Technology Innovation to Accelerate Energy Transitions

June
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Abstract

Japan's G20 presidency 2019 asked the International Energy Agency to analyse progress in G20 countries towards technology innovation to accelerate energy transitions. The Japan presidency, which began on 1 December 2018 and runs through 30 November 2019, has placed a strong focus on innovation, business and finance.[1] In the areas of energy and the environment, Japan wishes to create a "virtuous cycle between the environment and growth", which is the core theme of the G20 Ministerial Meeting on Energy Transitions and Global Environment for Sustainable Growth in Karuizawa, Japan, 15-16 June 2019.

A first draft report was presented to the 2nd meeting of the G20 Energy Transitions Working Group (ETWG), held through 18-19 April 2019. This final report incorporates feedback and comments submitted during April by the G20 membership and was shared with the ETWG members.

This final report is cited in "Proposed Documents for the Japanese Presidency of the G20" that was distributed to the G20 energy ministers, who convened in Karuizawa on 15-16 June 2019.

This report, prepared as an input for the 2019 G20 ministerial meeting, is an IEA contribution; it is not submitted for formal approval by energy ministers, nor does it reflect the G20 membership's national or collective views. The report sets out around 100 "innovation gaps", that is, key innovation needs in each energy technology area that require additional efforts, including through global collaboration.

[1] For an overview of the vision and priorities of the G20 Japan presidency, see www.japan.go.jp/g20japan/.

High-level recommendations for G20 priority action

IEA innovation analysis, including in this report, sheds light on key priority actions to accelerate energy technology innovation in the context of the G20. Key recommendations are as follows:

- **Rigorous tracking of public- and private-sector investment on energy technology innovation is vital** to better identify gaps and opportunities to enhance the efficiency of resource allocation. Measurement of progress in clean energy innovation needs to go beyond the flow of investment to also focus on performance indicators.
- **Cost reduction is the priority.** The main goal of innovation is to enable low-carbon technologies to become widespread and self-sustaining so that their expansion can continue without direct government financial support. In this way, innovation will contribute to accelerate the scale-up of low-carbon technology, irrespective of fossil fuel price volatility and independent of climate policy agreements.
- **The active engagement of the private sector is critical.** Mobilising the innovation capacity of the private sector is of prime importance. Traditionally, public-supported research provides a vital source of knowledge and discovery, and the private sector is crucial for bringing new technologies into the market. Businesses, entrepreneurs and investors are best suited to identify, evaluate and support the most promising ideas for commercialisation and to turn innovations into products and companies. Flexible, market-based policy measures that incentivise the private sector to search for the most efficient solutions among businesses and entrepreneurs are needed.
- **Innovation requires a multidisciplinary, portfolio approach.** The most attractive new solutions may be found at the interface of different areas, such as between the energy and digital sectors. As innovation can be an uncertain process, innovation policy frameworks need to ensure that effort is balanced between potentially competing approaches and include public investment in basic research as well as robust intellectual property rules. Flexibility in innovation policy design is also important: the portfolio of low-carbon technologies may change as technology progress and transition pathways evolve. Continuous monitoring and adjustments will be needed.
- **Innovation is broader than technology research and development (R&D).** Innovation should cover the complete technology life cycle. Increased R&D investments are important but, in isolation, will not bring needed results. Technology innovation focuses on pre-commercial improvements to technology performance and costs but can also include improvements to commercial technologies – all of which must be aligned with a broader market deployment strategy.
- **Innovation is also broader than innovation policy.** Framework conditions that include tax regimes, market designs, regulations or technology standards as well as ancillary policy measures such as climate and environmental policy or product safety, can be strong policy determinants of innovation.

- **Innovation challenges span borders.** In addition to efforts at national level, international collaboration can be an essential enabler of accelerated progress. In particular, governments working together to increase cross-border and public-private collaboration can use a range of mechanisms, including Technology Collaboration Programmes (TCPs), Mission Innovation (MI), Innovation Accelerators and Regional Centers.
- **A wide range of sectors and technologies need to contribute.** The sectors with the least innovation progress toward decarbonisation are those where policy incentives and long-term perspectives are lacking. This includes heavy industry as well as freight transportation and aviation. It may be necessary for governments to both make some direct investments and leverage incentives of the private sector to accelerate the development of better technologies, thereby reducing the cost of pursuing long-term policy objectives.
- **Some industries require global, sector-specific understandings.** The aviation, shipping, iron and steel, and chemical and petrochemical sectors, and to some degree cement, cannot be solely transformed through one government's national policies alone due to their global nature. For such sectors, global collaboration, standard-setting and and/or agreements for deployment of innovative technology solutions can be indispensable.
- **The needs of both developed and emerging economies need to be considered.** Historically, innovation for low-carbon technology has been driven mostly by industrialised economies. However, a large amount of future growth in energy consumption will come from emerging economies, which have different economic, technology and geographical contexts. Energy services and technology performance needs are often different in these developing economies. An enhanced focus will thus be important going forward for innovative solutions that meet the needs and contexts of developing countries. Examples include clean cooking solutions and decentralised off-grid technologies for providing electricity access.
- **The interlinkages between Sustainable Development Goal 7 (SDG 7)[2] and other goals need to be exploited.** SDG 7 is closely interlinked with other goals such as poverty eradication, food security, water, education, health, gender, environment, climate change and economic growth. Innovation can be a key enabler of all of these goals. While SDG 9 includes a specific focus on innovation (build resilient infrastructure, promote inclusive and sustainable industrialisation, and foster innovation), clean energy technology innovation can play an essential role in achieving many other goals if interlinkages among goals are fully understood.

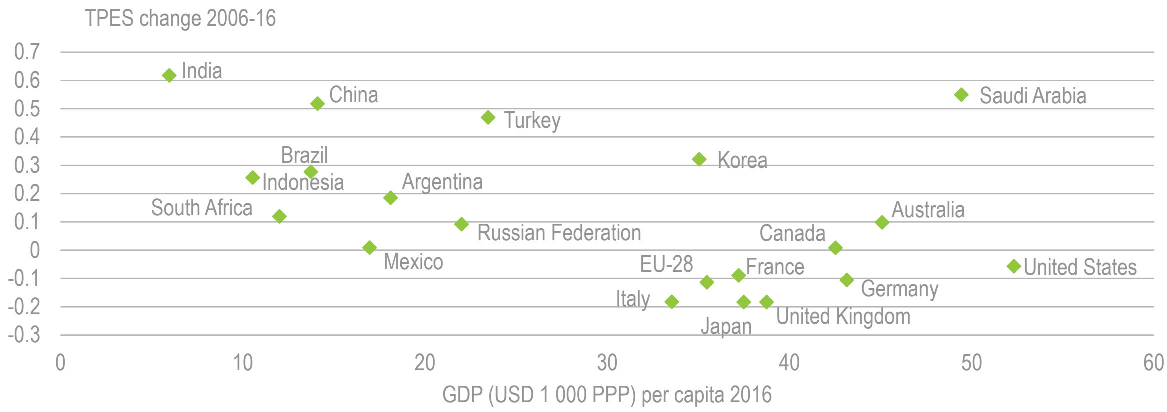
[2] This analysis draws also from a Policy Brief developed by the IEA with the United Nations Industrial Development Organization (UNIDO), the International Renewable Energy Agency (IRENA), and the United Nations Environment Programme (UN Environment) to support SDG 7 review at the United Nations (UN) High-Level Political Forum in July 2018.

1. Innovation is critical for meeting long-term policy goals

The G20 in the changing energy landscape

Today, G20 members account for 87% of the global economy, 75% of world trade and nearly two-thirds of the global population. In 2016, G20 countries collectively were responsible for 81% of energy-related carbon dioxide (CO_2) emissions and 78% of global energy consumption. Energy pathway changes in this group of countries have a significant impact global energy markets and technologies. Annual growth in total primary energy supply (TPES) during 2006-16 illustrates that gross domestic product (GDP) has been the driver for energy demand growth in half of the G20 countries in the Middle East, Asia, Latin America and the Pacific. TPES growth in European Union (EU) countries, the United States (US) and Canada has declined owing to greater energy efficiency and structural changes to their economies.

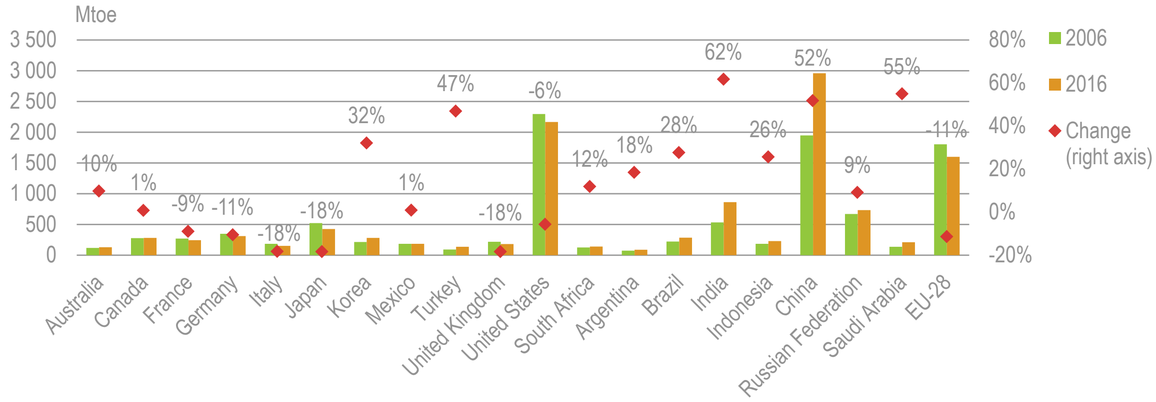
Figure 1. TPES change 2006-16 by GDP per capita



Note: China = People's Republic of China ("China"); EU-28 = the 28 member countries of the European Union; PPP = purchasing power parity.

Source: IEA (2019), *World Energy Balances 2019*, www.iea.org/statistics.

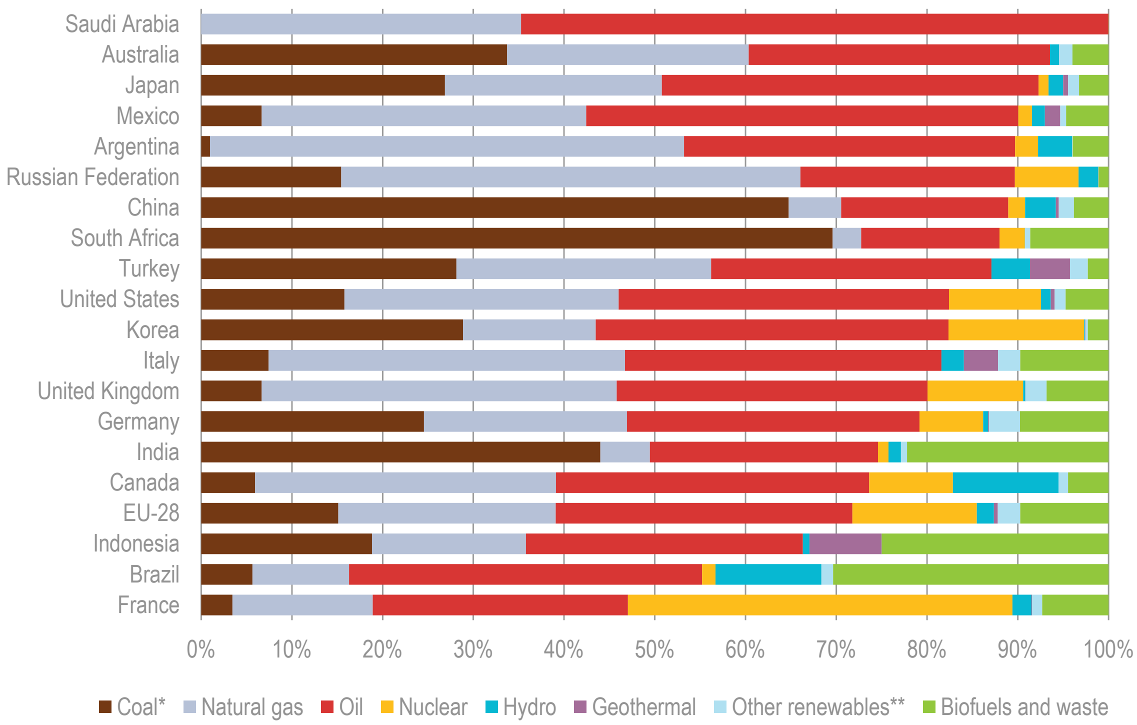
Figure 2. TPES by country, 2006 and 2016



Note: Mtoe = million tonnes of oil equivalent.
Source: IEA (2019), *World Energy Balances 2019*, www.iea.org/statistics.

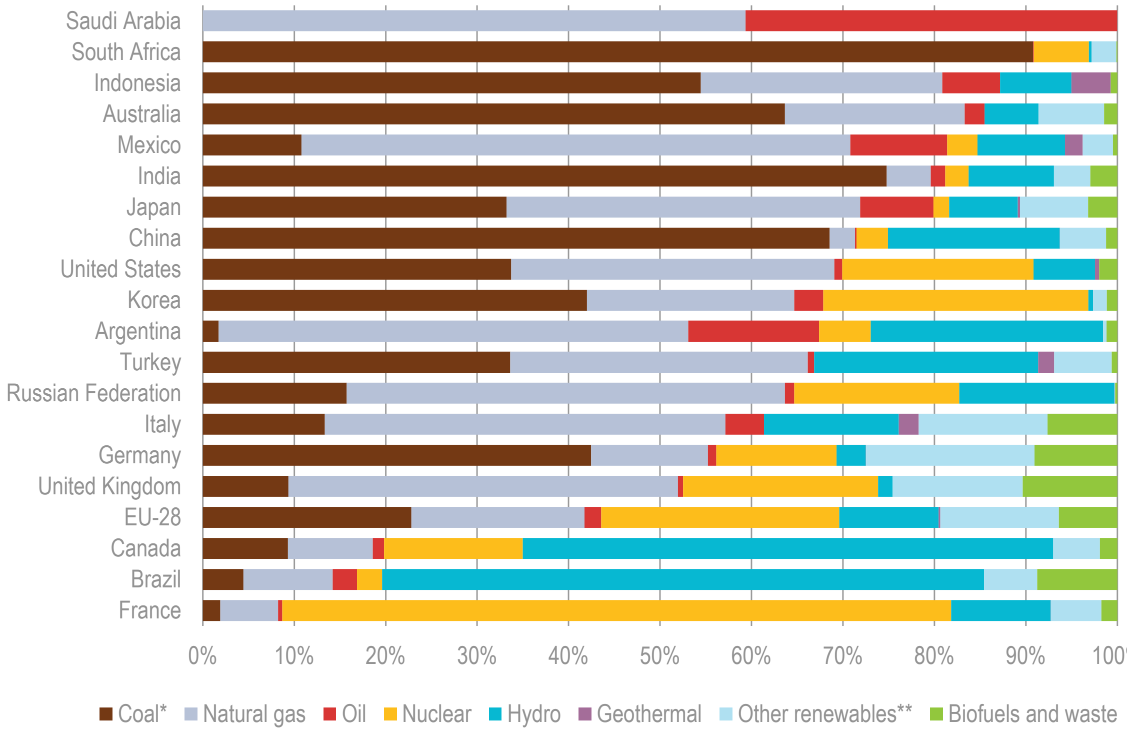
The G20 collectively relies on a high share of fossil fuels in its total energy supply. Coal remains the largest energy source for electricity generation, accounting for 43%, while oil products dominate G20 final energy consumption (39%). Energy supply has increased across all fuels in the last decade, notably new renewables in power generation.

Figure 3. TPES by fuel, 2016



**Coal* also includes shares of peat and oil shale.
***Other renewables* includes wind and solar.
Note: Does not include electricity imports and exports.
Source: IEA (2019), *World Energy Balances 2019*, www.iea.org/statistics.

Figure 4. Electricity generation by fuel, 2016



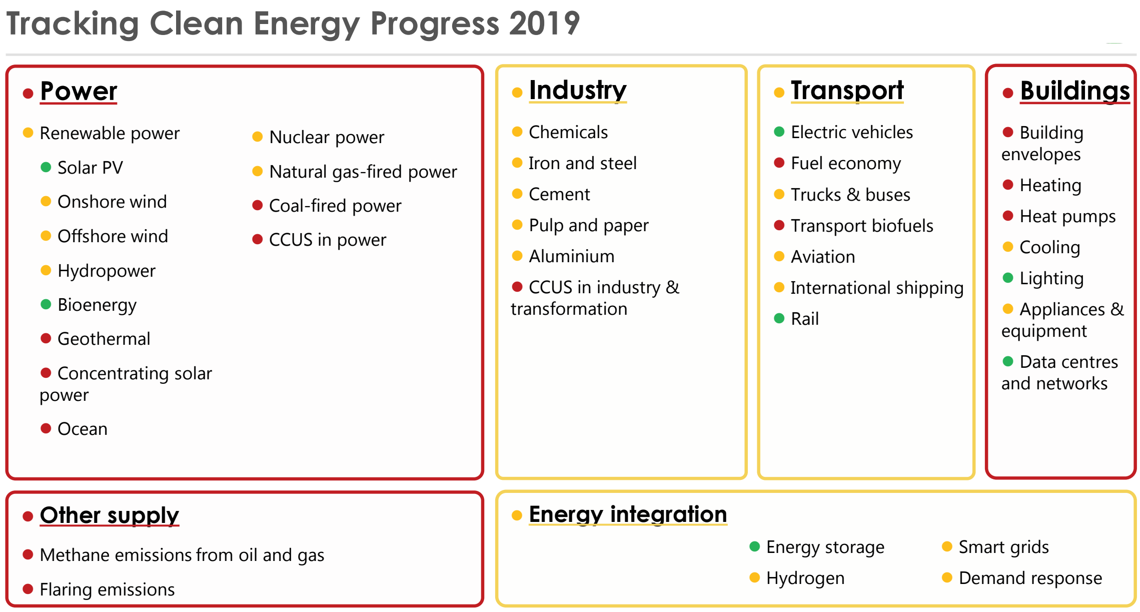
**Coal* also includes shares of peat and oil shale.

***Other renewables* includes wind and solar.

Source: IEA (2019), *World Energy Balances 2019*, www.iea.org/statistics.

Energy technology progress has not been consistent across sectors, with lagging progress in many sectors and technologies that are critical for effective global energy transitions. The online IEA publication, *Tracking Clean Energy Progress* (*TCEP*), assesses policy, investment, deployment and innovation progress in 43 sectors and technologies, rating them green if on track with the transition, yellow if further efforts are needed and red if fully not on track (Figure 5).

Figure 5. Tracking Clean Energy Progress, 2019



Note: CCS = carbon capture and storage.
Source: IEA 2019. All rights reserved.

These and further trends can be fully explored through the IEA tracking portal (www.iea.org/tracking).

Innovation as an engine of the future

Innovation is central to putting the world onto a sustainable energy path. It creates value in the economy by improving existing processes and generating new ways of meeting the needs of the different actors. Within the context of achieving long-term policy goals, technology innovation augments the portfolio of options available and the potential strategies to meet those goals; over time, it brings down the costs of achieving them. Technology innovation does not evolve in a vacuum: the structure of the market, public support for entrepreneurship, and direct government investment all influence how rapidly new technologies emerge and are adopted. This is as true for energy as it is for other sectors of the economy.

Technological innovation is often described as a linear process comprising four main stages: research, development, demonstration and deployment. While technology innovation does often occur rather slowly through incremental adjustments, this linear approach oversimplifies the relationships among these stages. Innovation in the real world is more complex; few technologies follow a seamless transition from one step to the next, and this model fails to capture many realities that can occur in the process. For instance, even once a technology is very successful in one country context, it may be unfit for purpose or even inadequate in all market settings and may require very early-stage attention in parallel with subsidy-free deployment elsewhere. As we continue to gain a better understanding of how innovation works, the tools available to policy makers to accelerate its benefits also increase.

Innovation in the energy sector tends to have particularly slow rates, reflecting the fact that technologies tend to be large, complex and built to last for many years. But disruptions do occur, particularly under strong pressure from geopolitical (e.g. the 1973 oil embargo), political (e.g. targets for rapid renewable energy deployment), structural (e.g. demographic tipping points) or social factors (e.g. a consensus to retire nuclear plants). Solar photovoltaics (PV), electric mobility, energy storage, and particularly the pervasive adoption of information and communication technologies (IEA, 2017) are among the disruptions on the current horizon. These trends have been supported by the pervasive impact of innovation, which has expanded the range of options, improved performance and reduced costs in key technology areas.

Policies to drive technology innovation

The efficiency and robustness of a country's innovation system can greatly accelerate or hinder technology progress. The recommendations below highlight what constitutes a well-functioning R&D policy framework. They are the product of the IEA's long-standing expertise reviewing energy policies of member countries and beyond, accumulated through the country reviews programme since 1974, at a rate of six per year.

Demand-pull measures accelerate innovation by setting the boundary conditions for innovations to reach a path to market. Wherever energy and environmental policies and regulations are well aligned with other policies that push for the development of technologies from the early stage, step changes have been made to industrial production and consumer behaviour, bringing about strong environmental benefits.

More fundamentally, governments have an important enabling role when it comes to setting the adequate framework for energy research, development and demonstration (RD&D) and innovation along the value chain of research, development and demonstration and commercialisation. International experience shows the growing trend to merge energy RD&D into a broader innovation effort. Several G20 countries have adopted innovation frameworks.

The United States, the United Kingdom and Nordic countries have very strong energy RD&D policy frameworks thanks to a combination of fiscal incentives (tax credits, grants or others), market-based instruments, or budgetary allocations to national research institutes and laboratories that compete for public funding. The United States has been able to attract and develop a world-class system of national laboratories which attract significant human capital and foster the country's innovative capacity. The United Kingdom has adopted a strong policy framework based on so-called sector deals (nuclear sector deal, offshore wind industry deal, among others). These deals bring together the government and the industry stakeholders towards a common vision for the sector and pool a shared commitment from private and public funding to reach scale and cost reductions on critical low-carbon technologies. Under its national climate change policy strategy, India has adopted mission-based policies with several national missions dedicated to the scaling up of technology opportunities and innovation. India has worked on the National Mission for Enhanced Energy Efficiency (2009), the National Solar Mission (2010), the National Electric Mobility Mission (2012), the National Smart Grid Mission (2015) and the National Mission on Advanced Ultra Super Critical Technology (2017).

Fiscal incentives are an important element in North America, notably in the United States and in Canada. The 2018 US budget bill extended renewable tax credits and credits for energy efficiency, nuclear and fuel cells, as well as expanded incentives to companies that can use captured CO_2 and reduce emissions under the so-called "45Q" tax credit for storing CO_2 permanently underground from USD 22 today to USD 50 in 2026. It is an example of how relatively small policy incentives can tip the scales towards investment when the infrastructure and industrial conditions are already in place, as the United States is leveraging an existing market and pipeline network for enhanced oil recovery.

Government also make increasing use of market-based mechanisms to support commercialisation and technology innovation, including through the critical role of public procurement. For instance, India's Unnat Jyoti by Affordable LEDs for ALL (UJALA) programme has radically pushed down the price of light-emitting diodes (LEDs) available in the market and helped to create local manufacturing jobs to meet the demand for energy-efficient lighting. The public procurement company, Energy Efficiency Services Limited (EESL), has helped replace over 350 million lamps with LEDs resulting in annual savings of 45.5 terawatt-hours. The success of this procurement model is being replicated across different product categories. Equally, competitive tenders for renewable energy deployment enabled cost reductions and innovation in wind and solar power, and the design of the auction is very important to also reward technology innovation.

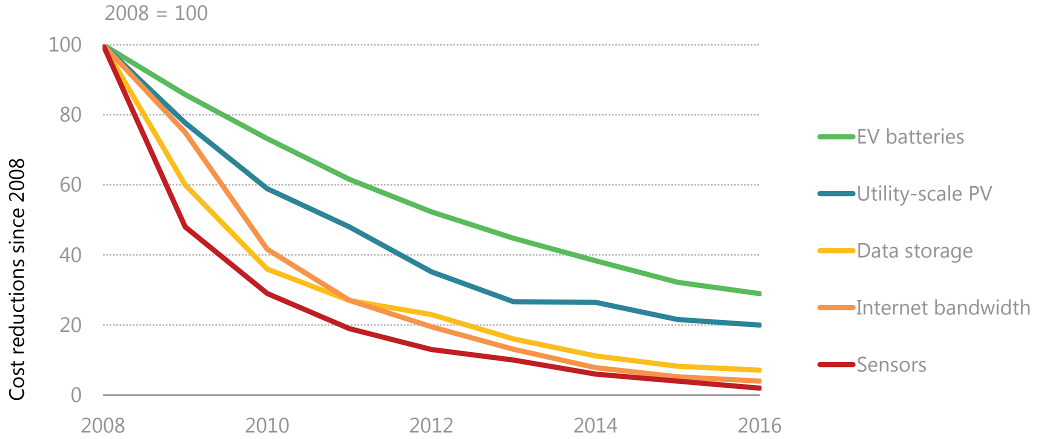
International experience suggests the importance of a strong energy RD&D component as part of an innovation ecosystem in order to ensure consistency, continuity and results over time. To best support such an energy component under an overarching innovation framework, governments need to:

- Ensure a coherent strategy for energy RD&D with clear priorities, aligned to and in support of long-term policy goals.
- Dedicate stable funding and policy support, including a legal framework for intellectual property rights, product standards, etc., co-ordinated within the government and other stakeholders.
- Maintain a strong engagement with industry to leverage private funding and engagement.
- Monitor, track and evaluate the results over time to adjust priorities and ensure value for money and cost-efficient outcomes and avoid technology lock-in or picking winners/losers.
- Make best use of complementary capabilities in research and technology by collaborating internationally on priority areas, leveraging global experience for national RD&D development.

The way the energy sector innovates is changing

Innovation in emerging areas such as digitalisation and distributed energy is very different from traditional, capital-intensive hardware innovation. New technologies for software and digital-based products have shorter innovation cycles and can be brought to the market quicker. They require less investment and fewer consumables, and they can be prototyped more quickly and tested in a variety of environments simultaneously. They also do not need costly manufacturing facilities or value chains to be deployed. The result can be a lower unit cost of innovation, which is especially valuable where digital solutions can directly solve problems that would otherwise have required a physical alternative. But it also changes the nature of competition. It becomes vital that products be brought to the market quickly to reduce the risk that competitors acquire market share first.

Figure 6. Speed of cost reductions in key energy sector technologies, against those in the digital sector



Note: EV = electric vehicle.

Source: Based on BNEF (2017), *Utilities, Smart Thermostats ans the Connected Home Opportunity*; Holdowsky etal. (2015), *Inside the Internet of Things*; IEA (2017), *Renewables*; *Tracking Clean Energy Progress*; *World Energy Investment*, Navigant Research (2017), *Market Data: Demand response*. Global Capacity, Sites, Spending and Revenue Forecasts.

The energy sector is also much less siloed than in the past. The interactions among energy companies and those in other sectors are multiplying. To respond to increased technological and corporate competition in many parts of the energy system, traditional energy companies have been reorienting some of their R&D and innovation activities. This, in turn, has implications for government policy.

International collaboration is increasing. The exchange of knowledge and innovation activity has been steadily growing as evidenced by the rapid growth in patents co-invented by two or more countries (Johnstone, 2014). At the same time, private and public initiatives that pool knowledge and resources are multiplying.

Technologies beneficial for energy transitions need different, more systemic and collaborative approaches to innovation

A more systemic approach to innovation also extends beyond the technology-focused "hardware" innovation process to include analysis of actors, networks and institutions. It recognises an interactive process involving a network of firms and other economic agents (most notably users) who, together with the institutions and policies that influence their innovation and adoption behaviour and performance, bring new products, processes and forms of organisation into economic use. It needs technologies to be prototyped and tested much faster, and carried over to new markets or in new areas of application.

It includes understanding the people involved in creating and using technologies, and the social and political norms through which they interact. Many of the technologies that become widespread in the future will rely on society adapting to their specific qualities. This could include new routines for using and fuelling vehicles, more individual control over household energy provision, and new industrial practices that will require different regulatory approaches.

2. The energy technology innovation process

Energy technology innovation is an evolutionary, complex and interactive process

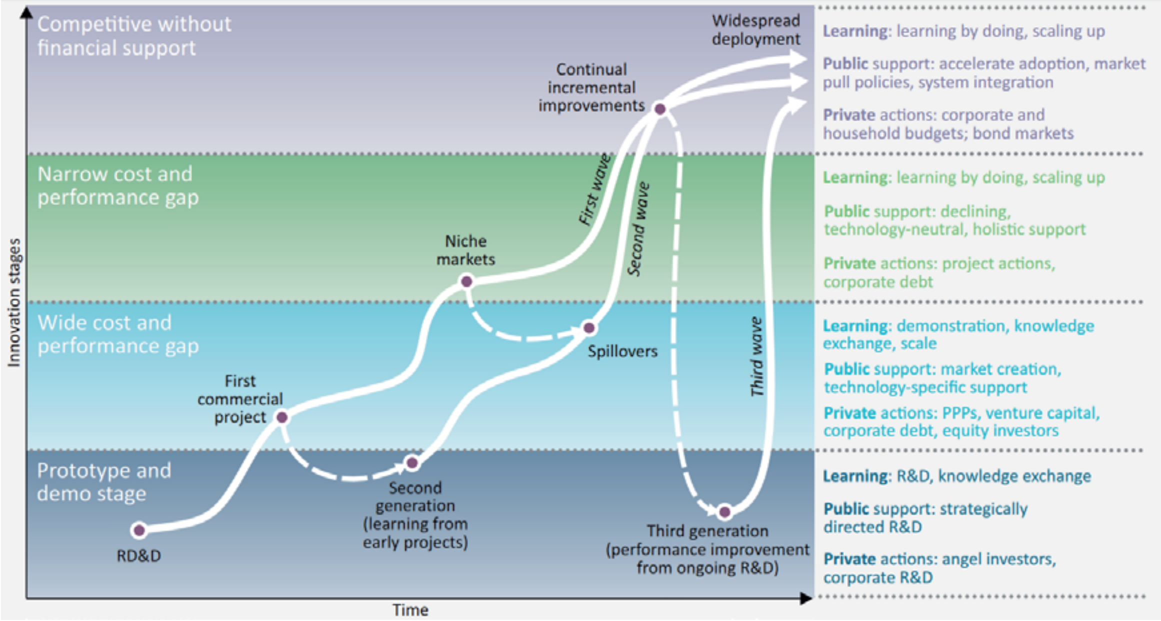
The innovation journey has strong similarities with biological evolution in the natural world. Users adopt new technologies based on how well they fit the environment in which they arise. Technologies that can adapt to the needs and resources of a greater number of users will have staying power, expanding their market share. As in the natural world, the selection environment itself is not static. Changes in related technologies, consumer behaviour, firm dynamics or policy choice can iteratively improve the value of a given technology, making it more likely to be selected. Governments can play a crucial role in shaping and influencing the marketplace for technologies. In turn, technologies can shape societies, and governments need to ensure that they support policy goals without detrimental social impacts.

This journey is different for each energy technology innovation, but can be represented in four main stages:

- prototype and demonstration
- high cost and performance gap
- low cost and performance gap
- competitive without financial support.

As technologies pass through each stage, the level of risk taken by investors is successively reduced and likewise the need for public support. However, innovation is not usually a linear progression from research to development, demonstration, deployment and, finally, diffusion. A given technology will be at different stages of the process in different markets and applications. In addition, as the development of a technology area generates new ideas for improvements, alternative configurations and potentially better components will always appear at the prototype stage even after one configuration has become competitive. Thus, the stages overlap and run concurrently, feeding on one another. Further, just as many existent technologies have built up the advantages of infrastructure, familiarity, scale economies and institutional support over decades (i.e. the environment has adapted to them), the same can happen with emerging technologies: the first versions to be selected will be hard to displace even if they have worse like-for-like performance.

Figure 7. The energy technology innovation process



Source: IEA 2019. All rights reserved.

Innovation improves the performance and reduces the costs of emerging technologies. Horizontal measures such as intellectual property frameworks, tax credits or market-based environmental measures can accelerate the process. More fundamentally, these measures need to be balanced and complemented by targeted support to technologies depending on their stage of development and the type of technology. Solutions to "gaps" in the technology development process all vary but rely on four main sources of innovation activity:

- RD&D for novel technologies and improvements to existing technologies
- learning-by-doing, the process by which engineers and other actors make incremental improvements as they get more experience with the technology
- scale-up of production, enabling economies of scale and optimised value chains
- exchange of knowledge among different stakeholders across sectors and regions.

RD&D are the processes that generate new ideas and test prototypes of novel or improved technologies. Through RD&D, brand-new technologies and variants of existing technologies become available for selection. R&D precedes demonstration and is undertaken in corporate research labs, universities, government research institutions and small firms. Demonstration is a subsequent operational step in a real-world environment at or near commercial scale to show technical and commercial viability. Demonstration projects provide information on costs and performance to manufacturers, potential buyers and policy makers.

Demonstration is associated with the prototype and demo stage of the innovation process. At this stage, investors typically face the highest risks, and the share of government support is at its highest. Once a technology is demonstrated as safe and effective in a particular real-world application, it may be selected by the marketplace and enter a cycle of learning-by-doing. However, RD&D is rarely left behind entirely, because new knowledge and needs give rise to opportunities to improve components and test them before incorporating them into the commercial version.

The role of governments in technology innovation

Financing to drive energy innovation

Investments in RD&D are unlike other energy sector investments. The resulting assets are often intangible, the returns are highly uncertain, and investments in innovation cannot easily be recovered in the market. Financers may have difficulty evaluating projects, mainly due to information failures on new players and new goods or services – especially if the only way to learn about a technology is to invest in it. Knowledge that is procured can be employed by competitors at low marginal costs. RD&D has long lead times and is often part of a collective, cumulative enterprise involving multiple organisations. Thus, finance must be willing to bear high risks, be strategic and be patient.

While finance sources such as venture capital (VC) and private equity funds are successful at identifying technologies with high medium-term value, they have not been as successful as strategic long-term investors. Financial markets can be accessed by companies for major research projects, but investment can be limited by a vicious cycle: raising finance for research on a technology cannot be justified until a clear demand arises for the product; market actors cannot generate demand for the product until the technology is proven to be effective; the technology cannot be proven without finance for research. As a result, investments in innovation can be biased towards opportunities affording short -term gains.

Governments are a vital source of long-term, patient finance. Policy instruments can be used to enable access to finance for risky projects. As a result, much innovation by the private sector builds on publicly funded programmes for early-stage, higher-risk research. Well-targeted public RD&D can "crowd in" other sources of funds in pursuit of long-term strategic missions. The commercial results of public energy RD&D investments can be dramatic. Within 20 years, China transformed itself from a technology importer into a major manufacturer and exporter of several low-carbon technologies.

The IEA tracks budget expenditures on RD&D, as well as R&D budgets of some state-owned enterprises. However, governments invest in clean energy RD&D using a more diverse variety of instruments and policies that can serve different purposes (Table 1). These instruments are most commonly employed at the level of national or subnational governments, but there is a positive trend toward more engagement of cities at one end of the scale and intergovernmental collaborations at the other. Cities can effectively support projects, such as smart city demonstrations, that are tailored to local needs, while international initiatives can fund projects that countries cannot fulfil alone.

The portfolio of public RD&D investment can also include, for example, VC and seed funding, which are not solely the territory of private finance. Finland's Sitra directs investment to over 40 funds that support start-ups solving ecological, social and well-being challenges. While it is financed from the yield on its investments, its mission to help bridge the gap between R&D and deployment for clean technologies is enshrined in legislation.

Other countries such as the United Kingdom and the United States have programmes that provide seed funding to small innovative businesses. In many countries, governments are active in public-private partnerships, loan guarantees, incubators and business networks that facilitate early-stage investment in clean energy entrepreneurship.

The appropriate combination of policy instruments and funding sources differs for different technologies and industrial partners (Table 1). Direct support for RD&D (e.g. grants, loans, tax credits) and non-RD&D support for business innovation (e.g. support for VC and assistance for starting up entrepreneurial activities) need to be balanced with targeted policies that foster demand and markets for clean energy (e.g. pricing mechanisms, public procurement, minimum energy performance standards, energy efficiency labels and mandatory targets). Any of these policies implemented alone would be less effective and more expensive.

Table 1. Innovation policy best practice calls for a broad, need-specific portfolio of support mechanisms

Funding instrument or policy	Description	Purpose
100% grants	Funding awarded to researchers in public or private institutions for projects selected by government agencies.	Address private underfunding of research and direct efforts towards government priorities.
Co-funded grants	Funding for private research projects is contingent on use of own funds by the company, ranging from 5% to over 50% of costs.	Compared with 100% grants, co-funding reduces the risk of "crowding out" and uses public funds more efficiently.
Research by state-owned enterprises	Governments can use their ownership rights to direct the level and type of research undertaken.	Support national champions that are committed to preserving the returns to RD&D within the country. Direct corporate strategy towards national interests.
Public research labs	Government can employ researchers as civil servants and establish long-term research programmes.	Provides funding and job stability for researchers working on strategic topics free from commercial pressures.
VC and seed funding	Capital, usually equity, is provided to new small enterprises in the expectation that a small proportion of the investments can be sold for a substantial profit several years later.	Government VC funds create a market for risky, commercially oriented innovation and can give a social direction to capital market-based technology selection.
Loans and loan guarantees	Public loans can bridge funding gaps for companies on the verge of profitability, enabling them to construct demonstration plants or first-of-a-kind facilities.	Public lenders can be more tolerant of risk in the pursuit of public goods, lending at lower than market rates.
Tax incentives	Lower tax rates or rebates for R&D expenditures; tax allowances; payroll tax deductions; tax refunds for not-yet profitable start-ups.	Encourage firms to undertake more RD&D in all sectors, raising skills and keeping local firms competitive.
Targeted tax incentives	Favourable tax treatment for a specific sector or type of R&D.	Stimulate more activity in a part of the innovation chain or strategically shape a sector.
Prizes	Funding awarded to winners of competitions to meet a specific technology performance target or outperform rivals.	Use the prize money (or other reward) to stimulate innovation and help policy makers of technology status at reduced public cost.

3. IEA innovation gaps

A key component of the recommendations above is the tracking of technological progress, providing in turn targeted support with a portfolio approach that spans a full set of technologies. Sound policy making in the innovation area needs to balance the long-term technology needs that will emerge, with the particular challenges of moving solutions that will meet those needs along the innovation journey. In some cases, technologies might be ready but are missing a large-scale demonstration effort; in others, only further collaboration efforts might be needed. Some areas might be more impactful in the long term, but perhaps face a very fundamental technology challenge. As such, it is often hard for policy makers to allocate innovation risk and prioritise investments in a sector as diverse as energy.

To address this need, the IEA innovation gaps project aims to track the current status and innovation needs for 100-plus key innovation gaps across the whole energy sector. Within each gap, the project addresses what the current innovation activity is as well as the level of technology readiness of solutions, current investment levels, relevant initiatives, start-ups and corporate activity, and collaborations. The gaps analysis also assesses what actions and milestones are needed in the short term and in the medium term to bring the technology solutions that address a given gap to the next level of development. The project draws on the expertise of IEA analysts in different technology areas, as well as input and review from the IEA TCPs and the broader IEA Energy Technology Network.

The aim of this project is to provide a global repository of energy R&D gaps, helping governments and companies to better set innovation priorities. The target audience include public R&D managers, energy sector policy makers, multilateral research partnerships and initiatives, private-sector innovation managers, researchers, and corporate and start-up strategists. The project aims to provide analysis of the current status and necessary actions to advance innovation in the key R&D gaps across the energy sector. The gaps analysis can assist decision makers in three ways:

- First, it helps track the global status of ongoing activities in key areas necessary for achieving sustainability objectives, allowing real-world decision makers to position their own efforts and ensuring consistency of international R&D collaborations such as MI and other collaborations at a more fundamental and operational level.
- Second, it provides actionable recommendations by a range of energy sector stakeholders across each gap, in terms of what short- and long-term milestones and actions need to be taken to take technologies that address an R&D gap to further levels of developments.
- Third, the project provides a framework to evaluate disruptive technologies: in specific technology areas, it describes the milestones that, once achieved, would enable a particular technology to make the envisaged impact in IEA scenarios.

Annex B will include all 100-plus innovation gaps to be completed by the final release of this paper in June as an input to the G20 Energy Ministerial. As a living tool on the IEA website, the innovation gaps will then also be progressively expanded both in scope and depth over time.

Each innovation gap will consist of the following items:

1. **Identification of the key global innovation gaps across 40 technology areas:** The most important technology innovation challenges that need to be overcome based on IEA scenarios and modelling.

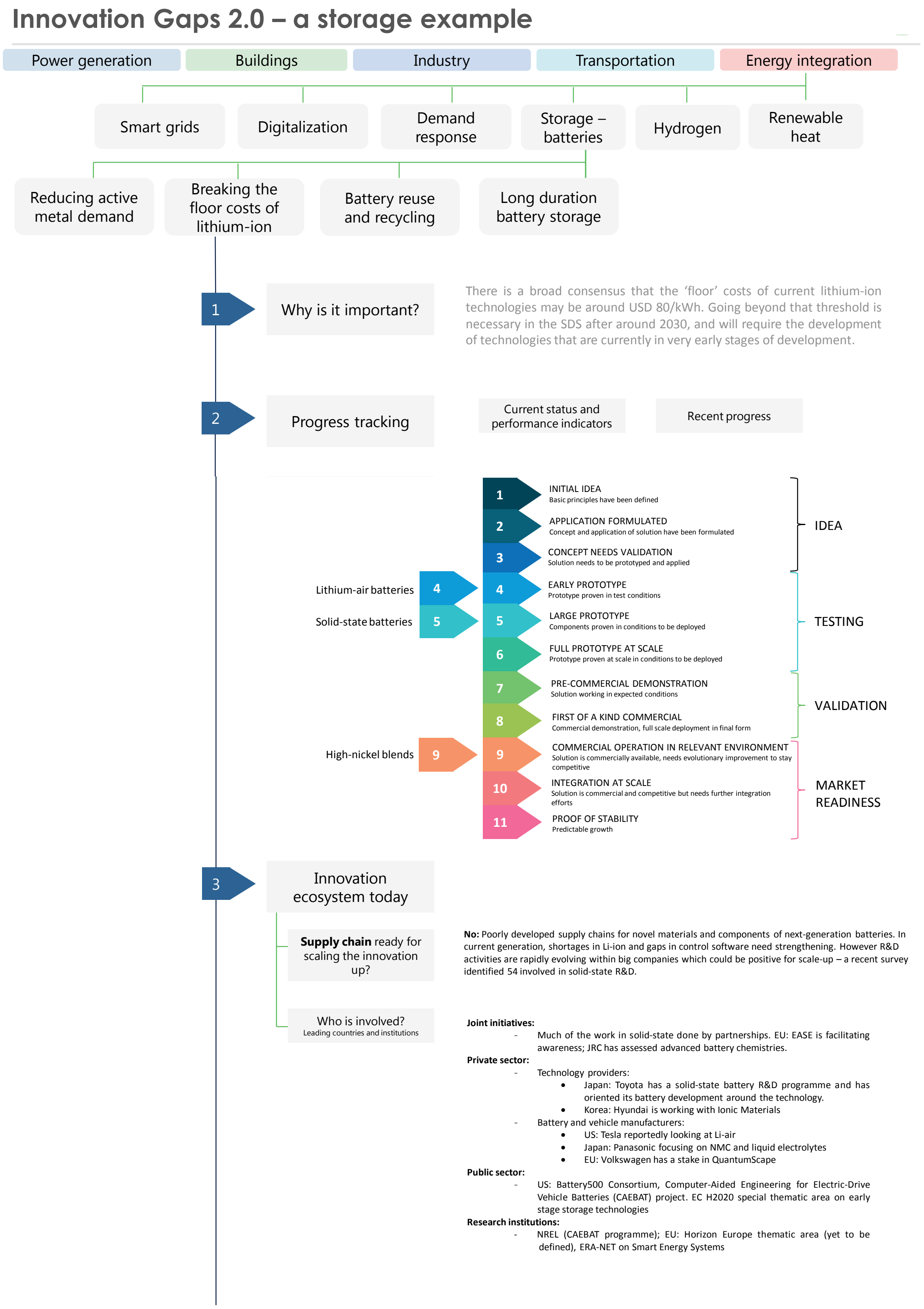
2. **A technology progress tracker:** Based on a Technology Readiness Level (TRL) indicator, it assesses at what level of development are the solutions to the gap today, from the idea/basic research stage, to different kinds of prototypes and scaling-up stages. It also assesses recent progress in the area.

3. **Mapping of innovation landscape:** For each gap, mapping who is involved in technology development, leading countries and initiatives from public/private/academia, and how they select and fund research.

4. **Key actions and milestones:** What needs to be done by each to achieve solutions by various ministries/agencies, companies, research institutes, non-governmental organisations, intergovernmental organisations (IGOs), etc.

Figure 8 shows what each gap will look like on the IEA website in June. (Box 1 includes the content from another example.)

Figure 8. Innovation gaps 2.0: Illustration of the gap approach – energy storage



Notes: kWh = kilowatt-hours; SDS = Sustainable Development Scenario.
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Box 1. An innovation gap example for hydrogen: Ammonia production with electrolytic hydrogen

Four innovation gaps are key in the chemicals sector, two of them directly related to hydrogen. This section details ammonia production from hydrogen produced via electrolysis as an example of the typical content in each IEA innovation gap.

<u>**Ammonia production with electrolytic hydrogen**</u>

Why is this innovation gap critical? Developing and deploying innovative technologies and process routes will be crucial to decarbonising the chemicals and petrochemicals sector. Key new and emerging low-carbon processes involve replacing fossil fuel feedstocks with electrolytic hydrogen, bio-based feedstocks, electricity as a feedstock and/or captured CO_2. Further development of carbon capture, utilisation and storage (CCUS) technologies will also be important for decarbonising the sector.

This process route through electrolytic hydrogen would avoid the generation of CO_2 emissions in ammonia production, if renewable electricity is used for hydrogen production.

- **How ready are the solutions today and what challenges remain**? TRL 7-8. Individual technologies for the process are available. Full system integration of the technologies needs to be completed. Key challenges associated with this gap include the procurement of low-cost electricity from renewable sources in areas where production will take place, the need for cost reductions and efficiency improvements in electrolysis technology, and the need to integrate either economic buffer storage or flexibility in the synthesis step to accommodate a variable electricity input.
- **What are the leading initiatives?** The first large-scale demonstration plant of ammonia production using solar power is under development in Pilbara, Australia. The project is a joint venture with participation from Yara Pilbara Fertilisers and ENGIE Energy Services. The plant is expected to begin operation in 2021 at the earliest.
- **Recommended actions by specific stakeholders to advance the technologies to the next TRL level:**

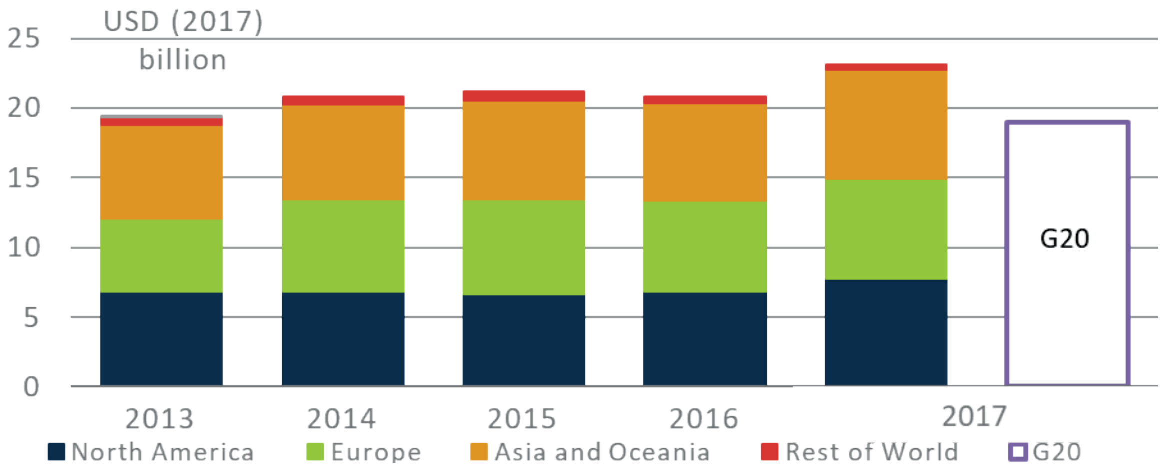
Actors (who)	**Actions** (what)	**Timeline** (when)
Industrial producers	Develop and demonstrate at commercial scale a fully integrated electrolytic hydrogen system for ammonia production.	By 2021
Industrial producers	Optimise process system integration of electrolytic hydrogen-based ammonia plants with subsequent urea synthesis.	Next 5 years
Industrial producers	Improve performance of electrolytic hydrogen production and reduce costs.	Next 5 to 10 years

Actors (who)	**Actions** (what)	**Timeline** (when)
Industrial producers	Investigate hybrid concepts with flexible operation based on both electricity and natural gas.	Next 10 years
Industrial producers	Work towards large-scale generation of hydrogen from renewable electricity.	Next 5 to 10 years
Finance/economy ministries	Collaborate with industry to help fund demonstration efforts.	Next 5 to 10 years
Environmental, energy and resource ministries	Adopt or increase the stringency of policies that promote renewable electricity generation.	Next 5 years
Environmental, energy and resource ministries	Support development of hydrogen production infrastructure.	Next 5 to 10 years
Environmental, energy and resource ministries	Set medium- to long-term reduction targets in the carbon intensity of ammonia production, to encourage development of low-carbon ammonia production technologies.	Next 5 to 10 years

4. Global trends of energy investment and innovation funding

The IEA tracks annual investment in technology innovation activity in its *World Energy Investment* and *TCEP* analyses. In 2017, global R&D spending in energy reached around USD 115 billion – an increase of 2.5% in real terms. More than three-quarters of this spending came from the private sector. Overall, there is a clear but sluggish trend towards higher spending on low-carbon energy R&D across the public and private sources of funding that are tracked. While public R&D on energy technologies in total grew at an average rate of only 2% per year over the five years to 2017, it jumped by 8% last year. The general trend in the private sector is also upwards, though at a slower rate. On a sectoral basis, growth is concentrated in the transport sector, where technologies related to electrification of vehicles, powertrains and related products are seeing the biggest increases in spending. Among the leading economies, Japan remains the largest spender on energy R&D, as measured by the share of GDP, ahead of the People's Republic of China (hereafter, "China") and Europe. In absolute terms, the United States spends more on energy R&D than any other country. These and further trends can be explored through the IEA innovation portal, www.iea.org/innovation

Figure 9. Energy R&D expenditure in the public sector



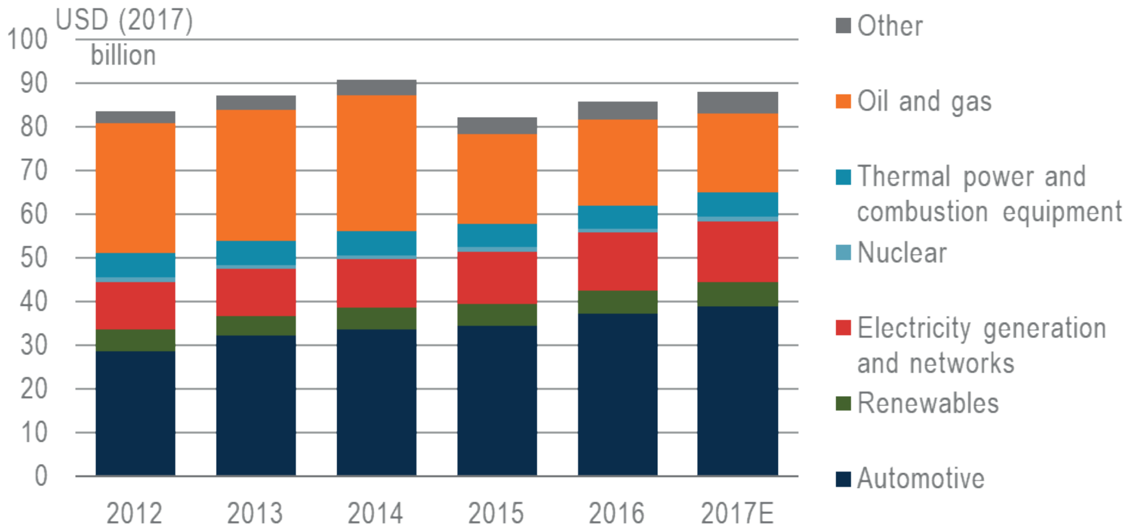
Source: IEA 2019. All rights reserved.

Energy RD&D has been essential in providing today's technology options, especially in renewables and nuclear, and its importance will increase as societies strive to achieve affordable, secure and sustainable energy systems into the future. Global investment in clean energy RD&D is estimated to be at least USD 26 billion, but it is not yet rising enough to be on track for a sustainable energy transition. Despite favourable progress in wind and solar energy, energy storage, and electric cars, broad-based energy innovation must be part of the energy transition. Innovation potential is high for heavy-duty transport, industrial energy use and seasonal electricity storage.

Reported RD&D spending on clean energy by IEA member governments doubled between 2000 and 2010 to around USD 15 billion – around 0.15% of their total budget expenses. This growth represents a fourfold increase if nuclear is excluded. Aggregated data from MI submissions and national budgets and reports show that clean energy RD&D expenditure by non-IEA G20 economies was around USD 4.5 billion in 2015, putting G20 public funding at USD 19 billion. This includes spending by major state-owned enterprises, which is a dominant source of publicly funded clean-energy RD&D in China.

The private sector as a whole spends much larger amounts on innovation in energy – albeit focusing in different stages of the innovation process, and emphasising different technologies (Figure 10). In fact, the energy sector itself is complementing funding from other sectors, increasing innovation activity.

Figure 10. Private-sector investment in energy R&D, by subsector of investing company



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However, spending on energy RD&D has stagnated since 2010, an observation that has underpinned the timely launch of MI. This landmark intergovernmental initiative groups together 22 countries (17 of which are G20 members) and the European Commission to accelerate innovation for clean energy technologies, in part through doubling public funding for clean energy R&D over five years. Seven Innovation Challenges have been launched with the aim of catalysing research efforts to meet MI goals of reducing greenhouse gas emissions, increasing energy security and creating new opportunities for clean economic growth.

5. The role of collaboration in accelerating global energy innovation

Innovation is the shared consequence of creativity, leadership and investment in research by both the private and public sectors. As highlighted earlier in this report, government intervention can assist in accelerating the innovation process beyond what would be expected from market forces alone, and catalyse early adoption. There are certain barriers that can prove much more costly to overcome and side effects that cannot be mitigated well without strong collaborative approaches, and governments play a key role in facilitating these efforts.

Such challenges are not unique to the energy sector and affect most technology-driven sectors. Examples include technologies brought to the market by competitors that did not conduct or fund the original R&D. Governments have a unique convening power to share best practices and set up robust knowledge-sharing and intellectual property mechanisms. In some instances, basic research may produce results that can be applied in a variety of domains, many of which were not foreseen. By pooling resources together, international collaboration can accelerate demonstrations, particularly in complex areas spanning many stakeholders such as CCUS, hydrogen or smart energy networks, and by better understanding the challenges of applying technologies in different contexts, they can pave the way for a faster deployment of a technology once it reaches scale. Governments can seek to address some of these hurdles by taking a strong collaborative approach to the implementation of national innovation strategies and visions.

International and cross-sectoral efforts can provide greater confidence that individual and collective actions align in terms of priorities, technology areas and desired goals for collaboration (IEA, 2011). A national strategy, if developed, can benefit from the application of a good practice RD&D policy framework, which ideally consists of the following six elements:

1. coherent energy RD&D strategy and priorities
2. adequate government RD&D funding and policy support
3. co-ordinated energy RD&D governance
4. strong collaborative approach, engaging industry through public-private partnerships
5. effective RD&D monitoring and evaluation
6. strategic international collaboration.

Co-operation and networking can increase effectiveness and maximise the impact of RD&D efforts. Energy technology innovation supported by international collaboration can bring more benefits and bolster effectiveness, priority setting and industry engagement. International collaboration exists in many models ranging from bilateral agreements to regional networks to multilateral fora.

The benefits gained from participating in multi-lateral RD&D efforts include: Access to facilities and expertise; improved competitiveness by spreading the costs and risks of RD&D reduced costs of emerging technologies through demonstrations and pre-commercial deployments in markets that are larger than those available domestically; and access for companies to international markets for innovative technologies.

Despite the recognised benefits, there is no global platform for comparison and appraisal of international initiatives and the related activities, to ensure the effective use of expertise and resources. The IEA and other international organisations are enhancing efforts to track energy innovation and to collaborate through a range of multilateral fora and mechanisms for technology innovation. The past decade has seen the inception, development and in some cases decline of numerous innovation-related initiatives, arguably revealing an evolutionary trend of growing interest for collective action to achieve sustainable, secure and affordable energy, sharing development costs and learning to speed progress.

Drawing from the unique experience of the IEA Committee on Energy Research and Technology (CERT) over four decades of guidance and oversight of a global network of TCPs, the IEA recently undertook a comparative analysis of efforts to accelerate energy innovation under four key collaborative mechanisms: TCPs, MI, Clean Energy Ministerial (CEM) and initiatives under the European Union's relevant programmes.

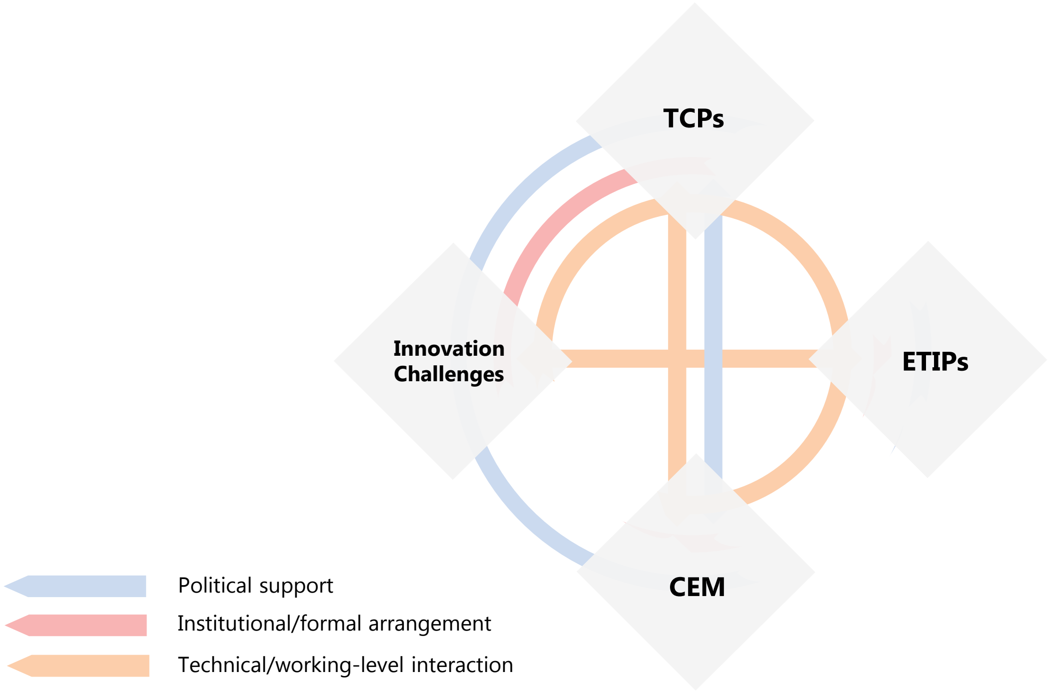
Under each of these four mechanisms, an array of anywhere from 8 to 38 individual initiatives exist. The existing collaborations between these initiatives are complex in themselves without taking into consideration the broader international plethora of collaborative mechanisms.

Figure 11 captures the current interactions between each initiative. While highlighting the breadth of collaborative activity already taking place, there are clear opportunities to increase or streamline these activities, as reflected in the key observations below. Many initiatives share commonalities in sectoral and technology focus, which encourages collaboration of many initiatives under different mechanisms.

Notably collaboration among TCPs within their own network is high; however, co-operation with other mechanisms such as MI and CEM continues to increase. This is unsurprising given TCPs were established in the 1970s and therefore have been present on the international energy innovation scene longer than other initiatives. In comparison, MI and CEM came into existence within the last ten years, quickly gathering political support and varied membership, including many emerging economies. A number of EU initiatives energy programmes were brought together as operative mechanisms under the Strategic Energy Technologies (SET) Plan adopted in 2015. While working closely together, there is substantial dialogue between EU programmes such as Energy Technology Innovation Platforms (ETIPs) and the European Energy Research Alliance (EERA), and international initiatives.

An examination of the connections among the initiatives under the four mechanisms and several others showed that there is varied but substantial interaction among them. It is clear initiatives are not operating in isolation and appear to have an awareness of the technical work of others. Technical and working level contact is the most common type of interaction among initiatives (Figure 11). Working-level interaction may include participating in the work programme of another initiative, presenting or participating at a technical workshop, or sharing information about its own research. Political support, such as referencing another initiative in high-level documents, is the second-most-common interaction.

Figure 11. Connections among initiatives



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Key observations emerging from this analysis are:

- **Non-legally binding agreements** (similar to TCPs) appear to be the preferred institutional basis for the selected collaborative mechanisms as these seek flexibility and responsiveness in their structures and work programmes. The institutional framework should respond to the desired longevity and innovation activities planned by the collaborative initiatives; however, **a binding framework can provide a more stable foundation for initiatives undertaking R&D activities over longer time spans**.
- Countries from the IEA family (member countries, countries that are pursuing membership and Association countries) have the broadest participation across the selected initiatives. Given the overlapping activities and mandates of the partnerships examined, it is a challenge for decision makers and innovators to determine which engagements are a priority and most effective. **An online repository of innovation-related international partnerships and initiatives would provide a valuable tool for decision makers.**
- The analysis of selected partnerships reveals a predominant focus on renewable energy, energy efficiency and cross-cutting technologies, with the highest crowding on solar energy, smart grids and CCS. Given the competing priorities of R&D national budgets, it has never been more important for innovation partnerships to work towards their visions as effectively as possible. For example, **collaborative initiatives should regularly explore co-location opportunities for conferences and meetings and co-branding for relevant innovation activities, to develop synergies and economies of scale effects wherever possible and minimise unnecessary duplication of effort**.
- The effectiveness of innovation partnerships depends on a variety of factors, ranging from adequate allocation of resources to the governance framework, as well as engagements of key public- and private-sector stakeholders at country level. It is critical that partnerships

take a strategic, proactive approach to engaging with stakeholders at the most advanced knowledge frontier as well as from markets with highest potential for innovative technology adoption, such as China and India. **There are considerable opportunities for further expanding stakeholder and additional market participation in the initiatives under consideration.**

- Given the proliferation of multilateral efforts around low-carbon energy technology innovation, there is clear potential for further and closer cross-initiative co-operation. Innovation partnerships could also further communicate their value proposition through high-level political platforms such as under the G7 and G20, and efforts under UN and regional fora.

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Annex A: IEA efforts to help accelerate global energy innovation

IEA work on energy innovation

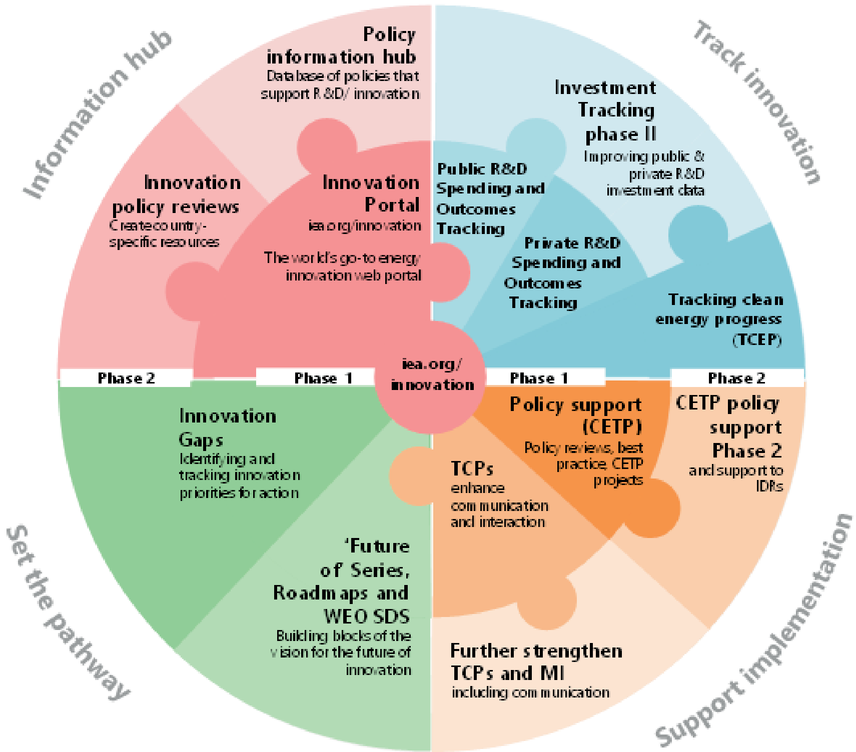
The IEA has long-standing and extensive expertise in analysing and providing policy-relevant recommendations across all areas of energy technology and innovation. IEA work on energy innovation has included the IEA *Technology Roadmaps* (2009-18); the past flagship publication *Energy Technology Perspectives* (2008-17); and several new publications – *The Future of Rail*, *The Future of Petrochemicals*, *The Future of Trucks* and *The Future of Cooling*; annual tracking of public and private investment in energy RD&D; and the online *TCEP* project, which follows the deployment and development of energy technology in 43 key areas.

Key IEA work streams relating to energy innovation are today all accessible at the new IEA innovation web portal (www.iea.org/innovation) and specifically include:

- **Tracking energy R&D investment**. Sound data on public- and private-sector spending on sustainable energy technology innovation are vital to enable decision makers to better identify gaps and opportunities to enhance the efficiency of resource allocation. The IEA has the most timely data on energy R&D investments worldwide, inclusive of both government and private-sector spending
- **Technology-specific information**, including **innovation gaps 2.0.** The IEA identifies and tracks the key long-term technology innovation gaps that need to be tackled to reach the SDS within each of the technologies and sectors in *TCEP*.
- **Country-specific information.** The IEA has an unparalleled wealth of information on energy innovation policies in energy policy review chapters, including country-specific innovation data and analysis from various IEA sources, including R&D funding levels (by technology); and case studies of clean energy technology development and innovation in emerging economies, as part of its efforts under the Clean Energy Transitions Programme (CETP).
- **The innovation policy database,** a comprehensive database of energy research and innovation policies worldwide, drawing from IEA in-depth reviews, as well as a global map of innovation policies and measures
- **Partnerships' linkages.** The IEA supports, co-ordinates and facilitates collaboration with other inter-governmental organisations, multilateral partnerships and international initiatives on energy technology research, innovation and deployment, notably the TCPs, MI and other relevant multilateral efforts.

The enhanced IEA innovation work stream is bringing tangible value for and synergies with the following: policy makers setting R&D budget priorities and enacting supporting policies; businesses and investors improving their investment decisions and looking for trends; governments and analysts wishing to get a deeper understanding of the energy innovation landscape and specific technologies; governments, companies, researchers and funders seeking partners for projects and multilateral initiatives, including TCPs; and journalists.

Figure 12. A complex innovation system needs all supportive pieces to fit together



Note: WEO = *World Energy Outlook*.
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Annex B: Innovation gaps

The IEA's Innovation Gaps framework identifies key long-term technology challenges for research, development and demonstration that need to be filled in order to meet long-term clean energy transition goals. The framework highlights around 100 innovation gaps across 45 key technologies across the power sector, other fuel supply, industry, buildings, transport and energy integration. The following annex lists the innovation gaps, highlighting why they are critical to achieving the SDS. For the extended content, please follow the links in each gap.

Innovation needs in the power sector

The transition in the power sector calls a combination of scaling up innovations that facilitate the integration of new clean generation technologies at scale, as well as expanding and improving designs of older ones to make them compatible with the SDS. Solar PV will need smarter inverters to reduce grid integration costs, large volumes of small-scale PV will require innovation to manage and integrate and wind power will need to reach more remote and off-shore locations more cost-effectively. The success of other technologies in the SDS also hinges on accelerating innovation: CCUS requires end-to-end innovations to reduce cost penalties and demonstrate advanced power cycles, while new nuclear power plant designs like small modular reactors remain to be validated.

Nuclear power

While industry is confident that the overnight costs of today's Gen III/III+ Light Water Reactors can be reduced significantly as series are being developed, there is some uncertainty as to whether these large reactors can compete in a cost-effective manner in future low carbon energy markets, with increasing shares of variable and distributed generation.

More disruptive innovations may be required for nuclear to secure its role as a flexible, reliable and dispatchable source of energy. Three types of innovations are being pursued: The development of smaller reactors, which could have higher operational flexibility; the development of innovative fuels that could ensure higher performance at lower cost; and finally, the development of non-electric applications, such as process heat, hydrogen production and desalination, which could displace fossil-based processes.

Gap 1: Coupling reactors with non-electric applications

While there are several alternatives to decarbonise the power sector (renewables, CCS, nuclear), there are fewer to decarbonise applications for which fuel switching (electrification) is not possible or limited.

While nuclear energy is recognised as a proven technology to provide low-carbon electricity as well as grid services, its potential as a source of low-carbon heat is often neglected, even though there is proven industrial experience (nuclear district heating in Switzerland for over three decades; process heat in CANDU plants in Canada; nuclear desalination in Kazakhstan in the 1980s). Hence, demonstrating the coupling of advanced reactors with non-electric applications can provide policy makers with alternatives to decarbonise transport (carbon-free production of hydrogen using nuclear heat and electricity), process heat applications and other energy-intensive industries such as desalination plants.

Coupling nuclear reactors with non-electric applications can also provide energy system storage – i.e. storing energy in the form of heat or as an energy vector such as hydrogen. This is the basic concept of hybrid energy systems.

Furthermore, demonstrating the possibility of multiple revenue streams (sales of electricity as well as heat or hydrogen) can improve the case for investing in nuclear technology, which will remain a capital-intensive technology.

Read more about this innovation gap (www.iea.org/innovation).

Gap 2: Innovative fuels for nuclear power

Fuel design improvements can offer additional benefits such as enhanced performance and increased safety margins.

Innovative fuels may incorporate new materials and designs for cladding and fuel pellets. Testing in experimental reactors and validation in power reactors are needed before such fuels can be licensed.

Read more about this innovation gap (www.iea.org/innovation).

Gap 3: Small Modular Reactors and advanced reactor demonstration

While nuclear development has focused on constructing larger reactors in recent decades (typically light-water reactors [LWRs] of 1 400 megawatts electrical [MWe] to 1 750 MWe) to meet growing power demand within large-scale electricity grids, it has been recognised that future energy systems will also require different technologies. Smaller – perhaps more flexible – reactors will be needed for niche markets (small grids, isolated communities, or grids with large shares of variable renewables), to replace fossil fuel-based power plants in the 300 MWe to 600 MWe range, or to provide (in addition to electricity) low-carbon heat that can substitute for fossil fuel uses (desalination, process steam for industry, hydrogen production) or to burn nuclear waste. Advancing the design, certification and demonstration of SMRs and other advanced reactors such as Gen IVs for electric and non-electric applications will offer clean, low-carbon energy generation technologies to complement renewables and CCS.

In addition, countries with long-term policies to close the nuclear fuel cycle loop by multi-recycling nuclear materials are also maintaining efforts to develop Gen-IV fast-reactor designs (particularly sodium fast reactors) and the associated nuclear fuel cycle facilities.

Finally, countries with long term policies to close the nuclear fuel cycle with the multi-recycling of nuclear materials are also maintaining efforts for the development of Gen-IV fast reactor designs (in particular Sodium Fast Reactors) and associated nuclear fuel cycle facilities.

Read more about this innovation gap (www.iea.org/innovation).

CCUS in power

Innovation, in combination with targeted policy measures for deployment, is crucially needed to stimulate CCUS development and bring it into line with the SDS.

Innovation for CCUS in power generation needs to target cost reductions, improve the efficiency of CO_2 capture, and expand the portfolio of available CCUS technologies. Approaches like supercritical CO_2power cycles have gained public attention recently for their potential of lowering cost and high capture rates.

Reduce the energy penalty and cost of CCUS capture

Reducing the energy penalty of capture plants will reduce the cost of capture technology, one of the main barriers to widespread CCUS deployment today.

As the theoretical separation energy for capture is generally very low compared to the requirements of today's typical systems, in particular for post-combustion plants, opportunities for significant cost reductions exist.

Demonstrating supercritical CO2 power cycles at scale

Supercritical CO2 power cycles (sCO2) in principle allow for, in addition to higher plant efficiencies compared with conventional pulverised coal plants, lower pollutant emissions, higher power density (which could reduce capex) and easier CO2 capture. In some cases they could also allow for reduced water consumption. Plant sizes, which can vary from 1 MWe to 600 MWe, could be adjusted to specific electricity demand requirements.

CCUS applied to gas-fired power generation at scale

Applying CCUS to gas-fired power plants can substantially reduce the emissions of the gas-fired fleet. While there are no large-scale CCUS projects at gas-fired plants in operation today, the SDS envisions 35 GW by 2030.

Natural gas-fired power

Improving flexibility and increasing full- and part-load efficiency will continue to be research priorities for gas-fired power generation.

Generator flexibility is particularly important to integrate growing shares of variable renewables into the grid. Boosting flexibility and encouraging its use requires that power plant technology be improved, as well as system operations, market design, the granularity of pricing and access to revenue streams for system services.

With ample, affordable gas becoming available in certain regions and countries (for instance the United States), full-load efficiency remains an important plant parameter.

RD&D should also be directed towards CCUS for gas-fired power generation. Like unabated coal, unabated gas is likely to be too carbon-intensive to reach ambitious climate targets beyond 2040.

Flexible operation of gas-fired power plants

Existing gas power capacity is not always optimised for the flexibility requirements of systems with higher shares of variable renewables. Growing shares of renewables in the power system challenges conventional operational practices of these plants.

Coal-fired power

Innovation efforts should focus on boosting overall full-load efficiency and plant flexibility, for example by increasing ramping speed (the pace at which generation can be increased to meet demand) and part-load efficiencies. Flexibility improvements to plants will be crucial to integrate a growing share of variable renewable generation into the grid system.

Reducing local air pollution from coal plants continues to be a priority, and the importance of improving CCUS for coal to conform with carbon constraints is increasingly being recognised.

Several innovative approaches are being explored, such as integrated gasification fuel cells, direct coal fuel cells and supercritical CO_2 power cycles. These technologies, which promise ultra-high efficiencies, are at different stages of development, with several technical and engineering challenges that still need to be overcome.

Need for higher combustion temperatures and efficiencies for pulverised coal-fired power plants

Advanced ultra-supercritical (AUSC) coal plants promise higher combustion temperatures and efficiencies, and hence lower emissions. Certain technological limits have yet to be overcome, however, to address the high temperatures and pressures. The SDS envisions a shift in the coal power plant fleet towards the highest-efficiency plants (USC and AUSC), and away from subcritical and supercritical technologies.

Innovation needs in renewable power

Renewables require continued innovation efforts to reach the performance, reach and deployment in the SDS. The front-runners in deployment in the SDS, wind and solar, will require continued R&D into next generation modules, cells, turbines and system designs, as well as into balance-of-system components to ensure cost reduction trends are maintained.

More fundamentally, reaching high shares will require bridging innovation gaps in a host of integration technologies. New designs and prototypes are also needed to expand the reach of renewables, including floating off-shore wind turbines, ocean power or enhanced geothermal systems. Biomass technologies will require novel processes to reduce costs and tap into new feed-stocks.

Onshore wind

Increased efforts in wind technology R&D are essential to realising the SDS, with a main focus on reducing the investment costs and increasing performance and reliability to reach a lower unit cost of energy. Good resource and performance assessments are also important to reduce financing costs. Wind energy technology is already proven and making progress, and while no single element is like to dramatically reduce costs, taken together improvements can ensure the cost trajectory is maintained.

In particular, innovation efforts are needed to aid in resource planning that minimises the impact of scaling up wind power capacity, and system-friendly integration of wind power through digital solutions and advanced power electronics.

Gap 1: Advanced contribution of wind power to grid integration

Wind power generation creates well-known challenges for electricity grids and power systems through its variability and uncertainty and distributed nature. Wind power plants in many cases already contribute to their own integration through a range of upgrades, but their contribution will need to be ramped up in the SDS through a combination of regulation and grid codes and more innovative solutions for providing ancillary services and other services related to dispatchability.

Gap 2: Next generation turbine, power-train and system management technology

Large rotor diameters and higher hub heights have higher upfront and per unit power costs but increase production and decrease costs per unit energy while making better use of the resource and decreasing variability of output.

Gap 3: Improve resource assessment and spatial planning

Wind farm planning, both onshore and offshore, will require enhanced sensitivity assessment of the surrounding environment to ensure long term turbine efficiency and attractive return on investment.

Geothermal

Geothermal energy technologies have differing levels of maturity. The exploitation of hot rock resources, e.g. by means of EGS which is currently in the validation phase, has particular potential for improvement

Long-term, sustained and substantially higher research, development and demonstration resources are needed to accelerate cost reductions and design, and bring novel geothermal concepts to market. These advanced technologies have to be proven in pilot plants, meaning that strong government support for innovative small plants is needed.

R&D will need to focus on understanding better how fractures open and propagate in different stress regimes and rock types, in order to be able to better assess the hot rock potential. Similarly, a common approach in identification of advanced hydrothermal resources will help assessing its potential.

Ocean power

Technology innovation and learning by research are key to advance ocean power to maturity. Research should focus on key components and sub-systems, simplifying installation procedures to keep costs down, Advanced design concepts that are currently in the very early stages of innovation could break through, including ocean thermal energy conversion (OTEC), salinity gradient power and ocean current technology.

Scaling up low cost mechanical concepts and manufacturing for wave energy

Wave power captures kinetic and potential energy from ocean waves to generate electricity. Wave energy converters (WECs) are intended to be modular and deployed in arrays, but at present there is little design consensus for wave energy devices with no industry-standard device concept. Due to the diverse nature of wave resources, it appears unlikely that there will be one single device concept that is used. Rather, there will probably be a small number of device types that exploit different regions of this vast resource. These concepts however need to be trialed at scale.

Exploiting ocean energy through advanced design concepts

The vast majority of ocean technologies today are either wave or tidal energy. Increasing annual generation to reach SDS levels will also require that investments be diversified towards other alternative concepts and technologies such as ocean thermal energy conversion (OTEC), salinity gradient power and ocean current technology.

Solar PV

Innovation in solar power needs continued focus on increasing the performance of commercial PV systems and a shift to cell and technologies that are now only in the pipeline. At higher penetrations, innovation can enable PV to contribute to their own integration through smart grid capabilities, which can mitigate the impact of incidents on the grid. Innovation in digital technologies applied to solar PV systems can also deliver a higher share of mini- and off-grid systems and increase energy access in developing countries.

Maintaining the cost reduction trajectory for solar PV

While dramatic scale effects have been achieved in solar PV, R&D efforts focused on efficiency and other fundamental improvements in solar PV technology need to continue to keep on pace with the SDS. Mainstream technology at present is dominated by crystalline silicon. Within it, screen-printed Al-back surface field cells (Al-BSF) holds around three quarters of the market, with the remaining quarter dominated by Passivated Emitter Rear Cell technology (PERC). Strong global demand for higher-efficiency modules is driving a shift towards PERC and the next generation of technologies, like n-type HJT and IBC.

Smarter inverter systems and BOS cost reductions

Higher PV shares, particularly in distribution grids, will necessitate the development of new ways to inject power into the grid and to manage generation from solar PV systems. The inverter and the rest of the power control system is generally the gateway for smart-management measures, and while technology has been proved, systems will need to become smarter and provide a broader range of voltage, reactive power and other ancillary services to the grid. Beyond making inverters smarter, the overall balance-of-system (BOS) costs (which include inverters) should be a key area of focus, as they can take up 40-60% of all investment costs in a PV plant, depending on the region.

Increased integration of off-grid electrification systems

The wide array of system designs now available – off-grid, mini-grid and on-grid – increases the number of methods available to obtain electricity access. Off-grid technologies (such as stand-alone solar home systems), mini-grids and energy-efficient appliances are complementing efforts to provide electricity access from grid expansion. Such decentralised systems can help fill the energy access gap in remote areas by delivering electricity at a level of access that is currently too expensive to be met through a grid connection, and in urban areas by providing back-up for an unreliable grid supply.

Offshore wind

A great potential for cost reductions, or even technology breakthrough, exists in the offshore wind sector. In particular, innovation is needed in installation processes and foundation designs. An improved understanding of the requirements of wind technology in offshore conditions, as well as the management of large numbers of wind farms will be necessary to design turbines, systems and farms. Changes in design architecture and an ability to withstand a wider array of design considerations including hurricanes, surface icing, and rolling and pitching moments, are also likely to be needed. Improved alternative-current (AC) power take-off systems or the introduction of direct-current (DC) power systems are also promising technologies for internal wind power plant grid offshore and connection to shore.

Innovation in installation processes for offshore wind plant

Soft costs for offshore wind take up a substantial share of total installed costs, and together with interconnection they are a key challenge for reaching SDS cost goals. Offshore wind farms also need to incorporate high levels of resilience to stronger wind regimes and meteorological conditions off shore, particularly to mitigate the impact of long-term exposure to seawater.

Tapping deeper offshore wind resources through floating wind turbines

The richest offshore wind resource is located in deep waters, where attaching turbines to the seabed is not practical. Floating offshore foundations, offer the potential for less foundation material, simplified installation and decommissioning, and additional wind resource at water depths exceeding 50 m to 60 m. Several regions (e.g. the US or Japan) have a low share of their resource in shallow waters. Floating foundations may also be attractive for mid-depth projects, where saturation of onshore or near-shore potential or the possibility of standardising floating foundation designs and do not need heavy-lift vessels to transport foundations.

Reducing cost and risk of transmission and distribution of electricity from offshore wind

As turbine costs drop in the SDS, interconnection and balance-of-system take up a higher share of overall installation costs. Learning on design concepts as well as fundamental technology improvements to power engineering equipment will be necessary.

Hydropower

While hydropower is a mature power generation technology, with high energy payback ratio and conversion efficiency, there are still many areas where small but important improvements in technological development are needed. Work is underway to identify and apply new technologies, systems, approaches and innovations, including experience from other industries, that have the potential to make hydropower development more reliable, efficient, valuable and safe. Improvements along the lines of those made in the last 30 to 50 years will also need to continue, though with smaller incremental benefits: mainly in physical size, hydraulic efficiency and environmental performance.

Innovative hydropower designs

Dams have a high social and environmental cost, heavily disrupting ecosystems and populations where they are developed. Alternatives that do not require damming or resettlement of populations would help reach SDS levels.

Reducing the cost and impact of civil works

The cost of civil works associated with new hydropower project construction can be up to 70% of total project costs, and their social and environmental impacts can be considerable, so improved methods, technologies and materials for planning, design and construction have considerable potential.

Innovation needs in fuel supply

Alongside policy and regulation measures, developing and implementing new technologies will be essential to realise emissions reductions.

For methane, monitoring and measuring emissions on a continuous basis is a key gap for which innovation is required to identify major emission sources and assess the efficacy of emissions reduction actions. The development of new, low-cost leak detection and repair options would also encourage much more widespread adoption.

For flaring, large volumes of gas are often wasted in small-scale operations on an intermittent basis. A core challenge is to provide economically viable solutions to bring the gas to market, especially in offshore operations.

Leak detection and repair (LDAR)

Leak detection and repair (LDAR) programmes are one of the key instruments to reduce fugitive (or accidental) methane leaks in a cost-effective manner. LDAR programmes can be carried out at different frequencies (e.g. monthly, quarterly or yearly), and although more frequent checks will identify leaks more quickly and save more gas, the marginal cost of mitigation rises. The ability to carry out checks more frequently or – better still – on a continuous basis and at low cost would substantially reduce emissions.

Monitoring and measuring methane emissions

Emissions levels and abatement potential are based on sparse and sometimes conflicting data. There is also a wide divergence in estimated emissions at the global, regional and country levels. Accurate measurement is critical not just to advance scientific understanding of the problem but also to assess the efficacy of policy actions and to assure the public that the issue is being addressed.

Mobile gas utilisation technologies for small-scale operations

Existing flare capture technology solutions for large applications are mature and widely available. However, a large amount of flaring takes place in small-scale operations and on an intermittent basis. Gas that is flared also often contains a high level of contaminants. In these cases, it can be challenging to provide economically viable solutions to bring the gas to market, especially in offshore operations, so new solutions to utilise the gas are needed to eliminate the need for flaring. Mobile and modular gas utilisation facilities that can be deployed rapidly would also help in situations in which flared gas volumes can decline rapidly over time (such as in tight oil production).

Innovation needs in industry

- Innovation efforts are currently under way to avoid CO_2 emissions in industry, such as through low-carbon, hydrogen-based production of steel and chemicals; using alternative, lower-carbon binding materials in cement; and employing inert anodes for primary aluminium production. Other efforts focus on CCUS, particularly in the iron and steel, chemical and cement subsectors. While recent progress has been promising, acceleration is needed on key innovation gaps.

Chemicals

- Developing and deploying innovative technologies and process routes is crucial for chemical and petrochemical sector decarbonisation.
- Key new and emerging low-carbon processes involve replacing fossil fuel feedstocks with electrolytic hydrogen, bio-based feedstocks, electricity as a feedstock and captured CO_2. Further development of carbon capture, utilisation, transportation and storage technologies will also be important for decarbonisation.

Gap 1: Ammonia production using electrolytic hydrogen

- This process route could avoid generating CO_2 emissions in ammonia production if renewable electricity is used for hydrogen production.
- Technology principles: Ammonia production involves combining nitrogen with hydrogen in the Haber-Bosch process. Hydrogen can be produced either through steam reforming (with natural gas as the feedstock) or through electrolysis (with electricity as the feedstock). Hydrogen produced by electrolysis is often referred to as electrolytic hydrogen.

Read more about this innovation gap (www.iea.org/innovation).

Gap 2: CCUS applied to the chemical sector

- Carbon capture is needed to enable chemical production methods that use CO_2 as a feedstock. Combined with permanent storage, it could drastically reduce CO_2 emissions and even create negative emissions if combined with biomass-based production methods.

Read more about this innovation gap (www.iea.org/innovation).

Gap 3: Methanol production using electrolytic hydrogen and CO_2

- This production route could avoid direct fossil fuel use in methanol production if renewable electricity is employed for hydrogen production and CO_2 can be obtained from either biogenic sources or unavoidable industrial sources. In the short to medium term, fossil-based and otherwise avoidable emissions can also be used. In a strong decarbonisation scenario, unavoidable CO_2 emissions from fossil-based industrial by-products would become scarce in the long term, so extracting it from the atmosphere through biomass cultivation or air capture would become increasingly important.
- Technology principles: Methanol production requires creation of a syngas composed of CO, CO_2 and hydrogen gas. A wide variety of feedstocks can be used to produce the syngas: natural gas and coal are currently the most common, but biomass and waste can also be used. It can also be made from a combination of hydrogen (produced by natural gas-based steam reforming or electricity-based electrolysis) and waste CO_2 from industrial processes.

Read more about this innovation gap (www.iea.org/innovation).

Gap 4: Producing aromatic compounds from methanol

- This process route could replace fossil fuel feedstocks with low-carbon methanol to produce aromatics using conventional naphtha steam crackers, if low-carbon methanol were available. The method currently being explored uses technology similar to what has already been commercialised for methanol-to-olefin production, which employs a silver-impregnated zeolite catalyst.

Read more about this innovation gap (www.iea.org/innovation).

Cement

Technology innovation will be crucial to reduce cement subsector emissions, particularly process emissions for which commercially available mitigation options are relatively limited. CCUS can play a key role, with post-combustion chemical absorption carbon capture currently the most advanced technology. Other capture options under development include oxy-fuel capture, membrane CO_2 separation and calcium looping.

Processes are also being developed to utilise captured CO_2 for inert carbonate materials in concrete aggregates. Alternative cement constituents, which can be blended into cement to replace a portion of the clinker, require further deployment. R&D is needed on alternative binding materials that rely on raw materials or mixes different from those of OPC clinker, and in many cases result in lower emissions.

Of the various alternative binding materials under development, belite calcium sulphoaluminate (BCSA) shows particular promise in terms of a reasonable balance between remaining technical hurdles and CO_2 emissions reduction potential.

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CCUS applied to the chemical sector

Carbon capture is needed to enable chemical production methods that use CO_2 as a feedstock. Combined with permanent storage, it could drastically reduce CO_2 emissions and even create negative emissions if combined with biomass-based production methods.

Iron & steel

Although considerable CO_2 emissions reductions can be realised through greater energy efficiency and increased scrap-based production, innovation will be important to reduce emissions even further, particularly in primary production.

An array of technologies is under development. New smelt reduction technologies based on coal or hydrogen plasma can cut emissions from coke production. Direct reduction technologies based on natural gas, hydrogen or electricity could reduce emissions considerably compared with the conventional blast furnace-coke oven (BF-CO) route.

Additionally, adopting CCUS could achieve near-zero steel production emissions – and using the captured CO_2 to produce chemicals and fuels would also offer new economic opportunities. Top-gas recovery systems in blast furnaces are also being developed to reduce energy and carbon inputs for conventional BF-CO steel production.

Need for lower carbon steel production processes based on fossil fuels

The new smelting reduction process would circumvent the need for iron ore agglomeration and coking, avoiding 20% of the CO_2 emissions of the standard BF-CO route.

The use of pure oxygen (oxy-fuel combustion) makes the new smelting reduction process well suited to CCUS because it generates a high concentration of CO_2 off-gas and emissions are delivered in a single stack, as opposed to the multiple emission points of a standard steel mill. Equipping this process with carbon capture would result in 80% less CO_2 emissions than standard BF-CO production.

Part of the coal could eventually be replaced by natural gas and/or biomass, which would further reduce the CO_2 footprint of the new smelting reduction process.

Technology principles: Iron smelting normally occurs in a blast furnace with coke used as a feedstock and fuel; the coke is produced from metallurgical coal in a coke oven. The blast furnace also requires the conversion of iron ore fines or lump ore into agglomerates, such as pellets and sinter. Using metallurgical coal and iron ore directly in a smelter can avoid the coke production and iron ore agglomeration steps.

Direct reduction based on hydrogen

The use of hydrogen from renewable electricity in this process technology would enable a 98% reduction in CO_2 emissions compared with the reference BF-CO method.

Technology principles: An alternative to BF-CO steel production, the DRI route reduces solid iron ore using carbon monoxide and hydrogen.

CCS applied to commercial iron and steel technologies

Integrating CCS into existing iron and steel technologies could considerably reduce the carbon footprint of steelmaking. Achievable emissions avoidance depends on the iron and steel processes used, the capture technology and the amount of CO_2 captured.

Using steel works arising gases for chemical and fuel production (CCU)

Using CO_2 from steel works arising gases (WAGs) can reduce the lifecycle emissions of fuel and chemical production, since it makes use of CO_2 that would otherwise be emitted to the atmosphere. The net impact depends on what the WAGs are currently used for (e.g. flaring vs power generation), compared with their use as alternative feedstock for ethanol production.

For fuel production, this process would improve the resource efficiency of steelworks through one or more of the following: full process integration of by-products from ethanol plants into steel plants; increased use of low-temperature heat in steel plants for ethanol distillation; and replacement of pulverised coal injection with biomass in the blast furnace, reducing the direct CO_2 footprint of steelmaking. Using WAGs could also reduce the lifecycle-assessed CO_2 footprints of fuels by using ethanol produced through this method as a blending component.

For chemical production, this technology could facilitate wider penetration of variable renewable power generation by providing demand-load flexibility to the system, and could also reduce the life-cycle assessed CO_2 footprint of chemicals produced through this method. However, the net impact would depend on what the WAGs are currently used for (e.g. flaring vs power generation), compared with their use as alternative feedstocks for chemical production.

Technology principles: WAGs are the gases released during steelmaking. They are carbon-rich, so provide a relatively concentrated source of CO_2 for carbon capture and use.

Aluminium

Innovation in the aluminium subsector is essential to reduce emissions from primary production, given that the Hall-Héroult cells currently used produce process emissions during electrolysis. Although it is important to expand secondary production to reduce emissions, decarbonising primary production is also necessary because scrap availability will put a limit on secondary production.

Inert anodes are a key innovation to reduce primary production process emissions, and otherwise, any innovations that improve energy efficiency can also reduce electricity consumption – and thus indirect electricity emissions.

Several technologies (multipolar cells, novel physical designs for anodes, wetted cathodes, carbothermic reduction of alumina, and kaolinite reduction) offer energy efficiency potential, but many are still in relatively early stages of development.

Other areas for innovation are electrolysis demand-response, which could help with integrating variable renewable energy by providing flexibility services to the grid, and new physical recycling techniques that could increase scrap availability for secondary production.

Inert anodes for primary aluminium production

Using inert anodes would substantially reduce process emissions from primary aluminium production.

Technology principles: Primary aluminium smelting currently relies largely on carbon anodes, which produce CO_2 as they degrade. Inert anodes made from alternative materials instead produce pure oxygen and do not degrade.

Multipolar cells

While conventional Hall-Héroult cells have a single-pole arrangement, multipolar cells could be produced with bipolar electrodes or with multiple anode-cathode pairs in the same cell. They could reduce energy consumption by 40%, owing to lower operating temperatures and higher current densities. Since the cells require inert anodes, process emissions from the use of carbon anodes would also decrease.

Technology principles: The Hall-Héroult method is currently the main commercial process for primary aluminium smelting. It uses electrolysis to separate aluminium from aluminium oxide (alumina) within a cell. The carbon-lined cell acts as a cathode, and an anode is dipped into the electrolyte bath contained within the cell. A current is passed from the anode to the cathode to separate the aluminium.

Novel physical designs for anodes

The physical design of anodes can be altered to improve the energy efficiency of Hall-Héroult cells. For example, sloped and perforated anodes make electrolysis more efficient by allowing better circulation within the electrolyte bath, while vertical electrode cells save energy by reducing heat loss and improving electrical conductivity. Energy savings can be considerable, with one source estimating that slotted anodes can reduce energy consumption by 2 kWh to 2.5 kWh per kg of aluminium.

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Pulp & paper

Fuel switching and energy efficiency will be the primary mechanisms to cut CO_2 emissions in the pulp and paper subsector. Innovation is also important, however.

Several technologies still in the relatively early stages of development (TRL 3-4), including deep eutectic solvents and alternative drying and forming processes, could help raise energy efficiency considerably.

Black liquor gasification, which can produce carbon-neutral energy products for use in pulp and paper as well as other sectors, has already reached the initial stages of commercialisation but still requires further development and deployment.

Lignin extraction, which has been pilot-tested at commercial scale, could make lignin available for use as a biofuel or for new industrial products.

Black liquor gasification

Gasification of black liquor can produce carbon-neutral energy products such as electricity and steam for use in pulping plants, and liquid biofuels for use in transport.

Technology principles: Black liquor is a biomass-based by-product of chemical pulping. It can be combusted as a fuel in on-site utilities to generate steam and electricity, or it can be upgraded through gasification to create syngas.

Using deep eutectic solvents as low-carbon alternatives to traditional pulping

The process could use significantly less energy for pulping than the traditional chemical pulping processes because deep eutectic solvents enable pulp production at low temperatures and at atmospheric pressure. This process could also add value for the pulp industry by producing pure lignin that can be sold as a fuel or a material.

Technology principles: Deep eutectic solvents function by dissolving wood into lignin, hemicellulose and cellulose.

Innovation needs in transport

- Transitioning towards sustainable transport will require improving vehicle efficiency and adopting low carbon vehicle and fuel technologies. Innovation can accelerate the transition by cutting costs, promoting technology learning, and improving performance of both conventional and zero-emission vehicles (electric or fuel cell electric).
- Innovation on efficiency technologies and low-carbon vehicles and fuels is particularly important in harder-to-abate modes like heavy-duty vehicles, maritime and aviation, where technologies that are currently commercially available alone cannot deliver the emission reductions seen in the SDS.

- Innovation can also play an important role in improving systems-level efficiency. For instance, innovation in digital technologies -- from communications to deep learning algorithms -- can help match and optimise transport supply and demand.

Fuel economy of cars and vans

- The car industry is one of the highest spenders on research and development, representing nearly 25% of global R&D spending in 2018 (Auto Alliance, 2018).
- Numerous technologies can lead to fuel economy improvements, including:
  - energy efficient tires
  - improved aerodynamics
  - fuel efficient combustion technologies and engine downsizing
  - powertrain electrification
- Reducing vehicle weight is a key means to improve fuel efficiency. Lightweighting techniques such as using high-strength steel and aluminium in the chassis can reduce the mass of the vehicle while cutting both fuel consumption and total life-cycle CO_2 emissions (Serrenho, 2017).
- So far, however, most of the fuel economy benefits of lightweighting have been offset by the increased weight of upscale features, safety enhancements and increased vehicle size in many markets.

Gap 1 : Advanced internal combustion engines

- Despite the increasing market share of EVs, IEA scenarios show that a large share of the LDV fleet will be powered by internal combustion engines (ICEs) in conventional, hybrid and plug-in hybrid configurations until at least mid-century. Reducing ICE CO_2 emissions is thus a key part of a balanced strategy for limiting atmospheric CO_2 levels. Improving ICEs is also a cost-effective CO_2 mitigation strategy.
- ICEs operating on electrofuels generated when excess renewable electricity is available may even promote more rapid decarbonisation of the electricity supply while providing near-zero carbon emissions. Additional CO_2 emissions reductions could also be gained through the use of bio-derived or other low-carbon fuels along with ICE design optimisation to take full advantage of their properties.
- Reducing local pollutant emissions of particulate matter, unburned hydrocarbons and nitrogen oxides from ICEs remains an important challenge. The move to vehicle hybridisation with start-stop systems can also result in higher pollutant emissions if exhaust after-treatment devices are not operating effectively (SAE, 2018).

Gap 2: Lightweighting of light duty vehicles (LDVs)

Although the average weight of new LDVs remained relatively stable globally during 2015-17, in more than two-thirds of countries average LDV weight actually increased – with increases in three-quarters of countries in 2016-17 alone. This is the result of three counterbalancing trends: first, growth in the market share of large LDVs (SUVs and pick-up trucks) raised vehicle weight.

At the same time, however, an increasing volume (and share) of vehicles were being sold in emerging economies. These vehicles tend to be smaller and lighter than new vehicles sold in advanced economies, which tempered the effect of higher large-LDV sales.

Finally, lightweight materials such as advanced high-strength steel, aluminium, thermoplastics and even carbon fibre composites are used more widely in new LDVs sold in all markets because they have the potential to improve safety, performance and fuel economy while making the vehicle lighter.

Biofuels for transport

Advanced biofuels need to command a more significant share of transport biofuel consumption by 2030 in the SDS. However, currently only biodiesel and HVO production from fat, waste oil and grease feedstocks is commercialised, and there are limits on the availability of these feedstocks.

Therefore, scaling up advanced biofuel production volumes significantly needs innovation so other less mature advanced biofuel technologies reach commercial production. Cellulosic ethanol and biomass-to-liquid (BtL) synthetic fuels are important in this respect. This is because they can be produced from feedstocks with higher availability and potentially lower cost, such as municipal solid waste, forestry and agricultural residues.

Commercialisation of cellulosic ethanol

Cellulosic ethanol offers significant CO_2 emissions reductions compared with fossil-based transport fuels for internal combustion engine (ICE) passenger vehicles, as well as for trucks and buses when used as ED95 (95% fuel ethanol with lubricants and additives). Although regular vehicles can accommodate ethanol at low blend rates, CO_2 emissions reductions are maximised when it is used at high blend shares or unblended in flexible-fuel vehicles. Higher cellulosic ethanol production would also provide the additional benefit of curtailing agricultural residue-burning in fields, which deteriorates air quality.

Development of Biomass-to-Liquids fuel production from thermochemical processes

Biomass-to-Liquids (BtL) synthetic fuels produced from thermochemical processes, such as gasification and pyrolysis, offer the potential to convert low value biomass and waste feedstocks (including municipal solid waste) to low carbon transport fuels. The high availability of these feedstocks means that fully commercialised thermochemical technologies could open the door to significant volumes of advanced biofuels for the transport sector, providing diesel substitutes in sectors that are hard to electrify.

Trucks & buses

With the exception of the long-range Tesla semi variant and the prototype Nikola trucks, the range of zero-emission trucks is limited to below 600 kilometres. Together with the time required to recharge depleted batteries (or the high amperage, voltage, and power draw requirements of very fast charging), this points to the need for alternative infrastructure and operational models for long-haul trucking.

To date, three competitors seem most promising: dynamic charging on Electric Road System (ERS) corridors; continuing improvements in the performance, capacity, and costs of advanced lithium batteries; and hydrogen.

Improving the cost and performance of lithium-ion batteries

For trucks operating on regional delivery and long-haul segments, the suitability of electrification will depend upon continuing energy density improvements and cost reductions in lithium-based batteries.

There is a broad consensus that the 'floor' costs of current lithium-ion technologies may be around 80 USD/kWh. Going beyond that threshold is necessary in the SDS after around 2030, and will require the development of technologies that are currently in very early stages of development.

In long-haul, heavy-duty applications, gravimetric energy density is an important performance criterion on which advanced lithium-ion batteries will have to continue to improve in order to compete with fossil (diesel and natural gas) powered trucks. Advanced solid state chemistries may be able to achieve energy densities of 300-400 Wh/kg, and even more advanced chemistries (such as Lithium-Air) may have the potential to reach densities as high as 1000 Wh/kg or more.

Deploying Electric Road System (ERS) corridors

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Cost-competitive hydrogen fuel cell systems for FCEVs

There are two main types of zero-emissions vehicles: BEVs and FCEVs. Because of the long charging time and short range of EVs, FCEVs hold promise as a complementary technology, but they remain costly and their availability is limited. Transport modes such as trucks, buses, maritime and locomotive applications, may particularly benefit from fuel cell rather than pure electric, battery-based drivetrains. Several steps can be taken to reach cost targets: reduce precious metal use by downsizing the fuel cell stack; boost production of fuel cells and all ancillary components to obtain economy-of-scale cost reductions; and deploy targeted refuelling infrastructure tailored to specific modes and applications.

Electric vehicles

Innovation in EVs fundamentally needs to focus on continued improvements of the battery technology itself, including advancing alternative chemistries, to reach the cost, density and efficiency needed to reach the levels of deployment in the SDS.

These innovation efforts can also support more sustainable manufacturing and value chains for the large volumes of batteries produced under the SDS.

As the share of EVs increases, their impact on electricity networks, particularly on distribution grids, will become larger. If EV charging is deployed and managed smartly however, EVs can become a flexibility resource able to aid in their own integration and that of higher shares of variable renewables or other distributed energy resources into the grid.

Advancing technologies and reducing battery costs

In the SDS, annual EV battery deployment is 30 times higher by 2030. Reaching this level of deployment will require continued cost reductions, and battery efficiency and density improvements beyond what can be achieved with current technologies.

Electric cars currently cost more to purchase than similar-sized conventional cars, and even from a total cost of ownership perspective (including operational costs such as fuel), the economic advantages of electrification are limited to a relatively narrow range of cases. The cost challenges related to EVs are primarily linked to the battery, one of the major cost components. Technological advances allowing for more compact batteries with longer ranges, extra durability (the capacity to withstand a large number of charge/discharge cycles without performance being affected) and the capacity to charge at very high power (fast/ultra-fast charging, from 100 kW to 1 MW), will also influence level of EV adoption.

Allowing EVs to become a flexibility resource for the grid

High EV uptake with unmanaged charging can pose a challenge for the power system if charging coincides with the high-demand periods of the main power system, resulting in greater peak demand and requiring additional peak generation capacity. Increasing EV uptake can also overload distribution networks and necessitate local power grid upgrades such as transformer replacements and cable reinforcement.

Conversely, if adequately managed, EVs can also provide demand-side response (DSR) solutions across a wide range of timescales. Unlocking DSR opportunities from the participation of EVs would help integrate a higher share of variable renewables such as wind and solar power as well as other distributed energy resources. This is a major opportunity given the challenges of electricity system operators to conciliate supply and demand while integrating greater shares of variable renewable energy and other distributed energy resources.

Rail

Expanding high-quality urban rail transport depends on political champions, thorough project viability and costs assessments and effective funding, as much as it does on technical issues. Equally important are sound construction, installation of the necessary equipment and hardware, and well-managed operations.

Digital technologies can be used to help integrate rail with other transport modes, provide superior service and increase utilisation to raise revenues and reduce costs.

Digitalization of rail: automation, management and control systems

By reducing the time and distance between trains, digital technologies can facilitate more intensive use of rail infrastructure, which increases capacity and boosts investment returns while improving user convenience and maintaining high safety standards.

Establishing and expanding urban rail networks in existing and future large cities

A rich literature finds that the provision of reliable, convenient, and affordable public transit, and in the case of large cities, metro and light rail, not only reduces the per capita transport emissions in these cities, but can also contribute substantially to reducing levels of pollutants associated with road vehicles, and also enables reductions in the macro- and micro-economic costs of providing urban mobility.

Other studies identify economic and equity benefits that come from urban rail systems.

International shipping

To put international shipping on the SDS trajectory, it is essential to switch to low- and zero-carbon fuels, as they barely figure in the maritime fuel mix.

Interest in using alternative fuels such as ammonia, hydrogen or advanced biodiesel and ammonia mounted significantly after the IMO adopted its initial strategy to reduce GHG emissions from ships by 2050. This agreement happened shortly before the implementation of Emission Control Areas (which limit sulphur oxide [SOx] and particulate matter [PM] emissions near ports) and tighter sulphur emission regulations, which will come into force in 2020.

Although advanced biofuels, hydrogen and ammonia are potential low-carbon options to replace conventional fuels, an important uptake barrier is their high cost compared with conventional fuels. In the cases of ammonia and hydrogen, another barrier is the lack of infrastructure.

Transitioning to low-carbon ammonia or hydrogen fuel

In addition to diversifying the sources of maritime fuel supplies, adopting alternative fuels would help meet the tighter sulphur standards coming into effect in 2020; alternatives to bunker fuel will also be needed to meet SOx and PM emissions limits near a growing number of the world's ports (Emission Control Areas). These near-term air pollution targets can generally be met by switching to low-sulphur diesel or investing in scrubbers, and liquefied natural gas (LNG) is also an option because it does not emit SOx.

Oil demand in this fast-growing sector is set to rise 20% (to 6 million barrels per day) by 2030 unless measures are taken to enforce the IMO's long-term GHG emissions target. Ship owners must therefore make some important decisions very soon.

In the long term, GHG emissions from international shipping must be cut by at least 50% by 2050. A challenge to meeting this IMO target is that ship lifetimes generally span two to three decades. However, depending on eventual costs and incentives, using ammonia or hydrogen could be a solution.

Aviation

Aviation is likely to be the most difficult transport sector to decarbonise.

The largest potential efficiency gains can be obtained by completely redesigning aircraft. Considering the long lead times and investment required, such measures are unlikely to be commercialised by 2030. However, "clean sheet" wing and tube aircraft have the potential to reduce fuel burn by 40% (Kharina, 2017).

In addition to research and trials of new, more efficient aircraft designs, adoption of alternative, low-carbon jet fuels will be needed to reduce CO_2 emissions. Technology and scale-up barriers in producing such fuels can be best addressed through direct support from governments, incentives and standards.

Nearer term solutions, such as improving flight routing systems and switching to hydrogen and/or electricity during taxiing, can also improve the overall efficiency of the sector.

Shortening flight distances through better routing

Considerable fuel is wasted due to inefficient routing. While providing the same service, better flight routing could limit inefficient passenger activity growth and cut consumption by as much as 10%.

Innovation gaps in buildings

Transitioning to high-performance buildings by 2030 will require technical innovation to meet the energy needs of a variety of building types in multiple regions. Innovation is particularly needed to raise investment returns for high-performance building envelope technologies, taking energy prices, labour costs and the nature of the building design or retrofits into account.

Building envelopes

Boosting construction of high-performance buildings by 2030 will require innovative technical solutions and business models to meet the energy needs of a variety of building types in multiple regions. Innovation is also needed to improve investment returns for high-performance building technologies, taking energy prices, labour costs and the nature of the building design or retrofits into account.

Advanced windows

Windows are estimated to be responsible for 5-10% of total energy consumed in buildings – and even higher for certain buildings (e.g. with all-glass facades). Highly insulated windows have great potential to reduce energy consumption in new buildings and in structural retrofits.

Maximising/minimising solar gains (depending on the region) can significantly reduce heating/cooling demand, especially in buildings with considerable glass. Optimising visible light transmittance can reduce lighting energy demand.

Advanced air flow, air sealing and ventilation controls

Airtightness is a strong determinant of energy demand in buildings. In cold climates, exfiltration through the building envelope accounts for a significant share of a building's thermal losses.

Infiltration of cold air can also cause mould and lead to material degradation, which affects the health of occupants and the lifetime of the building.

Proper control of air flows and ventilation is even more important in hot climates to keep buildings healthy and comfortable. Enhanced building designs can allow natural ventilation and maintain comfortable temperatures without mechanical assistance. Ventilation systems can also help keep buildings healthy by removing indoor air pollutants and controlling the thermal environment.

Integrated storage and renewable energy technologies for buildings

Integrated storage and renewable energy technologies for buildings (e.g. pairing clean energy production with local storage and energy use) can address multiple climate change mitigation objectives at once. One such solution is thermal energy storage, which can displace cooling and heating demand while also enabling higher penetration of variable renewable sources in the energy system. Integrated renewables (e.g. on a building's facade) can also enable greater energy production, as the related area usually is much larger than rooftop space.

Heat pumps

Heat pumping technologies for space heating already exist and will deliver significant efficiency improvements and considerable CO_2 emissions reductions in many countries.

Innovation could help to address some known market issues, including high upfront prices and a lack of adaptability to multiple building contexts (e.g. multi-family residential buildings with limited outdoor space for exterior heat pump units). While packaging products can increase marketability, multiple synergies with other energy technologies such as solar PV and district heating networks could also be exploited to enhance system flexibility and efficiency.

Raise heat pump attractiveness

Increasing heat pump attractiveness would buttress the clean energy transition, ensuring good heating equipment efficiency that can be employed affordably in different building applications and with other clean energy technologies such as solar PV and energy storage. Further R&D investments would address many barriers to heat pump deployment by making them more compact, easier to install, more efficient, less carbon-intensive and more flexible than conventional heat pumps through enhanced interactions with the grid.

Enhance heat pump flexibility

Greater electrification of heat (and other end uses such as space cooling) will place greater pressure on electricity systems, requiring not only improved energy efficiency but also greater flexibility through demand-side response. Markets with high shares of electric heating (e.g. France) illustrate the impact of electric heat demand during the winter and on extremely cold days. Heat pumps with high energy performance factors can help reduce the overall tendency of demand peaks, but flexibility through demand side response will still be required to shift some demand to off-peak hours.

In addition, heat pumps have the potential to provide electricity grid stabilisation in the context of grid decarbonisation, especially with increasing shares of variable renewables in the energy mix.

Reduce costs of geothermal heat pump technologies

While extremely efficient, GSHPs are more expensive than other heat pump systems primarily due to installation costs, though these vary depending on the type of installation (e.g. shallow vs. deep drilling). Their reaction time to rapid or extreme temperature changes can also be long.

Geothermal technologies could help overcome multiple barriers to the decarbonisation of heating and cooling, such as increasing system efficiency by providing heating and cooling services at the same time, since commercial buildings often have simultaneous heating and cooling demand. Residential buildings can also have cooling demand at the same time as domestic water heating needs (e.g. during the summer).

Cooling

Improving AC energy efficiency will be critical to weaken cooling demand growth. While improving the efficiency of vapour compression technology is a priority, other high-efficiency solutions can also reduce the energy and environmental footprint of cooling.

Among the potential technologies, liquid desiccant evaporative cooling is an option that requires additional R&D to better understand its performance and the design requirements needed to support deployment.

Fully integrated solar PV cooling solutions

Until recently, solar energy was too expensive to be used in most cases to directly drive air conditioning units. This is why solar cooling has not been developed beyond the R&D and demonstration levels; solar PV is especially rarely used for vapor compression devices. With the arrival of competitive solar distributed PV electricity, however, integrated solar PV cooling solutions are needed to take advantage of local electricity production.

Research needs into potential for liquid desiccant cooling

This technology, particularly suitable for hot and humid areas, cools and dries air using a liquid desiccant to simultaneously dehumidify and cool. Liquid desiccant cooling systems typically use liquid water-lithium as the sorption material and can operate on low-grade solar energy (i.e. lower temperatures), allowing for high density and less energy storage in the concentrated desiccant. Desiccants can dry the air without first cooling it to the dew point: when the desiccant is saturated with moisture from the air, solar thermal energy is applied to dehumidify it, ultimately providing air conditioning.

Reducing the costs of solar thermal cooling

Solar thermal cooling systems typically combine heat-driven ad/absorption chillers, desiccant evaporative cooling, solar thermal collectors and thermal storage (hot water tank, phase-change material [PCM] or ice storage). The temperature of the solar thermal system depends on system composition, ranging from 40-70°C for traditional flat plate collectors with desiccant evaporative cooling, to 250°C for Fresnel collectors (a linear concentrating solar thermal collector) with absorption chillers.

In conventional AC systems, the sensible load reduces the temperature of the air until it reaches 100% relative humidity. The latent load then removes the moisture from the air, but this usually results in the air being too cold for thermal comfort, so it must be reheated using additional energy. Humidity (or rather the latent heat that humidity contains) is responsible for a large share of the cooling demand in many countries.

Solar thermal cooling systems with one solid/liquid desiccant wheel could reduce cooling demand significantly, as they do not require extra energy for reheating.

Appliances & equipment

Technology already exists and is readily available to improve the energy efficiency of appliances and equipment. Conventional policy measures can be employed to drive markets to adopt these more efficient technologies and put appliances and equipment on track with the SDS.

Innovation remains important to achieve mass deployment of products with even higher efficiency. Technology improvements include vacuum-insulated panels for refrigerators, heat pump technology for tumble dryers and improved silicon for electronic equipment. Innovation will also be required to continue reducing the cost of manufacturing equipment while improving energy efficiency and related performance. Furthermore, to take advantage of digitalisation benefits, consumer-friendly energy management tools are needed for smart appliances and equipment.

Development of vacuum-insulated panels and insulating materials for refrigeration.

In 2018, global electricity use by residential refrigerators and freezers was around 500 TWh and is expected to rise a further 35% by 2050. The efficiency of residential refrigerators can be doubled through known technology, such as using more insulation (though noticeably reducing useful internal space) and better compressors. The use of effective vacuum-insulated panels (VIPs), however, would raise energy efficiency while also increasing internal refrigerator volume (for the same external area), providing better service for consumers.

High cost of heat pumps in tumble dryers

Tumble dryers use a considerable amount of energy when in operation – globally energy consumption is approaching 100 TWh annually and is expected to more than triple by 2050 as ownership and use expand. Heat pump technology is therefore important, as it can significantly improve tumble dryer energy efficiency.

Data centres & networks

Demand for data centre and data transmission network services is expected to continue to grow strongly over the next decade. Innovation will be critical to ensuring that energy efficiency gains continue to keep overall energy demand in check.

Accelerating energy efficiency of mobile networks

Global internet protocol (IP) traffic is increasing rapidly, and is expected to triple by 2022. This traffic is increasingly shifting to wireless and mobile: wireless and mobile devices expected to account for more than 70% of traffic by 2022, up from around half in 2018.

This shift toward greater use of mobile networks may have significant implications for energy use, given the considerably higher electricity intensities (kWh/GB) of mobile networks compared with fixed-line networks at current traffic rates.

Applying artificial intelligence in data centres

Demand for data centre services is expected to continue to grow strongly after 2020, and data centre energy use will continue to be largely determined by the pace of energy efficiency gains. While the continued shift to efficient cloud and hyperscale data centres will reduce the energy intensity of data centre services, applying artificial intelligence (AI) and machine learning to tap further efficiency gains may become increasingly important.

Lighting

Although the shift to solid-state lighting (SSL) products is gaining momentum, LED technologies have not yet reached maturity. There are still innovation gaps that make it challenging to continue improving the efficacy of LEDs (to exceed 160 lm/W by 2030), develop the best regulation metrics (with respect to energy performance and light quality), and ensure that smart lamps and luminaires generate energy savings.

Defining and enhancing the quality of light for high-efficacy LED products

Closing the technical gaps for SSL sources and components can not only increase the efficacy of lighting products, but also ensure they provide high-quality light at prices that are competitive with the less-efficient, older technologies (such as fluorescent, halogen and incandescent lamps). Clear policy guidelines on quality and performance are therefore needed for SSL improvements.

Ensuring policy makers have the best metrics for regulation

Policy makers need robust and relevant metrics to set appropriate quality and performance requirements. With the transition to SSL, some of the lighting metrics have become outdated and are no longer the best for determining policy measures. For example, the 'colour rendering index' (CRI) metric was developed in the 1930s and uses an incandescent lamp spectral output as its reference source. This means that lamps mimicking incandescent light output will score 100 and other spectral outputs that have been judged more visually appealing score lower.

Ensuring energy savings through smart lamps and luminaires

Smart lamps and luminaires could significantly reduce electricity consumption for lighting by adjusting to daylight levels, room occupancy and interactions with building energy management systems. However, the additional energy used for network communications and rebound effects may offset these savings if clean energy policies and technologies do not provide appropriate solutions for growing consumer expectations.

Innovation gaps in energy integration

Hydrogen

Almost all hydrogen production is currently derived from natural gas steam reforming and coal gasification. Such hydrogen can be produced economically, but it leaves a large carbon footprint. To get in line with the Sustainable Development Scenario (SDS), emissions need to be reduced through the use of other production methods such as electrolysis using low-carbon electricity and fossil fuels with CCUS. However, as demand for low-carbon hydrogen is marginal, these production methods are still costly. It is essential to raise demand for clean hydrogen considerably to reduce its cost.

Reducing the cost of hydrogen applications is also important. Through fuel cell technology, hydrogen could provide a low-carbon solution in transport. However, even though five years have passed since FCEV commercialisation, the global stock is at only 11 200 vehicles. Reducing vehicle cost and increasing the availability of hydrogen refuelling stations is crucial to raise FCEV deployment.

Advanced Electrolysis

Hydrogen can be an important part of energy system decarbonisation, particularly in hard-to-abate sectors that have few alternative mitigation options, such as steelmaking and aviation. Today water electrolysis accounts for less than 2% of total global hydrogen production, but as low-carbon electricity becomes more available (owing mainly to less expensive generation from renewables), water electrolysis could become a key option for supplying low-carbon hydrogen. Electricity is currently the primary cost component for hydrogen production from water electrolysis, so improving electrolyser efficiency will be a development objective in the years ahead. Future capex and opex cost reductions are also possible, especially as electrolyser units become larger and industrial production scales up. Creating hydrogen demand will be essential to achieve this scale, however.

Cost-competitive fuel cell system for FCEVs

There are two main types of zero-emissions vehicles: BEVs and FCEVs. Because of the long charging time and short range of EVs, FCEVs hold promise as a complementary technology, but they remain costly and their availability is limited. Transport modes such as trucks, buses, maritime and locomotive applications, may particularly benefit from fuel cell rather than pure electric, battery-based drivetrains. Several steps can be taken to reach cost targets: reduce precious metal use by downsizing the fuel cell stack; boost production of fuel cells and all ancillary components to obtain economy-of-scale cost reductions; and deploy targeted refuelling infrastructure tailored to specific modes and applications.

Novel hydrogen production methods

A combination of reforming plus CCS and electrolysis will be necessary for early hydrogen markets in the coming two decades. In the long term, however, renewable hydrogen conversion processes, including biological processes, electro-assisted or photo-assisted electrochemical water splitting, as well as photoelectrochemical and bio-inspired technologies, will be key alternatives to produce hydrogen at scale and sustainably, i.e. minimising energy use, water needs and materials.

In addition to energy delivery (e.g. through hydrogen and methane), another key attraction of biohydrogen is the possibility to simultaneously treat waste and low-grade biomass feedstocks and recover water and other valuable resources. Although replacing platinum will be a major technological and economical obstacle to large-scale fuel cell deployment, producing hydrogen from waste/biomass or water and sun without electrolysis will cut production costs at the local level and could help promote a circular economy for local communities.

Hydrogen from fossil fuels with CCS

In most parts of the world today, the most cost-effective means of producing hydrogen with a reduced carbon footprint is to use CCS. The overwhelming majority of hydrogen is produced from natural gas and coal, resulting in around 800 million tonnes of CO_2 emissions per year. CO_2 capture can be applied to hydrogen production at a relatively low cost, and seven such facilities have begun operating since 2005. The CO_2 can be safely and permanently stored underground, as at the Quest facility in Canada, where low-carbon hydrogen is used to upgrade oil sands bitumen to synthetic crude.

However, most of the facilities for CO_2 capture from fossil fuel-based hydrogen production are for supplying hydrogen to facilities such as oil refining and ammonia production, which require a constant and uninterrupted source of H_2, allowing for constant CO_2 capture. In addition, these facilities currently capture only up to two-thirds of the CO_2 produced.

To reap the potential benefits of the relatively low costs of CCS for clean hydrogen production from abundant fossil fuels, it must be demonstrated that these two issues can be overcome. The objective is therefore to couple the potential cost, scale and industrial benefits of CCS with the emissions profile and flexibility of the main competing option: water electrolysis using low-carbon electricity.

General annex

Abbreviations and acronyms

AC	Alternative-current
AI	Artificial intelligence
AUSC	Advanced ultra super critical
BCSA	Belite calcium sulphoaluminate
BEV	Battery electric vehicle
BOS	Balance-of-system
BtL	Biomass-to-liquid
CANDU	Canada Deuterium Uranium
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CEM	Clean Energy Ministerial
CERT	Committee on Energy Research and Technology
CETP	Clean Energy Transitions Programme
CRI	Colour rendering index
DRI	Direct reduced iron
DSR	Demand-side response
EERA	European Energy Research Alliance
EESL	Energy Efficiency Services Limited
EGS	Enhanced geothermal systems
ERS	Electric road system
ETIP	Energy technology innovation platforms
ETWG	Energy Transitions Working Group

EU	European Union
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
GDP	Gross domestic product
GHG	Greenhouse gas
HJT	Heterojunction technology
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
IEA	International Energy Agency
IGO	Intergovernmental organisations
IMO	International Maritime Organisation
IP	Internet protocol
LDAR	Leak detection and repair
LDV	Light duty vehicles
LED	Light-emitting diodes
LNG	Liquefied natural gas
LWR	Light-water reactors
MI	Mission Innovation
OPC	Ordinary Portland Cement
OTEC	Ocean thermal energy conversion
PCM	Phase-change material
PERC	Passivated Emitter and Rear Cell
PM	Particulate matter
PV	Photovoltaics
R&D	Research and development
RD&D	Research, development and demonstration
SDS	Sustainable Development Scenario
SMR	Small Modular Reactor

SSL	Solid-state lighting
SUV	Sports utility vehicle
TCEP	Tracking Clean Energy Progress
TCP	Technology Collaboration Programmes
TPES	Total primary energy supply
TRL	Technology readiness level
US	United States
USC	Ultra super critical
VC	Venture capital
VIP	Vacuum-insulated panels
WAG	Works arising gases
WEC	Wave energy converters

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