-zero emissions across the entire energy system.

In transport, heavy-duty trucks, shipping and aviation all benefit from a greater availability of biomass resources. Biomass alternatives to energy-dense fossil liquids are particularly critical in shipping and aviation, where electrification is technically challenging. The total biofuel consumption of shipping and aviation combined would increase about 18% in the Faster Innovation Case relative to the Sustainable Development Scenario in 2050.

Box 4.2 Advanced aircraft designs

Since commercial passenger aviation began in the early 20th century, there has been little change in the basic tubular design of aircraft. Radically improved aerodynamic designs could bring about considerable energy efficiency savings in the future, and by so doing reduce the aviation sector's demand for high energy density alternative fuels. Take-off requirements, however, might still be limiting in some circumstances.

Research programmes at Airbus (MAVERIC) and Boeing (Boeing X-48) have tested small-scale prototypes of passenger aircraft with blended-wing-body designs with the potential to improve fuel efficiency by up to 20% compared with current single aisle airframes. Despite such designs having been already commercialised for military aircrafts, they have only reached small-scale prototypes for passenger aircraft. This is mainly due to the challenge of passengers accepting an aircraft without windows and the complexity of incorporating emergency exits in the theatre-like seating layout. The high wingspan-to-height ratio of blended-wing-body aircraft design makes it suitable only for large aircrafts, meaning that development costs cannot be split over a model family with different sizes.

The development of hybrid-electric aircraft is less constrained by the need for manifold improvements in battery power and energy densities than is the case with all-electric aircraft, but a hybrid could nevertheless deliver fuel-burn improvements of as much as 50% over today's best-performing aircraft. NASA is developing the STARC-ABL, a single aisle turboelectric aircraft design concept that uses boundary layer ingestion. Wright Electric has meanwhile developed a 186-seat electric aircraft for short-haul range and aims to introduce it to market in 2030.

The Faster Innovation Case assumes that such novel designs would reach passenger aviation fleets before 2050. As a result, total final energy demand in aviation in 2050 is reduced by 8%, and total final demand for liquid jet fuel in that year declines by more than 50 Mtoe, or about 15% of 2019 consumption, compared with the Sustainable Development Scenario.

Direct electrification of primary steelmaking

There are no economical and scalable technologies available today to make primary steel using non-fossil energy. The most advanced option, based on low-carbon hydrogen as a reducing agent, is expected to reach the pilot-project stage in 2021 and commercial-scale demonstration from 2025 (Hybrit, 2020). One promising low-carbon technology – direct electrification of primary steelmaking (known as iron ore electrolysis) – is technically feasible, but the two most advanced processes have so far only been tested at small scales. One of these is low-temperature alkaline electrolysis, which has recently moved to a 100 kg pilot (ArcelorMittal, 2020). The other is high-temperature molten oxide electrolysis, which was validated in the laboratory in 2013: a prototype cell was commissioned in 2014 and there are plans to test full-scale cells by 2024.

In iron ore electrolysis, electrolytic cells can be stacked to provide the capacity needed, allowing the possibility of expanding capacity by increments thereafter: the capital at risk in the first stages of investment in a given plant is therefore relatively small. Iron ore electrolysis is similar to chlorine and alkaline water electrolysis in this respect, while high-temperature molten iron oxide electrolysis and alumina electrolysis for aluminium production share many features in terms of their layout. Knowledge spillovers in design, operation and materials may therefore flow from aluminium, chlorine and water to iron ore electrolysis, and these may include knowledge about how to modulate plant operation as necessary so as to align it with the incentives for balancing a grid dominated by variable renewable electricity.

In the Faster Innovation Case, four factors would combine to make it possible to speed the deployment of iron ore electrolysis compared with other low-carbon processes for making primary steel in the Sustainable Development Scenario: relatively low risk in scale-up; spillovers from other electrolysis technologies;

standardised and repetitive manufacturing; and compatibility with electricity grid needs. About 10% of global primary liquid steel production would be produced from iron ore electrolysis in the Faster Innovation Case in 2050, increasing electricity demand for steelmaking by 60% relative to the Sustainable Development Scenario.

Advanced refrigerant-free cooling

The number of air conditioner units in use around the world is projected to nearly triple to more than 5.5 billion by 2050 in the Sustainable Development Scenario. Much of this dramatic growth in demand is driven by population and economic growth, in particular in emerging economies with hot weather: it is estimated that the global population living in hot areas will grow from 2.8 billion today to more than 4 billion in 2050. Accelerated innovation could curb the climate impact of the rise in demand through a combination of additional incremental early-stage efficiency gains, alternative cooling technologies, the integration of cold storage and changes in the use of refrigerants. In turn, spillovers from the faster growing demand for advanced cooling technologies could benefit technology development for heating services, tapping into additional mitigation potential. In the Faster Innovation Case, a combination of these measures and improved building performance would save 260 $MtCO_2$ emissions in 2050 compared with the Sustainable Development Scenario.

Many refrigerants currently in use in vapour-compression cycles – the standard technology for air conditioners – are powerful greenhouse gases. Hydrofluorocarbons are the most common refrigerant compounds. Under the Kigali Amendment of the Montreal Protocol, more than 195 countries have committed to reducing the use of hydrofluorocarbon refrigerants by more than 80% in the next three decades. In the Faster Innovation Case, refrigerant-free cooling technologies, which are currently in the prototype phase, would be progressively adopted ten years from now. Amongst these are advanced evaporative cooling, advanced desiccants and solid-state cooling technologies:

- Membrane-based evaporative cooling and desiccants would open up the possibility of controlling both humidity and temperature by decoupling latent (vapourisation) and sensible (temperature variations without phase change) heat loads. These technologies avoid the energy-consuming components of a vapour-compression cycle: they also avoid the need to use a refrigerant. In tests, membrane-based systems have shown promising coefficients of performance ranging from 5 up to 15.5 in advanced evaporative cooling systems.
- Solid-state cooling technologies represent a new approach to refrigeration, air conditioning and heat pump technologies. These technologies rely on caloric effects to provide cooling: at present, barocaloric (producing heat under

pressure variation) and electrocaloric (producing heat under an electric field) materials seem to be the most suitable for thermal applications. These technologies are at the prototype phase, but research in test conditions shows that barocaloric refrigeration, in particular, performs better than vapour-compression coolers in domestic applications, with improvements ranging from 5% to 150% depending on ambient, material and flow rate conditions.

The Faster Innovation Case assumes that successful demonstration of these technologies at scale would lead to them being increasingly used in the 2030s, starting in niche markets: membrane-assisted evaporative cooling and desiccants would be initially adopted in markets that need cooling with humidity controls, while solid-state technologies provide a range of building energy services, including water heating, thermal comfort and domestic refrigeration. The Faster Innovation Case also sees the initial deployment of advanced vapour-compression technologies using both low- or zero-global warming potential refrigerant, and next-generation components including more compact heat exchangers, refrigerant flow controls and electrochemical compressors.

Given the size of the market, more rapid innovation in alternative cooling technologies could bring spillover benefits in the Faster Innovation Case for vapour compression-based technologies equipped with next-generation components and low global warming potential refrigerants: these benefits lead to higher efficiencies and faster adoption of reversible heating and cooling systems, displacing gas heating earlier in the projection horizon. In the Faster Innovation Case, advanced space cooling technologies would account for more than 30% of global cooling capacity in 2050, allowing the average energy efficiency rating of the building stock to more than double to 9 by 2050, up from around 4 in 2019.

Taken together, the earlier adoption in the Faster Innovation Case of refrigerant-free cooling technologies and the knock-on effects of advanced cooling on other areas would speed up the decarbonisation trajectory of the buildings sector. Coupled with other measures to make buildings more energy efficient, they would lead to an additional 3 000 Mtoe of energy savings in the sector from 2030 to 2050 relative to the Sustainable Development Scenario, with two-thirds of these savings concentrated in the residential sector. These additional savings would be equivalent to more than the current final energy consumption of the buildings sector today. Innovative systems for heating and cooling would contribute up to 60% of total annual emissions reductions in buildings.

Potential negative impacts of Covid-19 on critical clean energy technologies – the Reduced Innovation Case

Clean energy innovation has the potential to play a major part in reshaping the future energy sector. However, threats to it in the form of reduced R&D spending and a potential loss of policy attention to long-term climate goals should not be underestimated, especially given the speed of technology development which is needed.

In this section we explore the impact that a slowdown in the pace of innovation resulting from the Covid-19 crisis could have on direct electrification, CCUS and hydrogen and hydrogen-derived fuels, which together account for about 40% of the cumulative emissions reductions in the Sustainable Development Scenario until 2070 compared to the Stated Policies Scenario. Each of these areas of technology depends on continued and rapid evolution in a wide range of technologies at different levels of maturity along the different steps of their value chains. This means that their ability to contribute to decarbonisation to the fullest extent depends on all the technologies along the entire value chain getting to the market and then scaling-up.

Starting from the assumptions of the Sustainable Development Scenario, this section assesses the implications of a possible delay in technology innovation on the basis of two key assumptions:

- For demonstration projects that are either underway or announced, we assume a five-year delay in their completion.
- For technologies at the early adoption phase, we assume a slowdown in the pace of deployment by 50% through to 2025, 30% to 2030 and 15% to 2040.

Direct electrification

Electric end-use technologies have generally seen increasing momentum in recent years, helped by a supportive policy environment. Over the last five years, the number of households purchasing heat pumps used as heating systems has increased at an average rate of more than 5% per year, and the rate of increase rose significantly in 2019 in many countries (heat pump purchases were up by 14% in Europe last year [EHPA, 2020], and by 6% in the United States). Growth has been consistent across most regions with cold and mild climates, including China, the European Union and the United States, thanks to dedicated incentives. But the increases started from a low base, and less than 5% of heating needs globally were met by heat pumping technologies in 2019. Heat pump sales are moreover mostly driven by installations in new buildings, while retrofits lag behind. That needs to change if heat pumping technologies are going to achieve their full potential: with a typical 80- to 200-year building lifetime in most developed economies, as much as three-quarters of today's buildings will still be in use in 2040.

Innovative design would help to make the most of the potential of heat pump technology. Such designs need to be compact, able to use existing piping, and able to deliver heat securely in poor-performance buildings, to integrate a storage unit (e.g. a heat battery, often directly connected to on-site solar PV panels) or to displace electricity use off peak. Some equipment providers are rising to this challenge by demonstrating new designs tailored to specific local conditions and able to deliver up to a two-fold increase in efficiency (e.g. super-efficient ground-source or air-source heat pumps with pre-heating in passive houses); others are demonstrating next-generation components such as electrochemical compressors (US DoE, 2019) and electrocaloric cycles (Fraunhofer ISE, 2019).

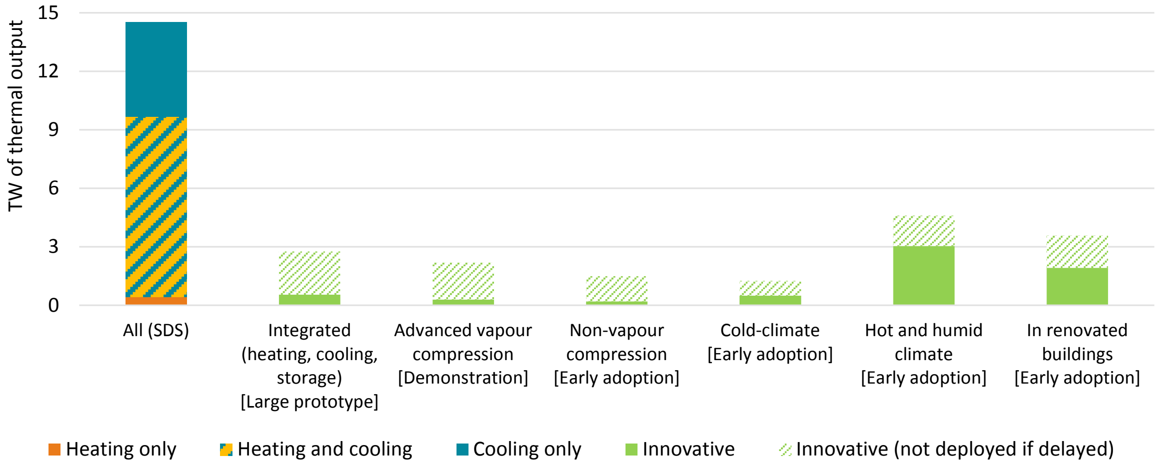
Global electric car sales grew by more than 60% every year over the past decade until 2019, when growth slowed to 6% as the regulatory environment changed in China and passenger car sales contracted in major markets. Global capacity to make Li-ion battery cells has expanded rapidly in recent years: manufacturers today globally can produce around 320 GWh of batteries per year for use in electric road vehicles, which is comfortably more than the approximately 100 GWh of batteries required for the 2.1 million electric cars that were sold in 2019. Some start-ups already provide commercial battery cells with advanced chemistries that are critical in the Faster Innovation Case. For instance, commercial Li-S cells are available for applications with low cycle life, such as unmanned aerial vehicles (Service, 2018). At the same time, developments to electrify long-distance transport are also advancing: while the demonstration of a fully electric and autonomous container ship design started in February 2020 (Skredderberget, 2018). Various start-ups, together with established aerospace and automotive companies, have meanwhile demonstrated autonomous electric passenger aircraft capable of carrying one to four passengers over the past few years (Marr, 2018; Hawkins, 2019; Hyundai, 2020). While such aircraft applications are bound to remain marginal over the coming decades, they could help to accelerate innovation in battery technologies and vehicle automation.

Pilot trials and feasibility studies are underway to test fully electrified processes in heavy industry. These involve, among others, the two most advanced processes to electrify primary steelmaking directly: there is now a 100 kg pilot for low-temperature alkaline electrolysis (ArcelorMittal, 2020), and a prototype cell for high-temperature molten oxide electrolysis, with plans to test full-scale cells by 2024. A consortium of six large petrochemical companies was also created in 2019 to investigate jointly how naphtha or gas steam crackers for high-value chemicals production could be operated using renewable electricity instead of fossil fuels: the consortium has agreed dedicated R&D budget commitments (Borealis, 2019). In addition, feasibility studies have been undertaken over the last two years in both Norway and Sweden to explore the scope for electrifying the heating process of cement kilns (Cementa, 2019; Gautestad, 2018).

It is uncertain what effect the Covid-19 crisis will have on adoption rates and development plans for electric technologies. Given the higher levels of risks associated with the development plans of technologies at small prototype or below, we focus our analysis of the impact of delayed progress on those technologies at early adoption stage, and in particular on heat pumps and electric road vehicles.

A lower uptake of **heat pump** designs that are already commercial combined with a five-year delay in the demonstration of innovative designs would result in in the Reduced Innovation Case in around 3 $GtCO_2$ of additional direct emissions from fossil fuel boilers in buildings cumulatively by 2040 (roughly equivalent to all building-related direct emissions in 2019) compared to the Sustainable Development Scenario. The installed output thermal capacity of innovative heat pumps would be 60% lower in 2030 in the Reduced Innovation Case than in the Sustainable Development Scenario (Figure 4.8). The products mostly affected by delaying testing and demonstration would be those integrating storage solutions or next-generation components (i.e. advanced vapour-compression cycles) and non-vapour-compression systems (e.g. evaporative cooling): these jointly account for around 60% of the decrease in thermal capacity in 2030 relative to the Sustainable Development Scenario. The lower uptake of heat pumping technologies would also reduce the opportunities available to learn from experience, preventing these technologies from achieving a reduction of 10% of their average cost in 2030. Higher technology costs would, in turn, make it more difficult for heat pumps to compete with incumbent fossil-based heating options, particularly in a context of limited household purchasing power.

Figure 4.8 Heat pumping technology deployment by market segment in the Sustainable Development Scenario in 2030 and portion not deployed if innovation is delayed



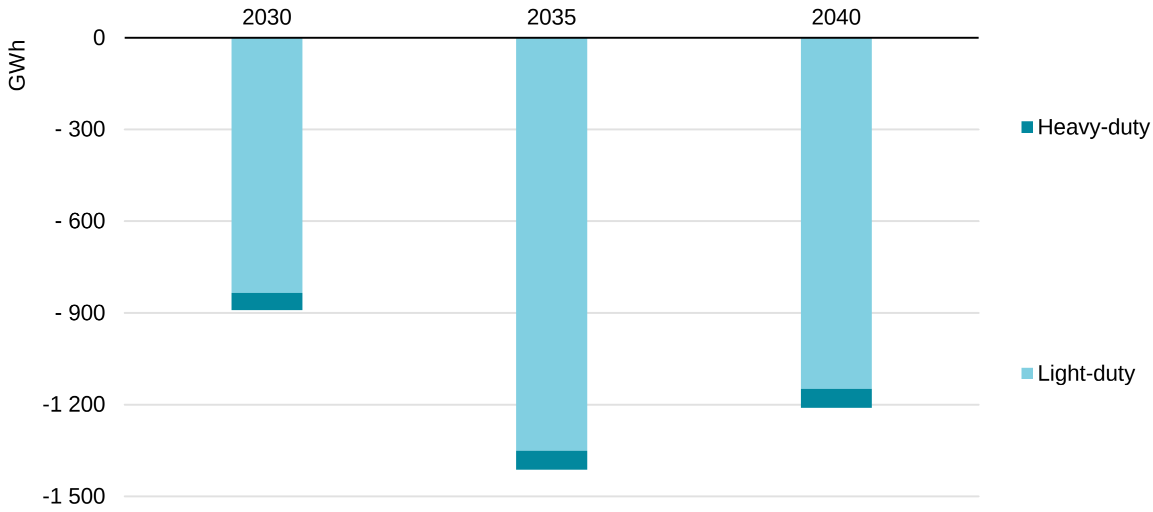
Notes: The capacity of heat pumps in renovated buildings only relates to heat pumps that are used as a heating device. SDS = Sustainable Development Scenario.

Delaying R&D investment, prototype testing and demonstration of innovative heat pumps results in the Reduced Innovation Case in a 60% decrease in related installed thermal output capacity in 2030 globally compared to the Sustainable Development Scenario.

The Reduced Innovation Case would result in a slowdown in the uptake of **electric road vehicles**; this in turn would lead to around 2.5 $GtCO_2$ of additional emissions cumulatively by 2040 compared to the Sustainable Development Scenario. This slowdown would translate into a 20% decrease in cumulative battery production by 2040 compared to the Sustainable Development Scenario (Figure 4.9). The annual reduction in battery manufacturing capacity in 2040 would be equivalent to 34 Gigafactories.[27] Such a reduction in battery manufacturing capacity and operations would imply a slowdown in learning-by-doing and other innovation drivers, which in turn would translate into an increase of 8% in average battery costs by 2025 relative to the Sustainable Development Scenario. Most of the battery demand loss would reflect a slowdown in the uptake of light-duty battery-electric vehicles, which drives the vast majority of battery demand up to 2040 in the Sustainable Development Scenario. The slowdown in the adoption of electric vehicles in the Reduced Innovation Case also has knock-on effects on the electrification of heavy-duty transport: it would delay improvements in battery performance and costs at a critical juncture when electric powertrains are just beginning to enter the heavy-duty vehicle market at commercial scale.

[27] Battery Gigafactory capacity considered at 35 GWh/yr.

Figure 4.9 Decrease in automotive battery annual demand between the Sustainable Development Scenario and the Reduced Innovation Case by segment



The Reduced Innovation Case would translate into a decrease in automotive battery demand in 2040 compared to the Sustainable Development Scenario equivalent to ten times the demand required for mobility in 2019.

CCUS

The CO_2 value chain has gained considerable momentum in recent years. Two Alberta Carbon Trunk Line projects in Canada became operational in 2020: they capture CO_2 from fertiliser production and oil refining, and have a combined capacity of 1.5-2 $MtCO_2$/year. The Gorgon CO_2 injection project came into operation in 2019: it captures CO_2 from natural gas processing. The world's first large-scale CCUS project related to biomass-sourced emissions started operation in the United States in 2017, and the world's first large-scale iron and steel facility with CCUS was brought online in Abu Dhabi in 2016. Plans to scale-up DAC deployment include a 1-$MtCO_2$/year facility being developed in the United States; it is scheduled to be operational by the mid-2020s. At least two pilot plants also started operations in 2019 to test the application of different CO_2 capture technologies to power generation in tandem with other decarbonisation strategies such as hydrogen and bioenergy. In Japan, for example, CO_2 capture tests started at the end of 2019 at an oxygen-blown integrated gasification combined-cycle power plant (160 MW): the project also plans to demonstrate the use of hydrogen in the combined-cycle power plant and in a solid oxide fuel cell system – integrated gasification fuel cell (Osaki CoolGen, 2019).

An improved investment environment has contributed to the development of a growing number of CCUS projects that target industrial hubs and low-carbon hydrogen production. In Norway, there are plans to develop a fully integrated industrial CCS system by 2024: feasibility studies are under way for CO_2 capture from a cement facility and from a waste-to-energy recovery plant, and a consortium of oil and gas companies is developing offshore CO_2 storage in the North Sea (Northern Lights, 2020a). Further full CO_2 value chain projects under development in Europe include the Porthos project in the Netherlands, which is scheduled to enter in operation by 2021 (Rotterdam CCUS, 2020); the Zero Carbon Humber and Net Zero Teesside projects in the United Kingdom, which are scheduled to come online by the mid-2020s (Net Zero Teeside, 2020a); and the Ervia Cork project in Ireland, which is scheduled to come online by 2028 (Ervia, 2020). These European projects will jointly bring up to 10 $MtCO_2$/year additional capture and storage capacity online over the next ten years. In the United States, at least 20 large-scale facilities are being developed, prompted by an expanded 45Q tax credit[28] and complementary policies such as the California Low Carbon Fuel Standard. These facilities cover a range of applications at different stages of maturity, including natural gas processing; biofuels and cement production; DAC; and gas- and coal-fired power generation.

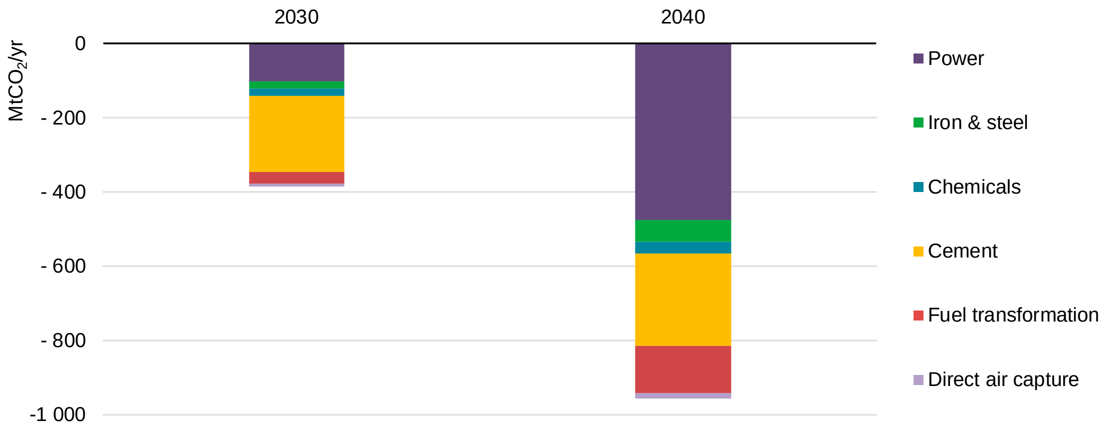
Planned investments could be affected by the economic fallout from the Covid-19 pandemic. In the Reduced Innovation Case, a delay in demonstration projects for pre-commercial CCUS technologies together with a slowdown in the deployment of CCUS technologies at early adoption stage would bring about a 50% and 35% reduction in CO_2 emissions captured in 2030 and 2040 respectively, compared to the Sustainable Development Scenario (Figure 4.10). As a result, CO_2 capture and storage deployment by 2040 would be reduced by around 8 $GtCO_2$ cumulatively, which is equivalent to the entire direct emissions of the transport sector in 2019. CO_2 captured from cement production and power generation would be the areas most affected in the Reduced Innovation Case over the next two decades, accounting between them for almost 80% of the reduction in CCUS deployment in that period compared to the Sustainable Development Scenario. Plans are already underway to demonstrate CO_2 capture in cement making as part of fully integrated CO_2 hubs, and deployment expands from the mid-2020s in the Sustainable Development Scenario. Two CCUS-equipped power plants are already in operation, and here too deployment expands in the Sustainable Development Scenario. Low-carbon cement production in particular is highly dependent on the demonstration of such technologies, because other technical options able to yield a comparable level of emissions reductions at scale (e.g. certain alternative binding materials) are significantly less developed today.

[28] Section 45Q is a tax credit that was expanded in 2018 and provides a credit of up to USD 50 per tonne of CO_2 for permanent geological storage, or up USD 35 per tonne for enhanced oil recovery (US Government, 2018).

The reduced level of CCUS deployment in the Reduced Innovation Case would mostly affect chemical absorption within the different capture technologies. As there is already considerable experience accumulated today in operating this technology, however, the cost of CO_2 capture by chemical absorption would be about 5% higher by 2030 in the Reduced Innovation Case compared to the Sustainable Development Scenario as a result of the reduced learning-by-doing. There would be a more significant impact on the costs of other less advanced CO_2 separation techniques that are at demonstration or prototype stage, such as physical adsorption and oxy-fuelling.

The relatively modest projected deployment of large-scale DAC in the Sustainable Development Scenario over the next two decades means that the delay in the demonstration of large-scale DAC in the Reduced Innovation Case would not significantly reduce the overall CCUS capacity expansion projected in the Sustainable Development Scenario over that period. Such delay, however, would increase by around 35% the cost at which large-scale DAC plants could be available in 2030 by severely limiting the scope for decreases in costs arising from learning-by-doing over the next decade.

Figure 4.10 Reduction in captured and stored CO_2 emissions in the Reduced Innovation Case compared to the Sustainable Development Scenario, by sector



CO_2 captured from cement production and power generation jointly account for almost 80% of the reduced CCUS deployment by 2040 in the Reduced Innovation Case compared to the Sustainable Development Scenario.

CCUS demonstration projects are capital-intensive, but they are associated with substantial job creation, particularly during the construction phase. Such jobs would be at risk in the Reduced Innovation Case. For instance, the Norwegian demonstration of a full-chain industrial CCS system could create almost 4 000 jobs during the investment phase (Northern Lights, 2020b). Other fully integrated industrial CCUS systems (with multiple capture facilities) have reported the potential to create several thousand jobs during construction: for example, Net Zero Teesside is expected to create 5 500 direct jobs in the United Kingdom during the construction phase (Net Zero Teeside, 2020b). Based on existing CCUS facilities, a stand-alone CCUS plant (e.g. with a single-capture source) is likely to have a job creation potential of between 400 and 1 200 jobs for an average three-year construction phase and between 20 and 60 jobs during several decades of expected operations (Northern Lights PCI, 2020; Government of Alberta, 2019; Lake Charles Methanol, 2020).

Hydrogen

Hydrogen technologies gained momentum in 2019. Hydrogen-producing capacity based on water electrolysis reached more than 25 MW last year, which is a record. The Fukushima Hydrogen Energy Research Field in Japan now has 10 MW of installed capacity, which is twenty times the average size of all projects since the early 2010s (Asahi Kasei Corporation, 2020). Large electrolysis-based hydrogen-producing capacities with hundreds of megawatts of capacity have been announced and are expected to be operational in the early 2020s: the hydrogen they produce will be used for fuels transformation, chemical production and hydrogen blending into natural gas grids. The fuel cell electric vehicle (FCEV) stock almost doubled in 2019 relative to 2018, mainly driven by a surge in demand in the Asian market, including demand for buses and light-duty trucks. Hydrogen refuelling infrastructure is expanding globally hand-in-hand with growth in the use of FCEVs: it saw more than 20% annual growth in 2019. Demonstration and pilot tests for up to 20% and 10%[29] hydrogen blending into gas distribution and transmission grids respectively have recently been carried out in France and Italy, while a large pilot plant to validate iron ore reduction for steelmaking based fully on electrolytic hydrogen is about to start operations in Sweden.

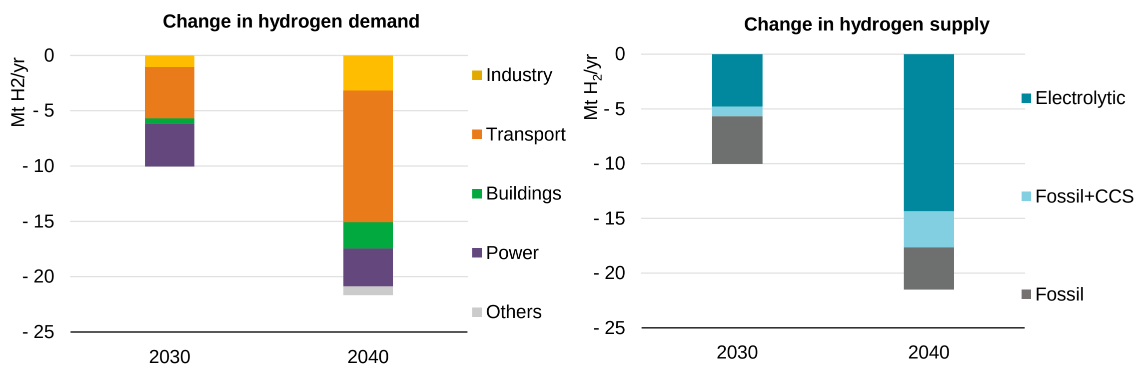
Whether this momentum will continue after the Covid-19 outbreak is to be seen. In the Reduced Innovation Case, a delay in demonstration projects for pre-commercial hydrogen technologies, together with a slowdown in the deployment of hydrogen technologies at early stage of adoption, would result in a reduction of 9% and 12% in annual hydrogen demand in 2030 and 2040 respectively, relative to the Sustainable Development Scenario (Figure 4.11). This reduction would result in more than 1.5 Gt of additional CO_2 emissions cumulatively by 2040 compared to the Sustainable Development Scenario, or almost twice the annual emissions related to hydrogen production today. Transport would see the largest hydrogen demand reduction: demand would fall by almost 12 Mt of hydrogen in 2040, or around half of the total

[29] Blending shares on volumetric basis.

hydrogen demand reduction in that year compared to the Sustainable Development Scenario. This fall would mostly reflect a delay in the uptake of heavy-duty FCEVs and of ammonia in shipping. Two-thirds of the fall in hydrogen demand in 2040 would be translated into reduced electrolytic production, which would also suffer a slowdown in deployment compared to the pace projected in the Sustainable Development Scenario because of a more uncertain build-up of hydrogen demand increasing investment risks.

A drop of almost 8 Mt/year global cumulative production capacity of electrolytic hydrogen by 2030 would result in an increase of almost 10% in the average capital expenditure of water electrolysers in 2030 relative to the Sustainable Development Scenario as a result of slower technology learning. This increase is barely noticeable in the levelised cost of producing electrolytic hydrogen, which would increase only marginally (up to 3.1 USD/kg)[30], but it would put additional stress on upfront investment financing for projects that are already highly capital-intensive, with potential implications for jobs: a cancellation of projects in the pipeline for 2020 and 2021 aiming to scale-up plant capacity of electrolytic hydrogen would put at risk between 3 300 and 4 400 direct and indirect jobs.[31]

Figure 4.11 Reduction in global hydrogen demand and supply by sector and process route in the Reduced Innovation Case, relative to the Sustainable Development Scenario



Note: H_2 = hydrogen; CCS = carbon capture and storage.

Transport would account for around half of the total hydrogen demand reduction in the Reduced Innovation Case in 2040 compared to the Sustainable Development Scenario; electrolytic hydrogen production would fall sharply.

[30] Hydrogen levelised cost is based on 69% (conversion efficiency), USD 50 per MWh (electricity price), 5 000 full-load hours and a weighted average cost of capital of 8%.

[31] Based on between six to eight jobs created by USD 1 million investment including engineering, manufacturing, construction and operation (IEA, 2020).

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Chapter 5. A once-in-a-generation opportunity to reshape the future

HIGHLIGHTS

- This report makes clear the importance of accelerating clean energy innovation to give the world the best chance of achieving energy and climate goals, including net-zero emissions. Without a strong continuing focus on clean energy innovation, our chances of success are shrinking. The opportunity offered to governments, industry and clean energy investors is enormous. In the Sustainable Development Scenario, annual average investments in technologies that are currently only at prototype or demonstration stages total around USD 350 billion through to 2040, and they reach nearly USD 3 trillion in the 2060s.
- We identify five key principles for compressing the innovation cycle and delivering net-zero emissions. They focus on areas of particular relevance to clean energy technology that often lack attention from energy policy makers or need strengthening. They build on the analytical findings of this report:
    1. **Prioritise, track and adjust.** Selecting a portfolio of technologies to support requires processes that are rigorous and flexible and that factor in local needs and advantages.
    2. **Raise public R&D and market-led private innovation**. Different technologies have differing needs for further support: from more public R&D funding to market incentives.
    3. **Address all the links in the value chain**. In each application, a technology is only as close to market as the weakest link in its value chain, and uneven progress hinders innovation.
    4. **Build enabling infrastructure.** Governments can mobilise private finance to address innovation gaps by sharing the risks of network enhancements and demonstrators.
    5. **Work globally for regional success**. The technology challenges are urgent and global, making a strong case for co-operation which could draw on existing multilateral forums.
- Covid-19 means that some of these key principles deserve immediate attention from governments looking to boost economic activity. In particular, it is important to maintain R&D funding at planned levels and to consider raising it in strategic areas. Current clean energy demonstration projects should not be allowed to fail. Market-based policies and funding could help scale-up value chains for modular technologies like electrolysers and batteries, significantly advancing their progress. Measures to spur innovation could be taken forward alongside related measures such as infrastructure investments in wider stimulus packages.
- Economic recovery measures also present new opportunities for innovation to reshape the future towards cleaner energy in the longer term. Innovation policies themselves – including technology prioritisation processes and tracking and evaluation systems – could be renewed and aligned with long-term goals. Investments in key demonstration projects in heavy industry and long-distance transport, which have often been neglected, could make low-carbon options available earlier and in time for scheduled investments cycles around 2030, avoiding “locking-in” significant emissions. Co-ordinated investments in R&D and enabling infrastructure for electrification; carbon capture, utilisation and storage; hydrogen; and bioenergy could also significantly boost clean energy transitions.

Introduction

This is an unprecedented moment in energy history. The world may currently be at an inflection point in the development of a clean energy technology portfolio that matches net-zero emission ambitions. The awareness of the importance of innovation and its role in transforming energy systems has never been higher. It has been brought into sharp focus by the ambitious targets for emissions reductions by 2050 which have been set by countries and companies alike. Major industrial sectors – including iron and steel, cement, fuels production, aviation, shipping, gas supply – that don't yet have commercially available solutions for deep decarbonisation are engaged in project and policy development. Emerging economies, such as Brazil, the People's Republic of China (hereafter "China") and India, are strengthening their innovation systems for home-grown technologies appropriate to their contexts.

Government policy will determine whether these positive trends translate into a faster pace of innovation more closely aligned with a clean energy transition to net-zero emissions, and the advent of the Covid-19 pandemic makes the role of governments more important than ever. At the outset of the current crisis, investment in R&D was not sufficient to meet the scale of the challenges, especially in sectors that currently have limited available commercial and scalable low-carbon options. There is an opportunity now to address this, including through measures that form part of economic recovery packages. Maintaining and increasing the rate at which promising new technologies enter the energy system is not only critical for meeting energy policy objectives, but also has the potential to drive future economic growth: this report points to a wide range of investments that make the longer term transition to net-zero emissions more likely, while at the same time spurring near-term economic recovery.

There is, however, also a risk that the economic damage done by Covid-19 may lead to reductions in R&D budgets and investment. That would be deeply damaging to clean energy innovation and to the prospects of achieving net-zero emissions. Innovation is a process that spans decades and, while many of the technology types deployed in the Sustainable Development Scenario are already advancing towards maturity, some key technologies still have a long way to go. Delayed demonstration of the competing options for decarbonising industry in particular would make it harder to meet climate goals, with delays to low-carbon hydrogen demonstration projects alone potentially leading to 1.5 Gt of additional CO_2 by 2040 (see Chapter 4). Value chains for new technologies are fragile, and global clean energy innovation systems could take years to recover from cutbacks in spending.

This final chapter draws together the conclusions from the analysis throughout this report into recommendations for policy action. The chapter begins by presenting five key principles for compressing the innovation cycle and delivering net-zero emissions. This focuses on areas of particular relevance to clean energy technology that often lack attention from energy policy makers or that need strengthening in the context of net-zero emissions ambitions. In response to the additional and equally urgent policy context of the Covid-19 pandemic, the subsequent sections of the chapter highlight more specific elements of the policy package that can address both near-term and long-term goals. They consider immediate actions to keep clean energy innovation on track through to 2025 and beyond, and new opportunities for innovation-related economic recovery measures to reshape a cleaner energy future. They then look at these actions and opportunities in terms of their relevance to key technology families for achieving net-zero emissions, giving concrete examples of what needs to be done.

Five key principles to accelerate clean energy technology innovation for net-zero emissions

This report brings out that innovation policy and energy policy need to be considered together, and that clean energy technology innovation should be seen as a core element in energy policy decision making. There has been a tendency in the past to treat R&D and innovation policy separately from energy policy. Feedback loops between energy strategy and the learnings from technology innovation programmes are sometimes not formalised. In some countries they have been housed in different ministries, while in others the links between the relevant divisions within a single ministry have been weak. Regardless of what organisational arrangements are in place, the two areas of policy need to be considered together, and those working on them need to collaborate closely.

The recommended policy actions in this section are grounded in the findings of the earlier chapters of this report. For example, the recommendation for governments to look more closely for synergies between technology types across sectors is based on the acceleration of innovation progress seen in historical cases such as solar PV and semiconductors and our identification of technology clusters that are central to achieving net-zero emissions, while the recommendation to look at value chains as a whole and identify the weakest links in value chains for a given technology design is based on analysis of areas where progress has been uneven, such as synthetic fuels.

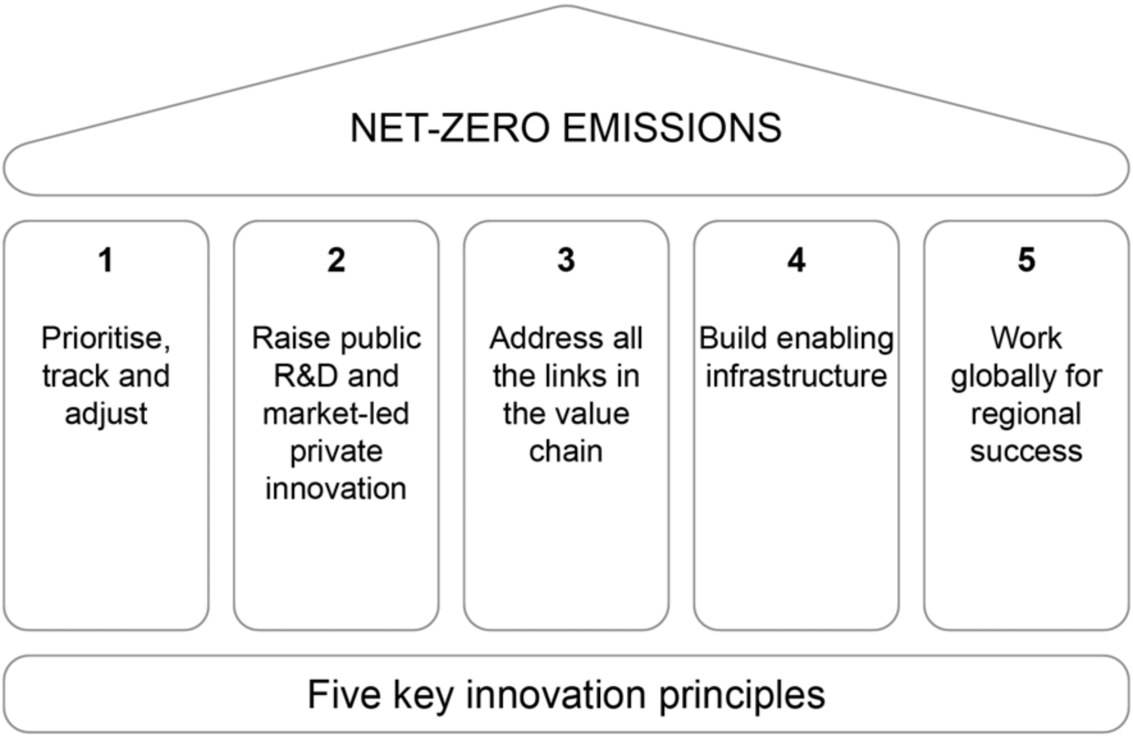
The recommendations are made with national governments and supranational authorities in mind, although many of them are also relevant to action by authorities in cities and other subnational authorities, and to companies too. Different governments will, of course, select portfolios and policy instruments differently according to their individual circumstances. From a global perspective, the adoption of different R&D portfolios by different countries, regions and companies is a strength, as long as all key innovation gaps are addressed in total: it supports competition and diversity in the face of uncertainty.

The recommendations do not attempt to provide a single technology portfolio that is suitable for all. Indeed, in general they are not technology specific, focusing instead on good practices that can guide technology choices and be adapted to unanticipated breakthroughs. As highlighted in the findings of Chapters 3 and 4, however, four cross-cutting technology areas underpin most of the long-term emissions reductions in the Sustainable Development Scenario and are therefore key to faster innovation. These are: 1) electrification of end-uses; 2) CCUS; 3) hydrogen and hydrogen-based synthetic fuels; and 4) bioenergy. All four are particularly relevant to sectors, where reducing emissions is hardest, and face challenges in co-ordinating innovation across their value chains in a timely manner. For this reason, examples involving these areas of technology are used to illustrate the recommendations wherever possible.

While the focus here is on public policy, the role of private sector entrepreneurs, companies and financers is also critical. Private sector participants in the innovation system greatly outnumber those from the public sector, with public sector employees representing just 5-25% of R&D researchers in most OECD countries (OECD, 2020). Success will depend upon the public and private sectors working closely together to agree the way ahead, identify projects and metrics, and learn together from past successes and failures.

The list of elements set out in this chapter for inclusion in a policy package to accelerate clean energy technology innovation is aimed at maximising the likelihood of a successful transition to net-zero emissions. It is not exhaustive: a successful clean energy innovation system needs various kinds of support, many of which are not energy specific (see Chapter 1). Rather, it focuses on areas of particular relevance to clean energy technology that often lack attention from energy policy makers or need strengthening for meeting net-zero emissions ambitions. These recommendations represent a package of good practices at any time, not just in the context of the repercussions of the Covid-19 pandemic. They are grouped under five core principles (Figure 5.1).

Figure 5.1 Key principles to accelerate clean energy technology innovation for net-zero emissions



By applying five key principles, governments can compress the innovation cycle and deliver net-zero emissions.

1. Prioritise, track and adjust

Innovation systems are stronger and have more impact if participants are working towards the same overarching goals. Visions of the future can be formulated and consensus promoted by using roadmapping processes that also identify realistic target markets for local technology development. Given the challenges of decarbonising certain end-use applications, there are strong arguments in favour of developing such visions on a sectoral or application-specific basis – such as supply of low-carbon steel or building heat – and not just at the level of technology type – such as biofuels, wind power or heat pumps. While multi-year priority setting is well established in places including China, the European Union and Japan, there is less experience with complementary processes to ensure flexibility and evaluation of outcomes against policy objectives. The key requirements are to:

- **Establish and publicise clean energy visions for key sectors in the long term**, and at interim milestones, in co-operation with technology experts, civil society and market analysts. Good roadmaps describe the journey and the destination in qualitative as well as quantitative terms: they also look at how the activities of the people and companies involved might change over time, so as to provide a foundation for a conversation about opportunities and trade-offs between all relevant stakeholders.

- **Identify the technology needs and innovation gaps to get from here to there**. Clean energy visions can be mapped onto the existing technology landscape to identify where improvements in cost and performance are needed, and where there are cross-sectoral interactions. Tools such as the ETP Clean Energy Technology Guide[32] can be used to help in this process (see Chapter 3). Technology needs assessments as promoted by the United Nations and as undertaken for the UK Energy Innovation Needs Assessment exercises are examples.
- **Prioritise a set of R&D topics, taking into account local expertise, local R&D capacity, comparative industrial advantage, and potential for spillovers.** Selecting the areas to prioritise is a difficult but essential exercise, and there is significant scope for governments to share good practice in this area. Based on the analysis for the Sustainable Development Scenario, we specifically highlight the importance of considering cross-sectoral spillovers. For example, cross-sectoral technology clusters that support "electrochemistry" or "lightweight materials" might accelerate innovation faster in some countries than clusters for applications such as "energy storage" or "mobility". Governments of smaller economies have particular incentives to prioritise R&D and select the technology types that they are best placed to contribute. Japan's Environment Innovation Strategy is an example of a priority-setting document, while Korea's technology cluster for batteries, solar PV and electronics is an example of clustering.
- **Track progress towards stated policy goals, embed evaluation ex ante into policy design and establish processes for regular review of priorities.** Committing to innovation means taking a long-term view and embracing uncertainty, but that does not diminish the importance of regular assessments of progress and policy orientation. There is considerable potential for better data to help governments assess how their clean energy innovation policies are performing, including by ensuring that the information needed for *ex post* evaluation is gathered along the way. Canada and Italy are examples of countries that collect data on private sector energy R&D to support policy making, while independent programme evaluations are well established in the United States, one example being the 2017 review of ARPA-E (Advanced Research Projects Agency – Energy) by the National Academies of Sciences, Engineering, and Medicine.

[32] For more information please visit: iea.li/CleanTechGuide.

- **Communicate the vision to the public and nurture and build socio-political support.** Energy innovation takes time and there is little room for manoeuvre if net-zero ambitions are to be realised. Compressing the timetables for scale-up and continual improvement requires mobilising all stakeholders. In practice, this demands transparency about the process and the identification of possible areas of public concern (and enthusiasm) in advance. The European Commission, for example, conducts regular Eurobarometer surveys of public opinion on energy.

2. Raise public R&D and market-led private innovation

Aligning innovation with the opportunities for a clean energy transition to net-zero emissions requires more resources than are currently devoted to clean energy R&D and innovation by both the public and private sectors. While it is not possible to specify the precise amount that should be spent, or who is best placed to spend it in each country, the innovation system needs sufficient funding to generate a steady pipeline of new ideas that align with sectoral net-zero emissions visions, and the proponents of these ideas need to be able to access funding to reach prototype scale, demonstration and scale-up into successive market niches, if their potential is proven at each stage. The key requirements are to:

- **Mix public funds and market mechanisms to maximise the contribution from private capital.** Depending on the technology areas prioritised, different mixes of instruments will be appropriate – including research grants, standards, deployment incentives, loans, prizes and project grants. For each concept or project, the level of maturity, unit size, modularity, value chain complexity and value for customers should influence programme and policy design. The history of the development of solar PV shows how research grants were followed by public procurement and then market-pull policies combined with manufacturing support, with the latter stimulating private sector innovation to drive down costs. Several governments have been adapting their energy innovation policy instruments to raise the efficiency of public funding, including through ARPA-E in the United States, InnovFin in the EU and National Major S&T Projects in China. Canada and India are among the countries seeking to enhance incentives for venture capital finance to encourage a vibrant start-up community with longer time horizons.
- **For each priority, support an evolving portfolio of competing designs at different stages of maturity, and favour options with rapid innovation potential.** Diversity and competition help to spur progress and leave some space for unexpected developments, while small, modular, mass-manufactured technology designs with high spillover potential offer rapid innovation dynamics. These types of technologies can be found among the proposed solutions for many of the current energy challenges and there is an emerging

body of work that supports their inclusion in technology portfolios. While solar PV and lithium-ion (Li-ion) are exemplars of how this kind of approach accelerated progress in the past, electrolysers, fuel cells, heat pumps and smart-home technologies could all benefit in the future.

- **Ensure that knowledge arising from publicly funded R&D is rapidly and openly shared with the research community and taxpayer value is maximised.** This is good practice for knowledge-sharing purposes – open access publishing is a condition of receiving EU R&D grants, for example – and can also raise public support.

3. Address all the links in the value chain

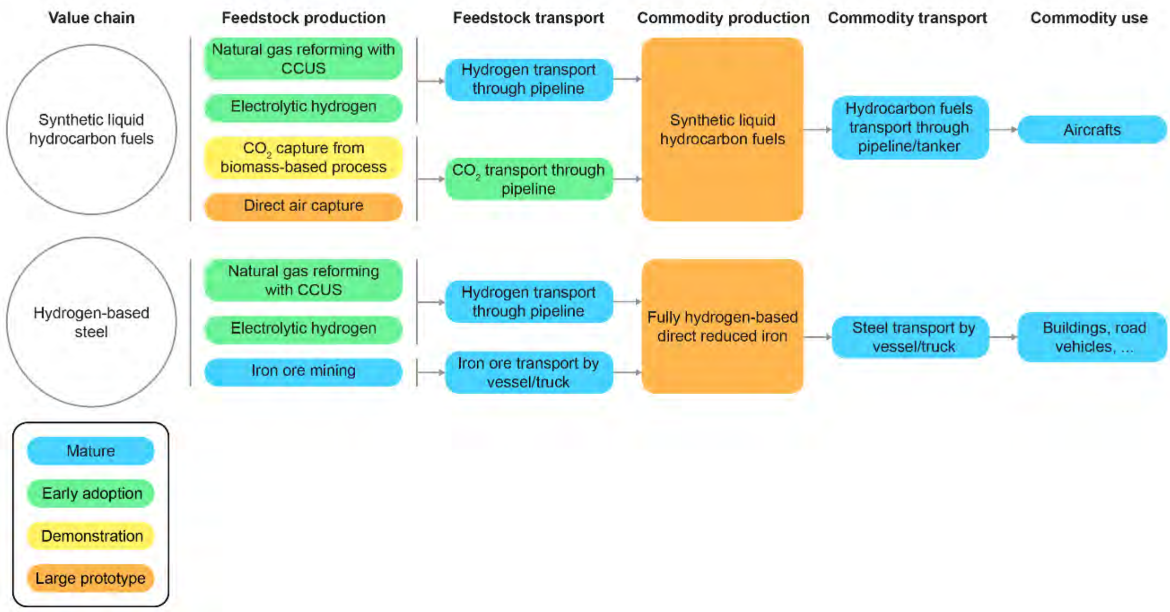
Delivering energy services to a specific end-use involves different technologies for supply, distribution, storage and use, and value chains spanning the process are only as strong as their weakest link (Figure 5.2). Individual countries and companies need not contribute technology improvements to all steps in a given value chain (indeed most countries don't have the capacity to do so) but, by considering the full value chain, they can more easily identify areas where faster progress is needed for deployment. In keeping with the findings about the importance of key end-use sectors in the Sustainable Development Scenario, an approach focused on value chains starts from the needs of each application rather than focusing on supply. The key requirements are to:

- **For each technology area, identify the position(s) in the value chain that present(s) the greatest opportunity for local innovators.** Energy-related equipment is a global industry, with countless specialised components and intermediates traded internationally. As part of the consideration of comparative advantage during technology prioritisation, governments should consider where their comparative advantages might lie in future trade networks, alongside strategic considerations about energy security, technology clusters and integration. For example, a small highly-skilled economy might prioritise hydrogen for industrial use, but recognise that its relative strengths relate more to project integration and gas handling than electrolyser manufacturing.
- **Ensure adequate support for all elements of the value chain.** Four of the key technology areas for net-zero emissions energy systems – direct electrification, CCUS, hydrogen and bioenergy – all have value chains that are advancing unevenly (see Chapter 3). For some, the issues relate to upstream supplies, for example in biomass production, while for others the issues are downstream, for example in CO_2 storage availability or smart grids. While uneven progress is inevitable to a large extent, all elements must reach sufficient maturity by the time the full value chain needs to be deployed. In the meantime, innovation in

the more mature elements can be taken to the next level by using market-pull policies to support niche markets. Early niche markets are often those requiring the shortest new value chains and therefore have the lowest risks: examples include the sale of captured CO_2 for enhanced oil recovery and the use of geothermal CO_2 for synthetic fuels production. Importantly, the best niche markets may not be in the same sectors as the future markets with the highest potential: for example, blending low-carbon hydrogen into gas grids or its use in refineries could be an invaluable springboard for its use in transport.

- **Co-operate regionally and internationally with developers of other elements of the value chains.** Multilateral and bilateral co-operation can help ensure timely and targeted investment in individual elements of value chains. International projects can help channel funds to where they are needed most.

Figure 5.2 Maturity level of technologies along selected low-carbon value chains



Note: CCUS = carbon capture, utilisation and storage.

The technologies that make up the value chains for synthetic fuels and hydrogen-based steelmaking are not equally mature, leaving them only as close to market as their weakest link.

4. Build enabling infrastructure

Several key areas that need to see rapid technical progress for reaching net-zero emissions require new infrastructure or upgrades to existing networks. Such infrastructure includes major demonstration facilities for industrial processes. Among the network needs are smart electricity grids, hydrogen-ready gas grids, low-temperature district heat networks, CO_2 storage infrastructure, and communications networks for connected appliances and vehicles. These types of investments have strong public good elements by virtue of being natural monopolies and having large returns to adoption, meaning that later adopters often face lower costs and obtain higher benefits. Once infrastructure is in place, it can be a platform for innovation, encouraging new ideas for how to make best use of it, especially if third-party access is guaranteed. On the other hand, it can be a major barrier to adoption if project promoters have to bear the risks of new infrastructure at the same time as they are bearing the risks of developing other elements of the value chain. There is therefore a strong rationale for governments to ensure that enabling infrastructure is put in place in line with demand for the new technology. The key requirements are to:

- **Incentivise network owners and operators to test and deploy enabling infrastructure** for new technologies to integrate into existing grids, pipelines and communication systems. Regulated network operators and utilities are usually obliged to minimise risk, which reduces their capacity to incorporate new enabling technologies into network infrastructure. New regulatory models are emerging to provide more scope for experimentation. For example, the RIIO 2 (Revenue = Incentives + Innovation + Outputs) price controls in the United Kingdom include provisions for network operators to access innovation funds and trial technologies with appropriate regulatory exemptions.
- **Take the initial investment risk in large-scale demonstrators that present a high-cost barrier to scale-up**. Technologies like CCUS for industrial facilities, fossil fuel-free iron and steel processes, new nuclear designs, and floating offshore wind all face high capital costs for the first commercial projects. These projects have the highest costs and risks, with subsequent entrants benefiting from the learnings. This provides a rationale for direct government investment in this phase of development, in tandem with action to create more market value for products such as low-carbon steel. Public funding for such projects could be conditional on the learnings from the projects being widely shared. For example, CCUS projects that received public support in Alberta (Canada), the European Union and the United Kingdom had their findings published for the benefit of the technical community. In some cases, the facilities can be made "open access" for testing of different designs, as has been done for CO_2 capture at the Technology Centre Mongstad in Norway and the US National Carbon Capture Test Center.

5. Work globally for regional success

The innovation gaps to be filled for a net-zero emissions future are global, reflecting the global nature of the climate challenge, and innovation will be most efficient if countries are able to share some of the burden internationally. Multilateral platforms for co-operation between governments already exist and can be strengthened as necessary to ensure that global innovation systems work as efficiently as possible. Appropriate intellectual property regimes also have an important role to play in maximising the innovation benefits of trade. The key requirements are to:

- **Work across borders to ensure that no essential technology areas remain underfunded because of high development risks that cannot be borne by one country.** Learnings and experiences in each country are global public goods because they advance the innovation frontier for all regions. In most cases, this contribution, coupled with the first-mover advantages for local innovators, justifies public financial support for R&D, demonstration and early adoption in a given economy. However, the risks can sometimes be too high for a single country to fund if the market players are multinational, the outlook uncertain and the project particularly costly – as is the case for CCUS, including for low-carbon hydrogen, and low-carbon industrial processes. Countries with smaller R&D budgets and companies with weaker balance sheets are likely to find collaboration especially attractive if it keeps local innovators from moving overseas. Pooling of innovation resources in this way is rare, but not without precedent, as the size of the budgets for EU energy R&D and cross-border nuclear fusion campaigns attest. As a recent example, the French and German governments announced co-financing of a floating offshore wind project in early 2020.
- **Exchange experiences with other clean energy innovation policy makers about good innovation policy practice.** Several of the recommendations in this list are for actions that would have positive impacts but for which there is not yet consensus on the best approach. R&D prioritisation, funding instrument design and evaluation fall within this category and could benefit from an exchange of experiences between governments.
- **Support networks for the rapid exchange of knowledge between researchers in overlapping fields and cross-fertilisation between sectors.** The benefits and speed of knowledge and application spillovers can be maximised by exploiting synergies internationally. International networks for knowledge exchange can also help avoid duplication of effort and identify innovation gaps not yet addressed. Existing multilateral platforms for co-operation provide a sound basis for deepening collaboration. They include the IEA technology collaboration programmes, which facilitate co-operation across 38 technology areas, Mission Innovation and the Clean Energy Ministerial, among others.

Covid-19: The case for rapid implementation of innovation policies to maintain momentum and accelerate the transition

Covid-19 does not change the elements of the net-zero emissions innovation policy package, but some of the elements deserve immediate attention as governments prepare policies to repair, stimulate and recover economic activity. The central role of government in supporting energy innovation is well established, especially in relation to the public good nature of R&D, and tackling the greenhouse gas externality is widely agreed to need strong government action over the coming decades. Energy innovation offers an opportunity to boost economic activity damaged by the Covid-19 pandemic and at the same time to help with the transition to net-zero emissions. It supports a sizeable workforce, including around 750 000 R&D personnel, and is a driver of economic growth: it is also essential to addressing climate change and other long-term energy and sustainability challenges. By the same token, reduced investments in energy innovation because of Covid-19 would have short-run economic costs as well as long-run costs for energy transitions, and would increase the difficulty of meeting mid-century climate goals.

When designing stimulus packages, it is critically important to consider overarching energy policy objectives such as improving energy sector resilience and addressing climate change, as set out in the IEA *World Energy Outlook Special Report on Sustainable Recoveries* (Table 5.1). The recommendations in that report identify the areas of energy investment where short-term and long-term interests converge.

Table 5.1 Policy actions for a sustainable recovery plan for the energy sector beyond clean energy innovation

Buildings	• Implement large-scale retrofit programmes for public buildings, provide subsidised financing for private retrofits • Implement appliance turnover schemes to replace inefficient appliances, install heat pumps and renewable energy systems that use solar water heaters and biomass boilers • Support clean cooking access by offering modern stoves, and developing advanced biomass and liquefied petroleum gases delivery systems
Transport	• Implement vehicle turnover schemes to accelerate efficient car and electric vehicle adoption • Boost high-speed rail and incentivise the purchase of new efficient trucks, airplanes and ships • Accelerate deployment of recharging networks for electric vehicles, upgrade public transport, and improve walking and cycling infrastructure

Industry	• Incentivise industrial energy efficiency, especially light-industry electric motor and process heat pumps upgrades • Improve waste collection and recyclable material recovery rates, especially where waste collection processes are informal • Upgrade to efficient agricultural pumps
Electricity	• Invest in electricity network upgrades, particularly distribution system strengthening and modernisation • De-risk and fast-track new wind and solar PV deployment • Extend lifetimes for nuclear plants near their end of life and repower existing hydropower facilities
Fuels	• Support for biofuel industries if they meet appropriate sustainability criteria • Implement methane leak detection programmes to address fugitive methane from upstream oil and gas operations • Reform inefficient fossil fuel subsidies without increasing end-use prices

Source: IEA (2020a).

The following sections of this report follow the same logic, identifying elements of the net-zero emission innovation policy package that could be included in recovery measures for their potential to meet two crucial objectives in the current context, one short-term and one medium-term:

- Keep the whole innovation system on track.
- Invest strategically and ambitiously to reshape the economy towards net-zero emissions in the period to 2030.

Analysis throughout this report indicates that there are significant benefits to renewing support for clean energy technology innovation out to both these time horizons and indeed beyond. There are two main reasons for this. The first is that the world cannot afford to drift further off-track in its capacity to tackle emissions in certain end-use sectors. The second is that the investment opportunity presented by stimulus funding and new market realities is unique: it could potentially carry some key technologies across the "valley of death" much faster than anticipated.

Keep the whole innovation system on track

In the short term, governments are looking to boost economic activities that are labour intensive, can be rapidly deployed and have large economic multipliers. Maintaining spending across the economy on innovation meets these criteria. Research, including public sector R&D, is a labour-intensive activity that underpins future productivity and growth. Manufacturing plants for new technologies and demonstration projects that are already at an advanced stage of planning are likely to be ready for rapid deployment, i.e. they are "shovel ready". R&D projects that had already started or were ready to start but now face funding uncertainty can be begun or ramped up quickly.

Each measure should be considered within the context of a systematic approach to maintaining momentum in the face of serious risks. Disruption to any of the key functions of the clean energy innovation system could choke the pipeline of new technologies, and it might take years for it to be replenished. This is a further argument in favour of a value chains approach, as highlighted in the recommendations below, and in favour of integrating support for clean energy innovation with other elements of stimulus funding, including infrastructure investments and corporate support.

The recommendations below are all elements of the five key principles introduced above. They have been selected for the contribution they make to counteracting short-term risks. They also incorporate lessons learned from the stimulus measures implemented in 2009 after the 2007-08 financial crisis (see Box 5.1).

Raise public R&D and market-led private innovation

- Maintain public clean energy R&D programmes already planned for 2020-21.
- In major economies, give early signals that budgets in 2021-25 will be raised counter-cyclically, consistent with the increases seen in 2009-11 (these were 100% or USD 4.7 billion in the United States, and 60% or USD 1.8 billion in other major economies).[33]
- Take low-cost measures to raise R&D productivity by enhancing professional networks, ensuring that results are published with open access and by enforcing existing regulations, for example in relation to intellectual property.
- Explore international finance options to avoid further widening the gap between emerging markets and global leaders in R&D and innovation.
- Make support for distressed companies conditional on commitments from them on clean energy innovation. Conditions in bail-out agreements for companies in energy supply or heavy industry and long-distance transport sectors where reducing emissions is hardest, could require purchases of new technologies, investments in enabling infrastructure or temporary reinvestment of profits in R&D. Conditional loans or tax incentives for corporations could require them to increase spending on clean energy technology R&D to counteract R&D spending cuts, following the example set by the European Investment Bank when it provided funding to car companies for electric vehicle (EV) R&D in the 2010s. Capital – such as short-term grants and loans or loan guarantees – can be provided to viable and innovative start-ups and SMEs, especially if it is administratively possible to target those in strategic areas.

[33] Canada, France, Germany, the Netherlands, Norway, Spain, Sweden and the United Kingdom.

Address all the links in the value chain

- Act across value chains for mass-manufactured technologies on the cusp of rapid scale-up by co-ordinating support for market demand, factory completions, field trials and R&D. This action applies particularly to new Li-ion battery designs, electrolysers, fuel cells, heat pumps and highly efficient air conditioners.
- Build on existing instruments to create niche markets and avoid the need for complex new regulations. Market-based support is likely to attract more private capital and have a long-lasting effect on developing new businesses. In 2009, US American Recovery and Reinvestment Act (the "Recovery Act") incentives leveraged the tax system, while the possible use of the EU Emissions Trading System to issue "carbon contracts-for-difference" that guarantee revenue to low-carbon hydrogen consumers in industry has been proposed in Europe.
- Give preferential treatment to innovative low-carbon solutions in major public procurement programmes within stimulus packages. Examples include low-carbon building materials, smart controls for energy management and novel approaches to manufacturing energy efficiency retrofits, such as off-site prefabrication and standardisation.

Build enabling infrastructure

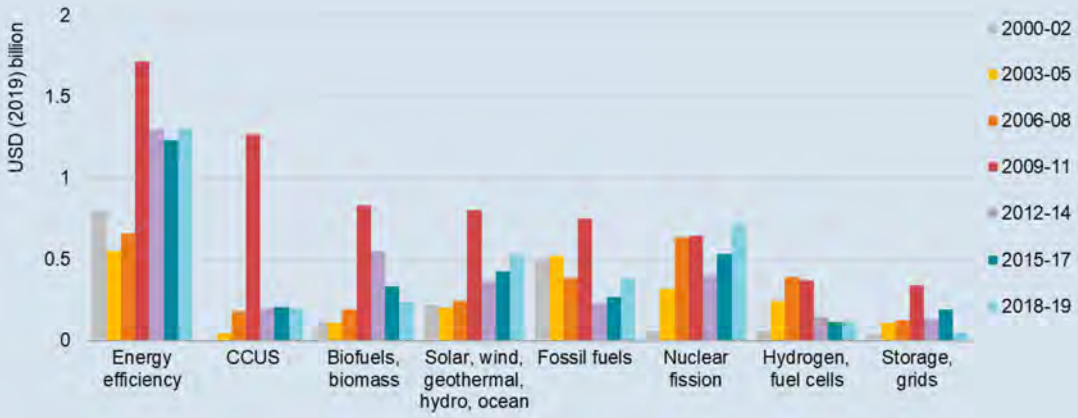
- Ensure that major technology demonstrations and large-scale field trials proceed to completion if they are at an advanced stage of planning and if follow-on commercial investments are still expected. Projects with simple value chains and infrastructure requirements are most attractive for rapid spending and job creation. In the area of CCUS, several of the 15 projects seeking support from the so-called 45Q tax credit in the United States are well advanced in their planning and have reasonable certainty about their CO_2 storage contracts; the Northern Lights project in Norway is also close to a final investment decision. In the area of smart grids, demonstrations of different implementation contexts for demand-response, load aggregation and electricity storage would build regulator confidence in faster/wider adoption.
- Network infrastructure is likely to be a target for investment by governments due to its economic multiplier effects, providing an opportunity to make it more compatible with a net-zero emissions future. In some cases, relaxation of certain regulatory provisions may be needed to allow regulated entities to make widespread investments in key enabling technologies. Examples include smart grid upgrades, EV charging, district heat modernisation and hydrogen-ready gas pipelines.

Box 5.1 Experience from previous energy innovation stimulus measures

Governments around the world, faced with the predicted severe negative impacts of the global financial crisis of 2007-08, passed wide-ranging economic stimulus packages by 2009. Among these, several major governments with sufficient economic resources chose to channel money to clean energy innovation. The rationale was generally to pair short-term stimulus measures with longer term investments in increased productivity and technologies that could reduce CO_2 emissions once the economy recovered.

The largest and most wide-ranging example of this approach was the 2009 US American Recovery and Reinvestment Act, which provided more than USD 90 billion in support of clean energy activities. Within this envelope, USD 7.5 billion was allocated to energy R&D and major demonstration projects, and other funds were directed to scaling-up value chains for early-stage technologies. By the end of 2010, an estimated 32 200 job-years through 2012 for innovation and job training had been created by the Recovery Act (CEA, 2010). In the three years from 2009 to 2011, federal R&D on energy efficiency was raised by over USD 1 billion per year compared to 2006-08, or 160%. Funding for carbon capture, utilisation and storage R&D and demonstration also rose by over USD 1 billion, a nearly 600% increase. Although smaller in absolute terms, the near trebling of funding for electricity grids and storage was also striking and came at an opportune moment for batteries development.

US federal funding for applied energy technology R&D and demonstration, 2000-19



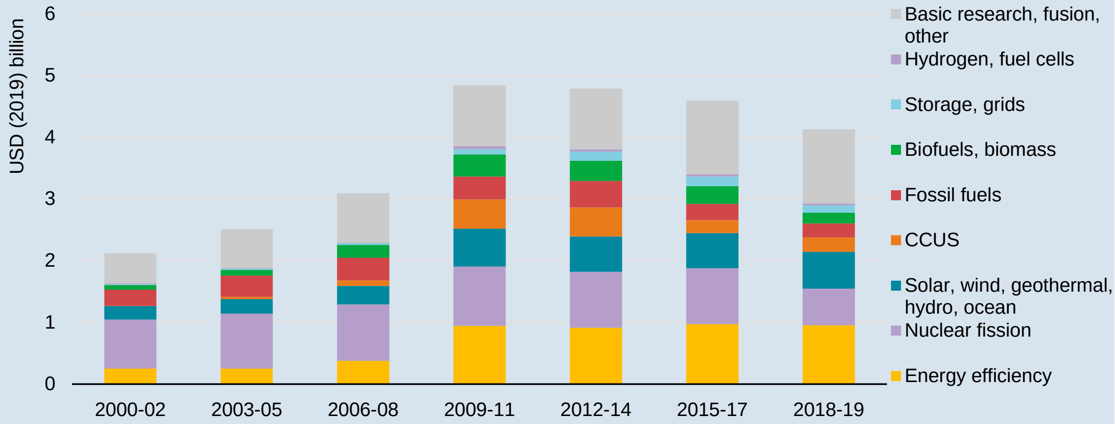
Notes: Does not include basic energy research or R&D for nuclear fusion nor ARPA-E (Advanced Research Projects Agency – Energy) funding. CCUS = carbon capture, utilisation and storage.

Source: IEA (2020b); Gallagher and Anadon (2017).

The Recovery Act made a notable contribution to the development of Li-ion battery technology. The funding it provided for US battery R&D funding represented a significant increase in global R&D at a time when EVs were primed for market entry but needed better batteries, and when the United States produced less than 2% of the world's batteries for hybrid vehicles (Walsh, Bivens and Pollack, 2011). With new battery designs, the cost of EV batteries fell by 70% and the number of electric cars sold in the United States rose from 1 500 to 114 000 between 2008 and 2015 (US DoE, 2015; IEA, 2016). Not all of this can be attributed to the Recovery Act, but there is no doubt that the sector benefited from the timely allocation of resources to different parts of the value chain, not just R&D. The Act allocated USD 140 million to 12 grid-level demonstration projects; USD 400 million to 8 demonstration projects for EVs and chargers, plus workforce training and R&D; USD 160 million to 60 novel battery development projects under ARPA-E by 2015; USD 2 billion to 30 manufacturing facilities for batteries, battery components and EV drivetrain components; USD 33 million in tax credits to battery factories; USD 2 billion in loans to EV and battery manufacturing; and USD 2.2 billion to tax credits for EV purchases (US DoE, 2020a, 2020b, 2020c; Walsh et al., 2011). Twenty-six of the 30 manufacturing projects receiving grants were in construction by 2011; 2 of the battery factories were already in production.

Although the sums spent on clean energy innovation outside the United States were generally much lower than for the Recovery Act, Germany also allocated around EUR 0.5 billion to R&D for mobility (Deutscher Bundestag, 2009; Schmidt et al., 2009), and annual clean energy R&D budgets were increased around 60% in 2009-11 in other large economies that used stimulus in this way. In these countries, the increases in funding were often lasting, whereas many of the areas funded by the Recovery Act are today at near pre-2009 levels of funding, having fallen back after 2011.

Public energy R&D and demonstration funding in selected countries that used stimulus money for this purpose, 2000-19



Notes: Data for Canada, France, Germany, the Netherlands, Norway, Spain, Sweden and the United Kingdom. Consistent data for the European Commission is not available for the whole time period so is not included. CCUS = carbon capture, utilisation and storage.

Source: IEA (2020b).

A common feature of several of the largest economic recovery packages was investment in large-scale technology demonstration in complex engineering projects. The large sums of money unlocked by stimulus funding packages offered a welcome opportunity to get these financially risky, capital-intensive projects built. All projects generated valuable experience in relation to project permitting, regulatory challenges, financing and business models – which was sometimes shared publicly as a legal condition for receiving funding – but their success was mixed.

In 2009, USD 12 billion was made available for CCUS, concentrating solar power, offshore wind, smart grid and energy storage projects in Canada, the European Union and the United States. In Canada, this represented 1.2% of the total stimulus package and 59% of the energy-related budget, alongside funding for smart grids and renewables R&D. The EU and US levels were lower, at 0.7% and 33% for the European Union and 1.2% and 9.3% for the Recovery Act. Of the 58 projects that received funding, 40 were commissioned and have generated operational experience. Many of these were smaller smart grid and electricity storage projects in the United States. CCUS projects had a lower success rate, with 5 out of 19 commissioned to date, including one that started operations in 2020.

Demonstration project funding from economic stimulus budgets approved by governments in 2009

Programme		CCUS	CSP	Electricity storage	Offshore wind	Smart grids
Canada Economic Action Plan Clean Energy Fund	Budget (billion USD)	0.41	-	-	-	-
	Projects	3	-	-	-	-
	Commissioning of first project	2015	-	-	-	-
	Projects operating by 2020	2	-	-	-	-
European Union European Economic Programme for Recovery	Budget (billion USD)	1.46	-	-	0.35	-
	Projects	6	-	-	6	-
	Commissioning of first project	-	-	-	2011	-
	Projects operating by 2020	0	-	-	5	-

Programme		CCUS	CSP	Electricity storage	Offshore wind	Smart grids
United States American Reinvestment and Recovery Act	Budget (billion USD)	3.37	5.8*	0.14	-	0.42
	Projects	10	5	12	-	16
	Commissioning of first project	2013	2013	2011	-	2010
	Projects operating by 2020	3	5	11	-	16

* Loan guarantees.

Note: CCUS = carbon capture, utilisation and storage; CSP = concentrating solar power.

Sources: US DoE (2020a; 2020d); Herzog (2016); EC (2018); Government of Canada (2014).

Certain combinations of scale and complexity presented significant risks to projects aiming to spend capital quickly and mobilise employment in the value chain. Challenges included:

- Spending the money quickly enough. CO_2 storage facilities can take several years to develop from scratch, leaving no room for delays in order to meet the legal timeline for spending capital quickly. But competitive mechanisms take time to implement, respond to and evaluate, and the US Department of Energy needed to hire new people after its civilian energy budget tripled in a year. Delays also arose from permitting processes and social concerns that had not previously been tested, as well as from technical issues.
- Attracting co-financing alongside government funds at a time of economic difficulty, especially where the new technology was not a core business activity for the lead sponsors.
- Adapting to an uncertain market environment, including falling CO_2 prices and stalled regulation, within inflexible grant funding rules. Project sponsors sought certainty that new assets worth hundreds of millions of dollars would run for many years, not just the short time horizons of grants.
- Co-ordinating entirely new value chains involving firms from sectors with different appetites for risk.

Project failures can cause setbacks for a whole technology field if they lead to that field becoming associated with ineffectiveness, high costs or immaturity, or for other reasons. In much of Europe, for example, efforts to quickly deploy large CCUS projects became linked to concerns about the sustainability of fossil fuels.

Learning from prior experiences suggests that factors that favour success include:

- Plugging into existing infrastructure, such as electricity networks, fuel supply or CO_2 pipelines.
- Being the simplest and cheapest configurations to address technical or regulatory knowledge gaps.
- Being at or beyond the front-end engineering design stage at the time of award.
- Having dependable sales of output under existing market or bilateral offtake contract conditions.
- Having funding flexibility that can manage limited cost or time overruns.

Today, governments appear to be better equipped to implement a green stimulus package as a result of increased public awareness and improved national and international frameworks for climate policy (Kröger et al., 2020). In addition, some of the lessons set out above have already been learned, including in the design of the forthcoming EU Innovation Fund, while others, such as the relative effectiveness of grants and tax credits compared with loans, have been documented by the relevant agencies (Aldy, 2013).

Invest strategically and ambitiously to reshape the economy towards net-zero emissions in the period to 2030

The sheer scale of the stimulus packages under discussion is striking. The US measures passed so far amount to USD 2 trillion, which in real terms is almost exactly the total sum authorised for the 2008 US Emergency Economic Stabilization Act and the Recovery Act in the midst of the 2007-08 financial crisis. Measures totalling around USD 850 billion have meanwhile been proposed for the European Union, but not yet approved. These two packages alone represent more than double annual capital spending on all energy assets worldwide each year. So far, governments have announced measures worth about USD 9 trillion (IEA, 2020b). By comparison, the total amounts of money that could underpin a leap forward in clean energy innovation outcomes are relatively modest. Large demonstration projects cost in the order of USD 0.5 billion to USD 2 billion each. Furthermore, not all costs need be borne by taxpayers: with anticipated declines in capital costs, co-investment by the private sector could represent a significant share of total clean energy innovation spending if public spending is combined with loans, loan guarantees and measures that provide more revenue certainty.

Investing in a strategic portfolio of R&D, demonstration and infrastructure projects today could put the world on a pathway for net-zero emissions. It could also secure new areas of industrial leadership for first-mover economies and prevent a recovery that locks in high-carbon growth. In particular, there is a once-in-a-generation opportunity to unlock emissions for long-lived assets by avoiding a new investment cycle in high-emissions infrastructure occurring just at the wrong time (Box 5.2). Making cost-competitive low-carbon technologies available earlier substantially reduces the future costs of early retirements and disruptive refurbishments in order to meet the net-zero emissions goal. It also saves CO_2: the Reduced Innovation Case showed that there could be an additional 1.5 Gt of CO_2 emissions by 2040 if hydrogen demonstration projects are delayed by the Covid-19 pandemic (see Chapter 4). It is vital, however, that such a portfolio prioritises promising solutions for sectors where technologies for deep decarbonisation are lagging behind and capital for major demonstration projects is especially hard to raise. Clean energy innovation spending would also create jobs in science and engineering as well as construction supply chains.

Prioritise, track and adjust

- Review R&D funding and other energy innovation measures in the light of long-term goals. Many determinants of the effectiveness of public innovation policies are embedded in their frameworks and institutional processes, and relate to factors such as eligibility criteria, performance evaluation, progress tracking, dissemination of results, flexibility of funding instruments, intellectual property rights enforcement and competition law. New funding from stimulus funds could represent an opportunity to implement reforms, taking account of goals for the future and lessons from the past.
- Update clean energy technology prioritisation processes to take account of new developments, including the possibility of long-term structural and behavioural changes triggered by Covid-19.

Raise public R&D and market-led private innovation

- Where budgets allow, increase innovation funding for priority clean energy value chains that have been identified as having particular long-term strategic importance. While near-term actions to repair damaged innovation systems might concentrate on ensuring that the demonstration and early adoption stages continue to function, these longer term policies should be more focused on boosting the pipeline of new ideas reaching prototype stage. Technology areas that deserve more R&D attention than they currently receive include advanced battery chemistries, direct air capture (DAC) designs, algae-based biofuels, electrification of heavy industrial processes such as iron ore electrolysis, electric aircraft designs and connected appliances for buildings energy control.

- Look for the areas to focus on that are most appropriate for the post-crisis economy. If the global economy becomes more averse to putting large sums of capital at risk, this will strengthen the case for supporting smaller unit size, modular technologies. The appropriate support mechanism and potential contribution from private sector finance will depend on maturity, potential to scale-up quickly and ability to benefit from cross-sectoral synergies with other technologies.

Build enabling infrastructure

- Allocate capital resources to bring forward the planning and operation of important large-scale first-of-a-kind demonstration projects and field trials with end-users, while ensuring that the market will support investment in a follow-on wave of projects if these projects are successful. Examples of technologies that are critical to net-zero emissions targets but face challenges scaling-up include hydrogen-based synthetic fuels, CCUS for hydrogen production, cement kilns, or steelmaking, and hydrogen-based steel production.

Work globally for regional success

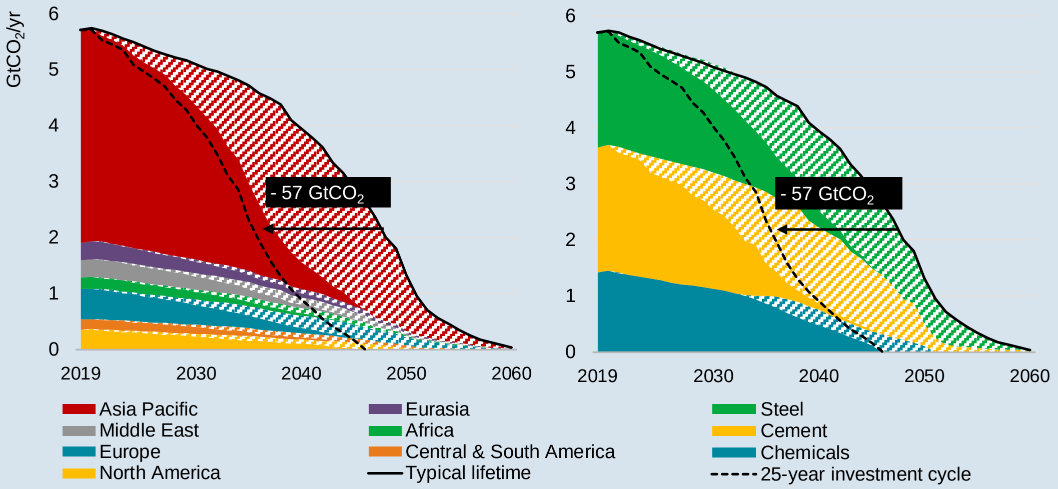
- Deepen international dialogue on common missions and funds, especially for high-cost, high-reward technology programmes that may be hard to finance at a national level in the current economic climate. New low-carbon processes in heavy industry, DAC, BECCS (bioenergy with carbon capture and storage), international low-emissions shipping, and aviation and offshore CO_2 storage all have strong global public good qualities. Many of them are "footloose", i.e. they can easily relocate, or are expected to be situated in jurisdictions outside the regulatory regimes of their customers.
- Participate in international dialogue on the timing of creation of additional, larger niche markets. This could help avoid gaps between programmes and corresponding disruption in global supply chains.

Box 5.2 The once-in-a-generation investment opportunity

For some sectors, 2050 is just one investment cycle away. In others, the next new capital assets might reasonably be expected to still be operating in 2070, the date of net-zero emissions in the Sustainable Development Scenario. This means that the timing of investments and the availability of clean energy solutions at the right time is of critical importance. If innovation timelines can be aligned with net-zero emissions objectives, then this will unlock multi-billion dollar markets for new energy technologies and avoid the risk of billions of tonnes of "locked in" emissions.

In the Sustainable Development Scenario, new low-carbon technologies are adopted rapidly once they are mature enough for early adoption. They enter the market as new capacity is needed or existing equipment either reaches the end of its lifetime or is retired earlier if needed. This leaves little room for manoeuvre, especially in heavy industry. In the cement, chemicals, and iron and steel sectors, today's lack of commercial low-carbon options means that technologies currently at the prototype or demonstration stage are starting to be deployed widely before 2030. This is because, despite most steel and cement plants being young and not reaching the end of their 40-year design lifetimes until 2045-55, they will face major refurbishment decisions in the next 10-18 years, which could lock in another 25 years of similar emissions if the same technologies are renewed. By changing the production technology to one compatible for deep decarbonisation after 25 years rather than 40 years, their owners reduce the cumulative projected emissions from the steel, cement and chemicals sectors by nearly 60 $GtCO_2$, or 38%, by 2070. Due to the size of the fleets and ages of the plants, these reductions would mostly occur in China and other Asian countries.

Avoiding "lock in" of CO_2 emission at the next investment point in heavy industrial sectors in the Sustainable Development Scenario



Notes: Typical lifetimes for steel, cement and chemicals assets are 40 years and 30 years respectively. In the "25-year investment cycle" case considered here, all assets are replaced by or converted to low-carbon alternatives at the first 25-year refurbishment point after the new technologies are assumed to be commercially available.

Intervening at the end of the next 25-year investment cycle could avoid "lock in" of nearly 60 $GtCO_2$, or 38% of projected emissions from existing equipment in the steel, cement and chemicals industries.

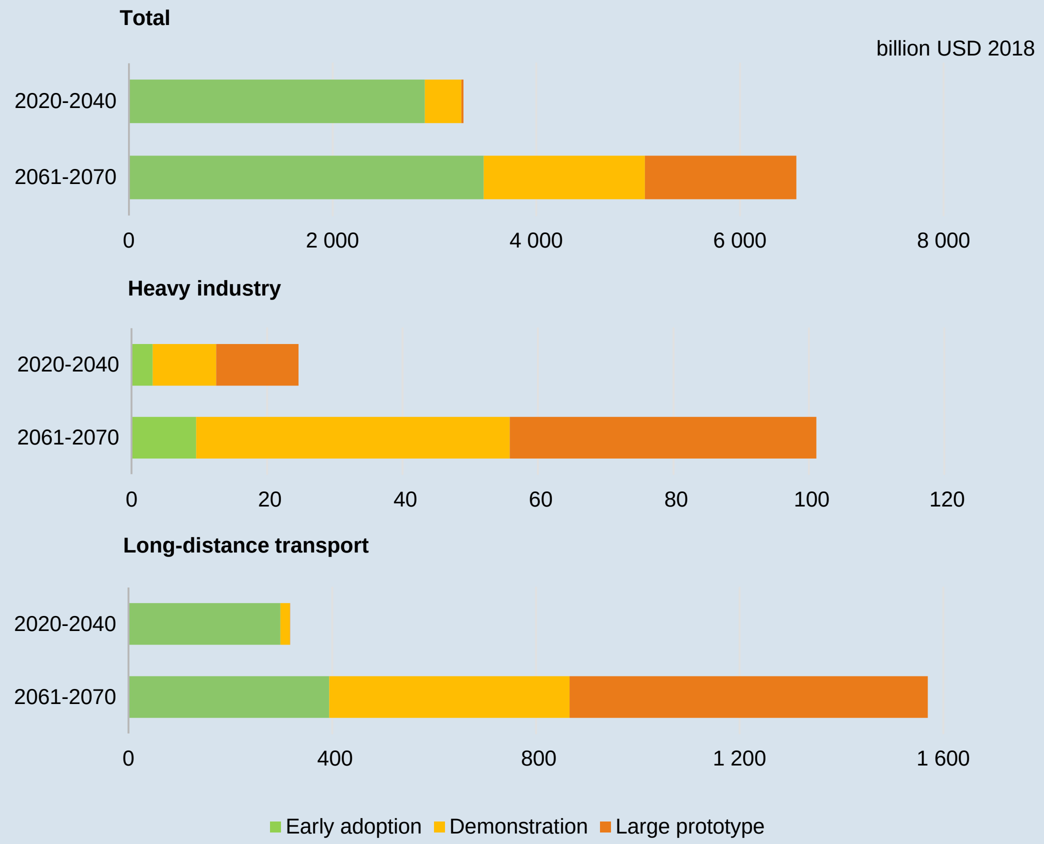
2028-35 is the earliest that most technologies for net-zero emissions in these sectors could reach the early adoption stage. For example, demonstration trials of hydrogen-based direct reduced iron for steelmaking are scheduled to run from 2025 until 2035 (Hybrit, 2020). Not keeping to this timetable for this and other pilot and demonstration projects would mean many plants in the cement, chemicals, and iron and steel sectors would lose the opportunity to switch to low-carbon technologies at the refurbishment point in their investment cycles: this would entail higher emissions, and higher costs later on from a combination of early retirements and more disruptive refurbishments or replacements part way through the lifetimes of operating plants.

Recovery packages present a major opportunity to invest in the near term in projects that help ensure that these technologies will be available in line with the Sustainable Development Scenario – an opportunity that may not recur. Recovery packages could support the series of commercial-scale demonstration projects (each with a declining level of public support) that are generally needed to give the market confidence in a new technology. Funds could also make capital available for adapting equipment that reaches its 25-year investment decision before 2028 so that it is compatible with retrofit of the new technology, a strategy that is mostly relevant to European and North American plants. In the specific case of hydrogen-based direct reduced iron, conversion of blast furnaces to direct reduced iron processes that can handle hydrogen could be undertaken as a preparatory step. Early conversion plans to adapt an existing blast furnace to this process in parallel to the trials in the first demonstration plant have already been announced (SSAB, 2020).

This opportunity is most evident in heavy industry – a higher share of investment in heavy industry goes to the deployment of technologies that are not commercially available today than to transport, buildings or power generation – but is not limited to it. We estimate that operating existing energy infrastructure until the end of its lifetime would lead to nearly 800 Gt of CO_2 emissions between now and 2070. While 150 Gt of this is from heavy industry, more is from the power sector, where 33% of the installed coal-fired capacity is under 10 years old. Technologies for retrofitting power plants with CCUS, and decarbonising long-distance transport need to be readily available to avoid a new investment cycle occurring just at the wrong time.

If these low-carbon technologies are successfully commercialised and supported by early markets, then they could open the way to enormous new commercial opportunities. Annual investments in technologies that are at prototype or demonstration stages today reach around USD 350 billion per year on average between 2020 and 2040 in the Sustainable Development Scenario. They increase to USD 3 trillion across all sectors by the 2060s, by when the market size for technologies of this maturity in heavy industry reaches almost USD 100 billion per year.

Average annual investment in technologies that are today at pre-commercial or early adoption stages by maturity level in the Sustainable Development Scenario



Note: Annual investments displayed here exclude those related to mature technologies.

Investments in technologies that are today at demonstration or large prototype stage become important investment opportunities in the Sustainable Development Scenario, particularly in sectors with less readily-scalable low-carbon options today, such as heavy industry and long-distance transport.

Tailoring the package to the needs of technology families

It is critically important for a transition to net-zero emissions that all energy end-users have affordable clean energy solutions available to them in line with the timetables set out in the Sustainable Development Scenario, or sooner if possible. At a global level, the portfolio of technologies to be refined and developed is a broad one, and represents a much more diverse set of technology types than the energy system has previously had to manage. It includes a growing number of smaller scale, decentralised devices on the supply side of the equation together with more flexible technologies on the demand side to integrate new fuels. These can be grouped in technology families spanning different low-carbon value chains (Figure 5.3). It also includes technologies that sit outside traditional energy networks, such as BECCS and DAC, that will have an important future role because of their ability to offset CO_2 emissions. Different technologies will be suited to different roles in economic recovery measures related to clean energy innovation.

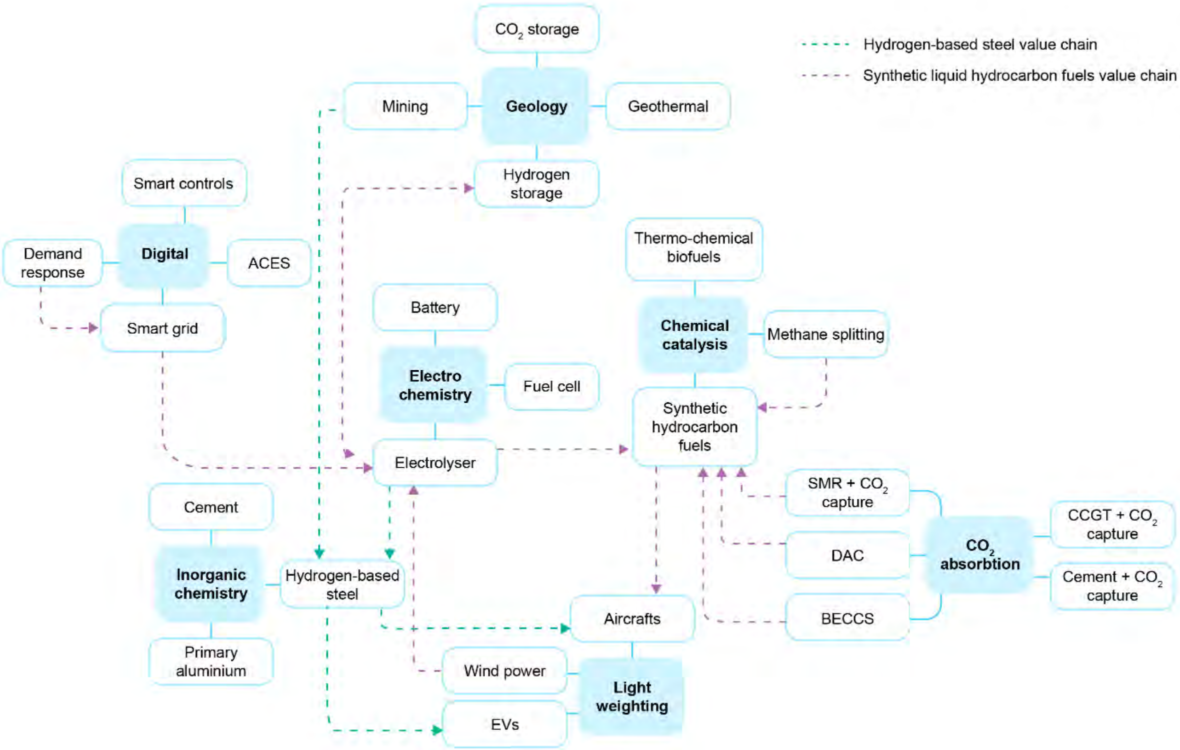
This section regroups the policy measures in the previous section by families of key technologies based on similar technology attributes. Within each of these families, knowledge and application spillovers hold significant potential to accelerate innovation if linkages are exploited: against this background, the section provides some concrete suggestions for action for each family of technologies to help policy makers to integrate tailored approaches for priority technology areas into overall strategies.

Technology families:

1. Electrochemistry: modular cells for converting between electricity and chemicals.
2. CO_2 capture: processes to separate CO_2 from industrial and power sector emissions or the air.
3. Heating and cooling: efficient and flexible designs for electrification.
4. Catalysis: more efficient industrial processes for converting biomass and CO_2 to products.
5. Lightweighting: lighter materials and their integration in wind energy and vehicles.
6. Digital: integration of data and communication to make energy systems flexible and efficient.

The list above is not intended to be exhaustive, but covers the types of solutions that hold the most promise for advancing value chains involving electrification, hydrogen and hydrogen-based fuels, CCUS and bioenergy. Among the other technologies that all have important roles to play in achieving net-zero emissions are large, scientifically complex technologies such as nuclear, including small modular nuclear reactors, and small-scale, consumer-led technologies such as flexible or buildings-integrated solar PV or high-efficiency motors. In between these extremes lie geological technologies to enhance geothermal energy, hydrogen storage or CO_2 storage, as well as such high-potential areas as ocean energy, prefabricated net-zero energy building envelopes, and thermal and mechanical energy storage.

Figure 5.3 Selected technology families and their footprint in low-carbon value chains



Note: DAC = direct air capture; BECCS = bioenergy with carbon capture and storage; ACES = automated, connected, electric and shared vehicles; EV = electric vehicles; SMR = steam methane reforming; CCGT = combined cycle power plant.

Low-carbon technology families span different value chains.

1. Electrochemistry: Modular cells for converting between electricity and chemicals

- Example technology types: batteries, electrolysers, fuel cells, electrochemical iron reduction.
- Relevant types of value chains for this family: electrification, hydrogen and synthetic hydrogen-based synthetic fuels.
- Relevant sectors where reducing emissions is hardest: iron and steel, chemicals, long-distance transport.
- Summary: action is needed to maintain the significant recent investor momentum in these areas and invest in a cleaner economic recovery by accelerating the scale-up of manufacturing and innovation for new markets.

- Key attributes:

Unit size[34]	Modularity	Value chain complexity	Value chain maturity	Consumer added value
• 50 kW to 20 MW	• Very high	• Low	• Low (e.g. hydrogen infrastructure and steelmaking prototypes) to • High (e.g. battery applications)	• Low (e.g. electrolysers) to • Medium (home battery storage, fuel cell-based micro combined heat and power)

- Policy recommendations specific to this family:

	Keep innovation on track	Invest to reshape the future
Prioritise, track and adjust	• Review priorities to focus on key net-zero emissions priorities. • Commission studies on the industrial and R&D landscape for these technologies, and local skills and capacity gaps.	• Identify R&D priorities for the next decade. • Support spillovers by creating research networks, exchanges and joint programmes. • Incorporate other applications of electrochemistry into R&D programmes, such as iron ore reduction and CO_2 reduction.
Raise public R&D and market-led private innovation	• Maintain R&D budgets and convene publicly funded researchers to exchange findings from the latest projects. • Support viable innovative start-ups and small and medium-sized enterprises to overcome liquidity challenges. • Embed conditions and decarbonisation targets in any support provided to companies in heavy industry, shipping, aviation, and oil and gas. • Consider loans to weakened large industrial companies in relevant sectors to maintain their R&D budgets and orient them firmly to electrification and hydrogen.	• Significantly increase public R&D funding for novel battery chemistries that are beyond the immediate focus of corporations and venture capital investors, including solid state, lithium-air and long-duration storage concepts. • Support researcher exchanges between firms, countries and laboratories working on different applications. • Fund open access demonstrators (e.g. for testing configurations of fuel cells with high capture rates for CO_2 capture, including with direct air capture). • Support the development and upgrade of end-use equipment able to handle higher hydrogen blending shares.

[34] Unit size is provided for the different technology families in energy units that refer to energy throughput capacity for all technologies, which could include electricity, fuels or thermal energy.

	Keep innovation on track	Invest to reshape the future
Address all the links in the value chain	• Financial support to manufacturers to continue scale-up. Support the development of automated manufacturing processes for electrolysers and fuel cells. • Implement vehicle turnover schemes to accelerate EV adoption, including plug-in hybrid. • Public procurement of low-carbon gases and municipal vehicles such as fuel cell goods vehicles or electric garbage trucks.	• Set a vision for the role of national innovation in future value chains for these technologies by sector. • Establish standards and targets for deployment in sector to create successive niche markets. • Ensure timely investments that protect supply chains for critical materials (lithium, platinum, etc.) for electrochemical device manufacturing as it expands. • Support the development of automated manufacturing processes for electrolysers and fuel cells.
Build enabling infrastructure	• Support deployment of batteries in grids. • Fund or incentivise the modification of gas networks to be ready to accept hydrogen. Expand EV charging and hydrogen refuelling.	• Establish field trials to test the performance of batteries and electrolysers in different electricity market contexts.
Work globally for regional success	• Accelerate efforts to harmonise standards, regulation and certification across borders. • Work regionally to ensure that purchase incentives in different jurisdictions reinforce market creation, increasing policy efficiency under budgetary pressure. • Explore international financing options to keep emerging market R&D and scale-up on track.	• Build on existing multilateral platforms to enhance knowledge sharing between countries and sectors.

2. CO_2 capture: Processes to separate CO_2 from industrial and power sector emissions or the air

- Example technology types: natural gas reforming with CO_2 capture, chemical absorption from fossil fuel flue gas, direct air capture, chemical absorption from cement emissions, process reconfigurations to raise CO_2 concentrations, novel capture approaches.
- Relevant types of value chains for this group: CCUS, hydrogen, electrification and bioenergy via CCUS-equipped plants.
- Relevant sectors where reducing emissions is hardest: cement, iron and steel, chemicals, long-distance transport via hydrogen or offsets.

- Summary: act to keep projects on track wherever local conditions give them a high chance of success and raise industrial and investor expectations about future regulation of emissions.
- Key attributes:

Unit size	Modularity	Value chain complexity	Value chain maturity	Consumer added value
• 50 MW to 500 MW • (15 kW for solid DAC)	• Low • (though some DAC fuel cell options are more modular)	• High (CCUS) • Medium (DAC)	• Low (dedicated CO_2 storage) to • Medium (enhanced oil recovery with long-term monitoring)	• Low

- Policy recommendations specific to this family:

	Keep innovation on track	Invest to reshape the future
Prioritise, track and adjust	• Commission studies on the industrial and R&D landscape for these technologies, and On local skills and capacity gaps.	• Identify R&D priorities for the next decade. • Support spillovers by creating research networks, exchanges and joint programmes.
Raise public R&D and market-led private innovation	• Maintain R&D budgets and convene publicly funded researchers to exchange findings from the latest projects. • Support viable innovative start-ups and SMEs to overcome liquidity challenges. • Embed conditions and decarbonisation targets in any support provided to companies in heavy industry, aviation or shipping. • Consider loans to weakened large industrial companies in relevant energy, industrial and transport sectors to maintain their R&D budgets and orient them firmly to commercial-scale CCUS, including DAC.	• Increase public R&D spending on novel techniques for CO_2 capture, especially modular approaches and those with very high capture rates. • Aim to enhance climate policies including carbon pricing systems, and expand their sectoral coverage, ensuring that they incentivise CO_2 removal via BECCS and DAC.

	Keep innovation on track	Invest to reshape the future
Address all the links in the value chain	• Public procurement of low-carbon hydrogen, low-carbon building materials and bioethanol from plants equipped with CCUS.	• Set a vision for the role of local innovation in future value chains for CO_2 capture in industry and synthetic fuels by sector. • Ensure that CO_2 capture from bioenergy and DAC are not laggards in the synthetic fuels value chain. • Establish standards and targets for deployment of low-carbon products and fuels in sectors (i.e. low-carbon fuel standards) to create successive niche markets.
Build enabling infrastructure	• Consider plugging arising financing gaps for large-scale projects that risk delay or failure, and adjusting regulatory deadlines or addressing value chain risks if they threaten viability. • Extend funding to existing efforts to explore and commission CO_2 storage facilities, and step up detailed studies of CO_2 storage options near all relevant industrial facilities and of CO_2 transport infrastructure. • Modify gas networks to be ready to accept hydrogen.	• Invest to bring new CO_2 storage facilities and pipelines to market near industrial clusters. • Provide operational support (tradable credits, tax credits, contract-for-difference) to projects that are ready to operate large-scale CO_2 capture plants in key sectors for net-zero emissions including bioenergy. • Provide capital support for DAC scale-up.
Work globally for regional success	• Work regionally to reduce the market risk of delays to CO_2 storage availability, for example, via co-ordinated storage sites in the North Sea. • Establish international "missions" and prizes for CO_2 capture that recognise it as a global public good challenge.	• Build on existing multilateral platforms to enhance knowledge sharing between countries and sectors. • Reinforce efforts to develop international markets for low-carbon products that align differential emissions pricing regimes. • Co-operate on international DAC projects in emerging market locations with suitable energy resources and CO_2 storage potential.

3. Catalysis: More efficient industrial processes for converting biomass and CO_2 to products

- Example technology types: methanation, methane splitting, liquid fuel synthesis, polysaccharide hydrolysis, algae processing, chemical hydrogen storage, bio-based and CO_2-based bulk chemicals, ammonia cracking, artificial photosynthesis.
- Relevant types of value chains for this family: bioenergy, chemicals, hydrogen-based synthetic fuels.
- Relevant sectors where reducing emissions is hardest: long-distance transport; high-temperature industrial processes.
- Summary: intensify efforts to find breakthroughs and direct the tremendous R&D capacities of the chemical and biotech sectors towards net-zero emissions challenges.
- Key attributes:

Unit size	Modularity	Value chain complexity	Value chain maturity	Consumer added value
• 50 MW to 100 MW	• Medium	• High (dependence on uncertain developments both upstream and downstream)	• Low (CO_2-based products and fuels) to • Medium (advanced biofuels)	• Low to Medium

- Policy recommendations specific to this family:

	Keep innovation on track	Invest to reshape the future
Prioritise, track and adjust	• Commission studies on the industrial and R&D landscape for these technologies, and on local skills and capacity gaps. • Communicate the importance and profitability of energy-related R&D challenges compared with those of other sectors competing for biotech talent.	• Identify R&D priorities for the next decade in collaboration with the chemical catalysis and biotechnology expert communities. • Support spillovers by creating research networks, exchanges and joint programmes.

	Keep innovation on track	Invest to reshape the future
Raise public R&D and market-led private innovation	• Maintain R&D budgets, support graduates and convene publicly funded researchers across sectors to exchange findings from latest projects relevant to CO_2 and energy. Consider funding cross-sectoral exchange of research personnel. • Support viable innovative start-ups and SMEs to overcome liquidity challenges. • Embed conditions and decarbonisation targets in any direct support provided to companies in fuel supply and transport sectors.	• Increase public R&D spending for energy at centres of excellence in chemical and biochemical catalysis with strong industrial links. • Establish inducement prizes for catalysis performance for key challenges, for example in CO_2 reduction, methane cracking or cellulose hydrolysis. • Establish standards and targets for deployment of low-carbon liquids (sustainable biofuels and synthetic hydrogen-based fuels) in fuel supply and low-carbon gases (including biomethane, hydrogen and synthetic methane) in gas networks to support niche markets.
Address all the links in the value chain	• Retain existing successful policies to ensure demand for sustainable biofuels to support existing production facilities during the current period of low oil prices and reduced mobility. • Look for efficiencies and synergies between projects under development for CO_2 capture, electrolysis and synthetic fuels production (including ammonia) to manage higher value chain risk.	• Ensure that slow CO_2 capture from bioenergy and DAC development do not impede progress in synthetic fuels deployment. • Support new demonstrations of ammonia use as a power generation fuel and hydrogen storage medium.
Build enabling infrastructure	• Consider plugging arising financing gaps for construction of advanced biofuel facilities that risk delay or failure.	• Fund test facilities to trial competing options for methane cracking, ammonia cracking, algal biofuels and others and publicise the results.
Work globally for regional success	• Establish international "missions" and prizes for key innovation gaps that recognise them as a global public good challenge. • Support knowledge exchange programmes between researchers and start-ups working in different countries on similar technology problems.	• Build on existing multilateral platforms to enhance knowledge sharing between countries and sectors. • Reinforce efforts to develop international markets for low-carbon fuels and gases that align differential certification and emissions pricing regimes. • Ensure that R&D for sustainable biofuels is focused on the types of feedstocks that have the most significant availability and therefore ability to contribute to net-zero emissions.

4. Heating and cooling: Efficient and flexible designs for electrification

- Example technology types: heat pumps, high-efficiency air conditioning, advanced refrigerant-cooling, district heating and cooling, thermal energy storage.
- Relevant types of value chains for this family: electrification, digital.
- Relevant sectors where reducing emissions is hardest: buildings, industry.
- Summary: stimulate R&D and spillovers to deliver more efficient and flexible designs that are adaptable to a wider range of applications, services (including flexibility) and climate conditions.
- Key attributes:

Unit size	Modularity	Value chain complexity	Value chain maturity	Consumer added value
• 1 kW to 5 MW	• High (except district energy)	• Low	• High	• Medium to High

- Policy recommendations specific to this family:

	Keep innovation on track	Invest to reshape the future
Prioritise, track and adjust	• Commission studies on the industrial and R&D landscape for these technologies, and on local skills and capacity gaps.	• Identify R&D priorities for the next decade. • Support spillovers by creating research networks, exchanges and joint programmes.
Raise public R&D funding and market-led private innovation	• Maintain R&D budgets and convene publicly funded researchers to exchange findings from latest projects. • Consider loans to weakened large industrial companies in relevant sectors to maintain their R&D budgets and orient them firmly to improved energy efficiency. • Embed conditions for building renovation in any support for deployment of efficient heating and cooling equipment. • Establish or reinforce product labelling and performance standards to stimulate market adoption.	• Increase public R&D spending on next-generation components, membrane-based evaporative cooling and desiccants, solid-state cooling technologies and compact, integrated heating, cooling, ventilation and thermal storage solutions, including products dedicated to fossil fuel boiler substitution. • Set long-term expectations for equipment performance standards and make available concessional loans or other forms of capital for scale-up or conversion of manufacturing for appliances with efficiency and performance that are beyond the regulatory frontier.

	Keep innovation on track	Invest to reshape the future
Address all the links in the value chain	• Support deployment of smart controls and business models so that households, district energy network operators and industries could provide flexibility services to facilitate grid integration of variable renewables through demand-side response and thermal storage.	• Fund purchase incentives for integrated designs, such as PV, heat pumps and storage.
Build enabling infrastructure	• Upgrade existing district heating networks to improve performance and include alternative low-carbon energy sources. • Support pilot projects to test new regulations and business models for third-party access to district heat and cooling networks.	• Establish standards and targets for super-efficient district energy networks deployment to create successive niche markets. • Fund field trials of heat pump and air conditioning operation in response to demand-response incentives.
Work globally for regional success	• Accelerate efforts to harmonise standards, regulation and certification across borders. • Work regionally to ensure that purchase incentives in different jurisdictions reinforce market creation, increasing policy efficiency under budgetary pressure. • Establish or reinforce international "missions" and prizes for super efficiency space heating and cooling that recognise it as a global public good challenge.	• Build on existing multilateral platforms to enhance knowledge sharing between countries and sectors. • Explore harmonisation of standards and public procurement between neighbouring countries in similar climatic regions. • Instigate improved testing procedures and, potentially, smart meter data, to reflect actual-use operating conditions and to close the gap between stated and real performance of equipment.

5. Lightweighting: Composite materials and their integration in wind energy and vehicles

- Example technology types and materials: carbon fibre reinforced polymer, 3D printing.
- Relevant types of value chains for this family: electrification, hydrogen and hydrogen-based fuels, and bioenergy (via more manageable costs of reduced fuel loads).
- Relevant sectors where reducing emissions is hardest: long-distance transport, energy-intensive sectors (via lower cost wind energy).
- Summary: act to support R&D and foster spillovers across multiple applications to reduce costs and improve competitiveness along different value chains.

- Key attributes:

Unit size	Modularity	Value chain complexity	Value chain maturity	Consumer added value
• Any	• Not applicable	• Low	• High	• Medium

- Policy recommendations specific to this family:

	Keep innovation on track	Invest to reshape the future
Prioritise, track and adjust	• Commission studies on the industrial and R&D landscape for these technologies, and on local skills and capacity gaps.	• Identify R&D priorities for next decade. • Support spillovers by creating research networks, exchanges and joint programmes for actors relevant to different applications of lightweight materials.
Raise public R&D funding and market-led private innovation	• Maintain R&D budgets and convene publicly funded researchers to exchange findings from latest projects. • Embed conditions and decarbonisation targets in any direct support measures for companies in road transport. • Maintain fuel economy standards in road transport and signal strengthened fuel standards for road transport and aviation.	• Increase public R&D spending on novel precursors and alternative carbon fibre production processes, and rapid cure, automated processes for the conversion of carbon fibre into carbon fibre reinforced polymers and advanced recycling processes.
Address all the links in the value chain	• Support exchanges and joint programmes that connect research on electric vehicle designs by manufacturers or wind turbine designs by manufacturers, on the one hand, with R&D to improve material performance by material producers on the other.	• Set a vision for the role of local innovation in future value chains for these technologies by sector including reductions in the CO_2 intensity of carbon fibre reinforced polymer production and recycling and other end-of-life management strategies. • Establish standards and targets that incentivise lightweighting in different sectors to create successive niche markets.
Build enabling infrastructure	• Expand of electric vehicles charging and hydrogen refuelling to support electrification of transport. • Expand of transmission networks that can connect distant offshore wind turbines and incentivise lightweighting of blades.	• Consider investments in new facilities and communication infrastructure for 3D printing as supportive of future lightweighting innovation. • Explore development of carbon fibre recycling networks, including collection, separation and processing facilities.
Work globally for regional success	• Accelerate efforts to harmonise standards, regulation and certification across borders.	• Build on existing multilateral platforms to enhance knowledge sharing between countries and sectors.

6. Digital: Integration of data and communications to make energy systems flexible and efficient

- Example technology types: sensors for energy efficiency monitoring, baselining and billing; smart home systems; emissions auditing; big data, machine learning and artificial intelligence for: processing for mobility and logistics management, smart charging, smart management of district heat systems, etc.; distributed ledgers and blockchain; smart contracts; distributed grid management.
- Relevant types of value chains for this family: electrification.
- Relevant sectors where reducing emissions is hardest: buildings, industry, long-distance transport.
- Summary: steer the exponential growth in digital capabilities and creativity towards energy system challenges that can engage energy users and seamlessly connect them with markets.
- Key attributes:

Unit size	Modularity	Value chain complexity	Value chain maturity	Consumer added value
• 1 mW to 10 kW	• High	• Medium	• Low to Medium	• High

- Policy recommendations specific to this family:

	Keep innovation on track	Invest to reshape the future
Prioritise, track and adjust	• Commission studies on the opportunities for these technologies, and on local skills and capacity gaps. • Communicate the importance and profitability of energy-related R&D challenges compared with those of other sectors competing for digital talent. • Convene leaders in machine learning and artificial intelligence (in automated vehicles, for example) to create roadmaps for key energy innovation gaps.	• Invest in technology tracking capabilities so policy makers and regulators can stay informed about the latest progress in data gathering and processing.

	Keep innovation on track	Invest to reshape the future
Raise public R&D and market-led private innovation	• Maintain R&D budgets for enabling hardware such as sensors and power grid controls, and support graduates with valuable skills to remain in the sector. • Support viable innovative start-ups and SMEs to overcome liquidity challenges. • Assist regulated utilities to trial promising new digital technologies for network and market management, for example via regulatory sandboxes and innovation funds.	• Establish inducement prizes for challenges that are under the radars of digital companies and researchers, such as decentralised grid control; distributed ledgers for mini-grids connected to larger grids; energy service contract performance and securitisation; demand response; emissions pricing and trading; and fuel carbon intensity accounting.
Address all the links in the value chain	• Advance electricity market improvements to enable more locational and time-based price signals.	• Identify gaps between physical performance and digital technology potential and, where appropriate, incentivise owners of assets to upgrade physical equipment such as power engineering equipment. • Advance market mechanisms that incentivise innovation in areas such as carbon intensity certification for fuels and demand response.
Build enabling infrastructure	• Ensure that energy efficiency and energy network investments made as part of stimulus measures incorporate forward-looking digital equipment, such as sensors and high bandwidth communication.	• Invest in the infrastructure to enable large open access demonstrators for public and private researchers of innovative smart hardware and software to run controlled trials enabling published comparisons of competing solutions. Smart charging, mobility, grid management, smart homes and distributed markets would all be appropriate applications. • Implement a multi-year plan for raising investment in enabling digital infrastructure for electricity, gas and heat networks. • Create incentives for regulated entities to rapidly test innovative solutions that could save money for consumers in the long run.

	Keep innovation on track	Invest to reshape the future
Work regional for local success	• Support knowledge exchange programmes between researchers and start-ups working in different countries on similar technology problems.	• Establish networks of demonstrators that enable like-for-like comparisons of performance in different sectors. • Build on existing multilateral platforms to enhance knowledge sharing between countries and sectors. • Reinforce efforts to develop international markets for low-carbon fuels and gases that align differential certification and emissions pricing regimes. • Co-ordinate work on open access protocols, standards and solutions for remote off-grid markets in developing regions.

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Annexes

Acronyms and abbreviations

ARPA-E	Advanced Research Projects Agency – Energy
AUD	Australian dollar
BECCS	bioenergy with carbon capture and storage
BICS	Bloomberg Industrial Classification System
CAD	Canadian dollar
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
CO_2	carbon dioxide
CCGTs	combined-cycle gas turbines
CFRP	carbon fibre-reinforced plastics
DAC	direct air capture
EOR	enhanced oil recovery
ESA	electro-swing adsorption
ETP	Energy Technology Policies
EU	European Union
EUR	euro
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FIC	Faster Innovation Case
GBP	British pound sterling
GDP	gross domestic product
H_2	hydrogen
ICT	information and communication technologies
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISIC	International Standard Industrial Classification
LED	light-emitting diode
Li-air	lithium-air
Li-ion	lithium-ion
Li-S	lithium-sulphur
LPG	liquid petroleum gas
NACE	Statistical Classification of Economic Activities in the European Community
NASA	National Aeronautics and Space Administration (United States)
OECD	Organisation for Economic Co-operation and Development
PEM	polymer electrolyte membrane
PV	photovoltaic
R&D	research and development

RD&D	research, development and deployment
SDG	Sustainable Development Goal
SDS	Sustainable Development Scenario
SME	small and medium-sized enterprise
STARC-ABL	single-aisle turboelectric aircraft with an aft boundary-layer propulsor
STEPS	Stated Policies Scenario
S&T	science and technology
TRL	technology readiness level
US	United States
USD	United States dollar
US DoE	United States Department of Energy
VC	venture capital

Units of measure

GJ	gigajoule
GJ/t	gigajoule per tonne
Gt	gigatonne
$GtCO_2$	gigatonnes of carbon dioxide
GW	gigawatt
GWh	gigawatt hours
GWh/yr	gigawatt hours per year
kt	metric kiloton
kW	kilowatt
Mt	megatonne
Mt	million tonnes
Mt/yr	million tonnes per year
$MtCO_2$	million tonnes of carbon dioxide
$MtCO_2$/yr	million tonnes of carbon dioxide per year
Mtoe	million tonnes of oil equivalent
MW	megawatt
MWh	megawatt-hour
tCO_2	tonne of carbon dioxide
TW	terawatt
TWh	terawatt-hour
USD/kg	United States dollar per kilogramme
W	watt
Wh/kg	watt-hour per kilogramme

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Typeset in France by IEA - July 2020
Cover design: IEA
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