#Renewables4Climate

IRENA
International Renewable Energy Agency

RENEWABLE ENERGY INNOVATION: ACCELERATING RESEARCH FOR A LOW-CARBON FUTURE

» For one-third of the world's anticipated energy use in the coming 20-25 years, no practical decarbonisation solutions exist today. Nearly all of this relates to energy demand for end uses, such as buildings, heat and transport.

» Research and development (R&D) needs to happen faster to make renewable solutions viable in these areas.

» Renewable power already makes good business sense. Fully realising its potential, however, requires further innovation to optimise system integration.

INNOVATION IS CRUCIAL FOR THE DECARBONISATION OF THE ENERGY SECTOR

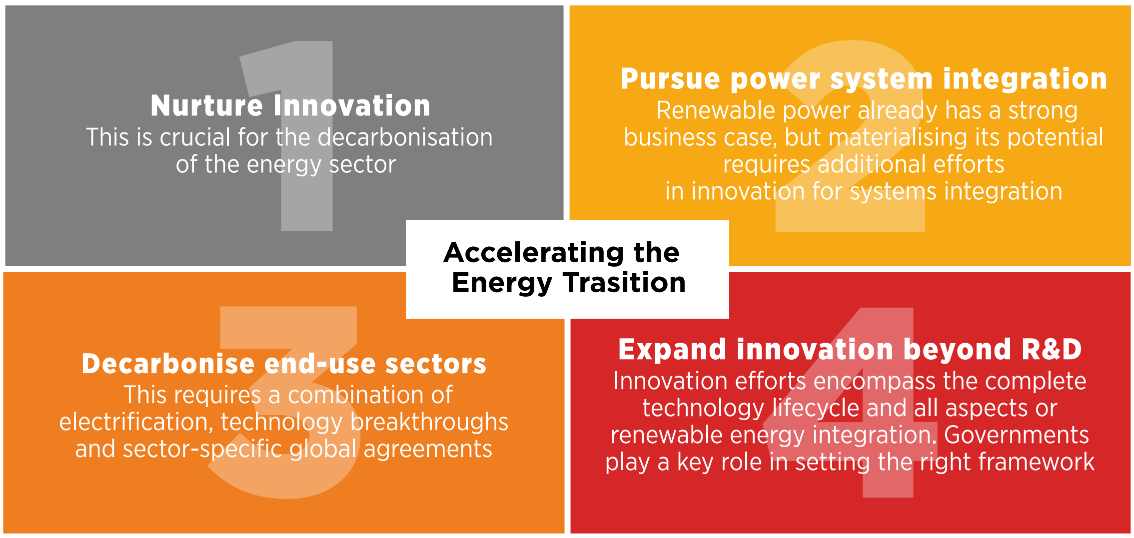
The worlds's energy transformation is accelerating. This is due to a combination of technological progress, developmental priorities and rising environmental concerns. Past experiences suggest that energy transformations were driven primarily by economic opportunity and technological development, not fuel resource scarcity. The ongoing transformation is evolving in the same vein, with innovation as one of its pillars.

The International Renewable Energy Agency (IRENA) estimates that by 2050, the accelerated deployment of renewables and energy efficiency can achieve 90% of the emissions reductions needed to achieve Paris Agreement climate goals.[1] This is, however, a major undertaking that requires significant acceleration in the deployment of existing solutions and additional innovation efforts. Given the rapid rate of change, an ongoing review is needed to focus efforts on priority areas and policy frameworks necessary to achieve energy transformation (IRENA, 2017e).

Looking beyond the power sector at total energy supply, economically scalable solutions are available for around two-thirds of supply requirements. For the remaining one-third, no solutions exist today. These solutions are needed most in end-use sectors (IRENA, 2017a).

On the one hand, we need innovation to accelerate deployment: driving cost reduction, improving performance and enabling integration of existing and emerging renewable technologies in energy systems. On the other hand, innovation is also needed to unearth and develop new technologies. Incremental improvements will continue to foster significant progress, but may not lead us to a complete transformation of the energy sector – game-changing technologies and approaches will be needed as well. Whether today's breakthroughs and early-stage technologies will become commercially available, and how soon, is difficult to determine in advance. Many new technologies for achieving decarbonisation undoubtedly have yet to be envisioned, and the solid prospects of today's solutions are no reason for inaction given the serious consequences of climate change.

Figure 1 Strategy for accelerating the energy transformation



[1] Limit global temperature increase to well below 2 degrees Celsius (2°C) above preindustrial levels.

Despite the encouraging progress observed in the power sector, policy makers need to further encourage both incremental R&D and breakthroughs, nurturing all phases of the technology life cycle, from early-stage research to commercialisation. Importantly, accelerating the deployment of the available low-carbon technologies requires not only continuous technology improvement, but also innovations to integrate those technologies. Innovation policy needs to be broader than technology R&D. Beyond generation technology, system integration entails innovation in infrastructure, new ways to operate energy systems, innovative business models to monetise services, and enabling policies and financial instruments. The four elements to be included in such an innovation policy framework for the energy sector are set out in Figure 1.

The growing number of initiatives that focus on innovation serve an important purpose to accelerate progress in R&D and technological innovation. But they need to align with priority areas. This brief offers the climate community suggestions for the means to refine and sharpen the innovation framework to better meet priority needs. Innovation is of paramount importance for energy transformation.

Decarbonising global energy use requires rapid innovation in electricity and other sectors

WHAT DOES ENERGY DECARBONISATION MEAN?

Decarbonisation requires global carbon intensity, the measure of an economy's carbon emissions, to be reduced by 85% over the next 35 years.[2] This clearly requires significant changes in the global energy system and the focus of this transformation should be directed toward the uptake of the most affordable and cleanest technologies.

Decarbonisation will require accelerated improvements in energy efficiency across all sectors to keep the total primary energy supply at the same level between 2015 and 2050 while the economy grows threefold in the same period. Energy efficiency is essential and the potential is large, but alone it is insufficient to achieve complete decarbonisation. Renewables are the other major component. Two out of three units of primary energy supplied must come from renewables by 2050. This requires renewables' share of total primary energy supply to increase at a rate of about 1.2% per year, an eightfold acceleration compared to the trend seen in recent years. To achieve this major increase in the share of renewables in the global energy mix, both faster deployment of available technologies and the development of new renewable energy technologies will be needed. Innovation must support both aspects (IRENA, 2017e).

[2] *Global carbon intensity CO_2 emissions per unit of GDP generated.*

MONITORING PROGRESS ON DECARBONISATION

The business case for renewable power

The power sector is by far the largest source of CO_2, accounting for about 40% of all energy-related CO_2 emissions. It is also the sector where the most significant advances are taking place. Since 2012, the bulk of capacity additions and investment in the global power sector have been in renewable energy (IEA, 2016). In 2016, 62% of added power capacity worldwide was from renewables. In the same year, solar PV capacity grew more than any other source of power generation (IRENA, 2017b). The economic case for renewable power is firmly established and is driven by rapid reductions in the cost of renewable energy. Innovation and the economies of scale have resulted in reductions of 80% in solar PV module costs over the past seven years. IRENA projects that this cost-decreasing trend will continue into the next decade (IRENA, 2016a).

Around the world, countries are raising their ambitions for renewable energy deployment. The leader in renewable energy growth, China, announced earlier this year that it was cancelling plans to build more than 100 coal plants (Mason, 2017). Saudi Arabia, as part of its newly announced 2030 vision, plans to invest up to USD 50 billion to achieve a target of 9.5 gigawatts (GW) of electricity from renewables by 2022 (El Gamal, Shamseddine and Paul, 2017). The generation of electricity from all types of renewables has currently reached about a quarter of all electricity supplied worldwide. Today, solar and wind power account for 2% and 7% of total generation worldwide, respectively. Each year the share of renewables is increasing by between 0.5% and 1% (IRENA, 2017b). Based on this trend, in 35 years renewables could supply 60% of all our electricity demand.

Countries such as Denmark, Germany, Portugal, Spain and Uruguay have proven that their power systems can manage a share of variable renewable energy (VRE)[3] higher than 25%, on an annual basis. However, there is no experience yet of countries managing power systems with a sustained penetration of VRE above 50% on an annual basis. Therefore, the next stage in innovation efforts has to address integration of very high shares of solar PV and wind. Innovation in operating and regulating power systems will offer new solutions, as well as innovative enabling infrastructure for renewable power systems based on advanced information and communication technologies (IRENA, 2015a; 2016b).

» **Analysis by the International Renewable Energy Agency (IRENA) outlines priority innovation areas by sector and technology, and for other critical areas such as policy and finance. It also provides a starting point to identify the key innovation areas to achieve decarbonisation.**

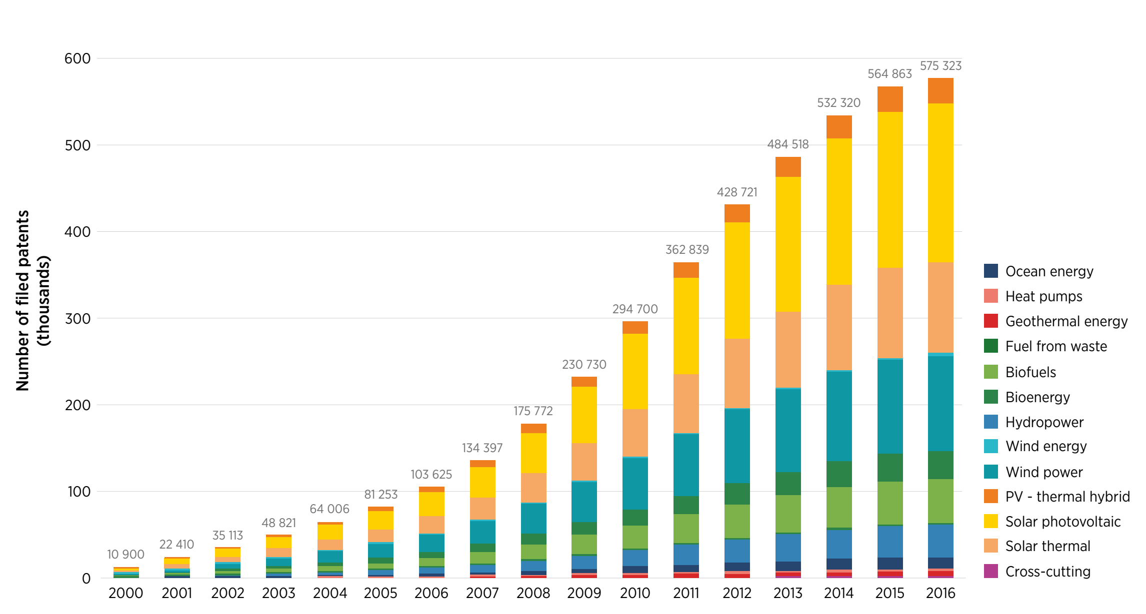
» **Technological innovation will not be sufficient. Innovation beyond technology R&D is necessary across the whole energy system, including for new system operations, innovative market design and regulation, out-of-the-box business models, and the enabling infrastructure to integrate renewables in energy systems.**

[3] VRE mainly comprises of solar PV and wind.

Renewable energy patent activity

Patent indicators show that renewable energy technology has experienced significant innovation in recent years (Figure 2). Renewable energy patents have grown at a rate above 12% per year since 1995, well above the average rates for other technology sectors (IRENA, 2017c). This provides a reassuring message on the prospects for future development of renewable technologies.

Figure 2 Renewable energy patents filed between 2000 and 2016



Source: http://inspire.irena.org

- **Nearly 600 000 renewables-related patents have been filed between 2000 and 2016**
- **The solar sector has seen the most progress, representing more than half of these patents**
- **Patents can help to assess the trajectory of future development**

Mixed technology success in end-use sectors

End-use sectors – industry, transport and buildings – represent 60% of all energy sector CO_2 emissions (Figure 3). So far, the deployment rates of low-carbon technologies in these sectors have been too slow to achieve significant emission reductions (IEA, 2016).

The industrial sector has managed to limit the growth of its energy demand in the past few years thanks to the continued uptake of energy efficiency technologies (IEA, 2017a). The sector is unique as fossil fuels are not only used for energy, but also as feedstock to produce plastics and fibres, where carbon is an essential building block. Moreover, industrial processes such as cement making represent around a fifth of total industrial direct CO_2 emissions (IRENA, 2017e). The share of renewables in the industrial sector has remained flat for the past few decades at around 10% (IRENA, 2014a).

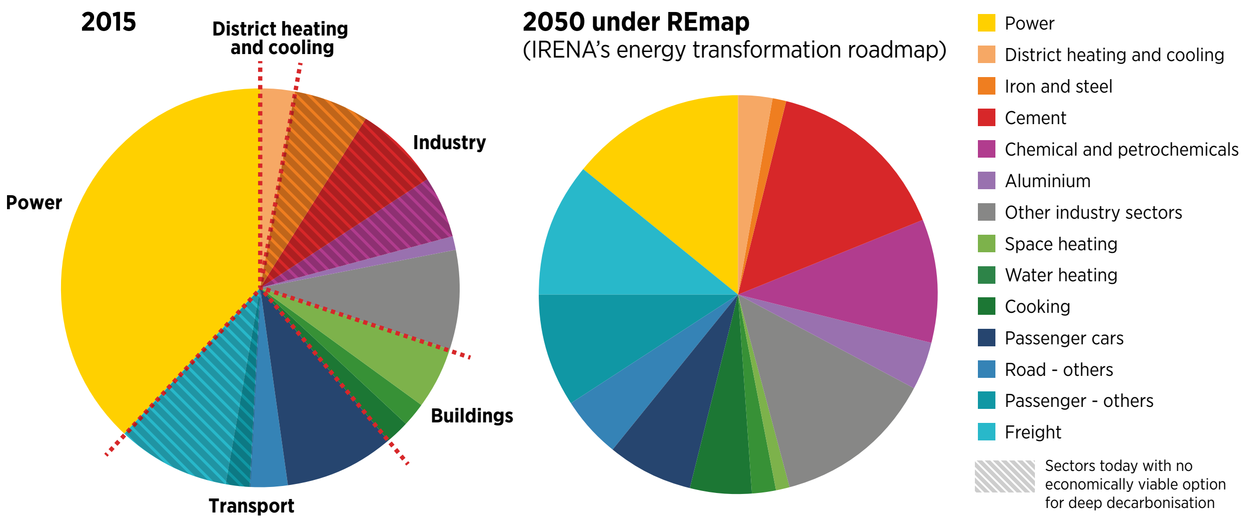
The transport sector is observing a sharp upward trend in the uptake of electric vehicles (EV). In 2016, new EV registrations hit a world record of nearly 800 000 units, around 1% of all car sales. In Norway, on average one out of every five cars sold is an EV. The 2 million threshold has now been crossed, and China, Japan and the United States (notably the state of California) account for around two-thirds of the total global EV stock (IRENA, 2017d).

The advent of EVs is going to be a game-changer for renewable power. Germany, India, Scandinavian countries and the United Kingdom are now committing to electric mobility by 2030 or 2040. China has announced an obligatory target of 10% EV in total car sales by 2019, and France and the United Kingdom have announced a ban on internal combustion engine vehicle sales by 2030. Progress in the use of transport biofuels is less promising than EVs. Biofuels today represent 2-3% of the total transport energy supply (100 billion litres fuel ethanol and 40 billion litres biodiesel) (BP, 2017; IEA, 2017b; RFA, 2017). Transport biofuel investments have been discouraged due to low fossil fuel prices and increasing sustainability concerns. Investment in new biofuel capacity has plummeted since 2009 – in 2015, it was one-tenth of that seen during the 2006/07 peak (IRENA, 2016c).

Buildings have experienced modest energy efficiency progress. They still lag in the fulfilment of their potential to reduce energy demand and increase the share of renewables. The technology and skills to build near zero energy buildings exist. However, the level of energy efficiency in many new buildings is still well below the technical potential. Renovation rates are also generally below the target level. Inefficient building stock in cold climates results in a significant amount of heating energy wasted. Related emissions are difficult to reduce without significant policy effort and financing options for citizens (IRENA, 2017e; IRENA, 2017a). Until 2014, promising growth was seen in renewable heat, notably for solar water heaters, but the world market has since shrunk (Weiss, Spörk-Dür and Mauthner, 2017). Heat pumps are another source of renewable heat, if they draw renewable power for their energy needs.

Roughly half of all renewable energy use is in the form of traditional uses of biomass – burning firewood – for water heating and cooking in buildings. Its share has been slowly decreasing in recent years, but the use of traditional biomass remains widespread, particularly in areas that lack affordable alternatives. Modern renewable solutions exist to reduce the traditional uses of biomass. The use of modern, clean cookstoves with improved solid biofuels such as briquettes and pellets can significantly improve both efficiency and indoor air quality (IRENA, 2016c). Ethanol gels, solar cookstoves and biogas are additional alternatives. Biogas is used in more than 50 million Chinese households today, thanks to a long history of development programmes that stretch back to 1960s (IRENA, 2014b). The trend in residential buildings is towards higher shares of electricity use in total energy demand, which also partly includes electric forms of cooking (IRENA, 2016c).

Figure 3 Changing breakdown of energy sector CO_2 emissions with accelerated uptake of renewables



No economically viable solutions yet exist for one-third of CO_2 emissions. Mainly heavy industry, long-haul trucking, aviation and shipping. By 2060 the world needs zero emissions. The emissions left in 2050 represent a real challenge, mainly in industry and transport.

THE NEED FOR TECHNOLOGICAL INNOVATION

The energy transformation has to be approached from a technical, policy and business perspective. It would be achieved largely by the accelerated deployment of renewable energy and energy efficiency measures (Figure 4).

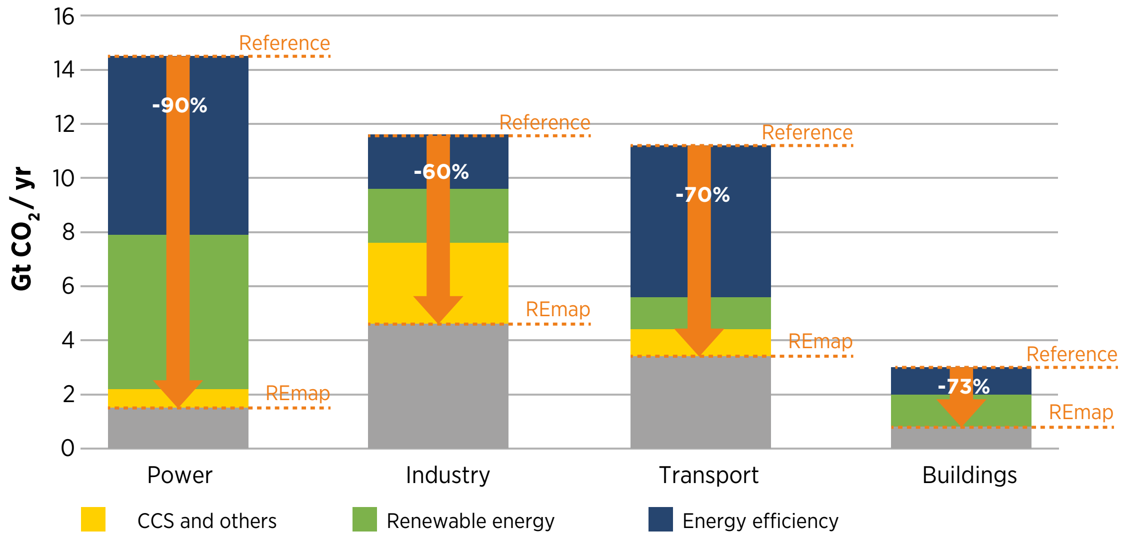
The **power sector** has the largest reduction potential, split roughly equally between renewable energy and efficiency of electricity use. Energy efficiency gains are due to reduction in demand and more efficient uses of electricity in buildings and industry.

Industry initially requires the deployment of all types of low-carbon technology, as well as efficiency in energy and resource use, followed by renewable process heat. Carbon capture and storage could also play a role for industrial processes involving high CO_2 concentration.

Transport requires a dual effort: major electrification coupled with renewable power (covered under energy efficiency) and the accelerated use of both conventional and advanced biofuels for applications where no other electric alternative exists. A modal shift from freight trucks, passenger cars and aircraft to renewable-powered electric railways will also be needed in areas where the development of such infrastructure is technically and economically feasible.

New **buildings** will need to be of the highest efficiency, while the retrofitting and refurbishment of existing ones must be accelerated. More renewable technologies must be used to supply the remaining energy needed for space heating/cooling and water heating, in combination with heat pumps and other types of electrification.

Figure 4 Technology needs for energy sector CO_2 emission reductions in 2050, compared to baseline



Reference: path set by today's plans and policies
REmap: accelerated renewable energy uptake, as per IRENA's REmap analysis

Notes: Gt = gigatonnes; CCS = carbon capture and storage

While the mix of options varies, renewable energy can play an important role in all sectors

DECARBONISATION REQUIREMENTS UNTIL 2050 AND TODAY'S GOOD PRACTICES

1. **Renewable power:** Supply 80% of power generation by 2050 from renewables (half of all generation from solar and wind) to significantly reduce coal use. Develop a combination of existing and new technologies such as storage and interconnectors, market and regulatory changes and new business models to enable this transformation.

   Today's good practices:
   - Germany maintained a power system that supplied electricity with a renewable share of 80% for several hours in 2015. Consumption of power from wind in Denmark averaged 42% in the same year.
   - Large-scale deployment of solar PV and onshore wind capacity at competitive prices in all parts of the world. Among many examples, to name but one: wind energy time shift and frequency response with sodium-sulphur batteries in Japan.

2. **Iron and steel:** By 2050, incentivise the development and accelerate the deployment of energy-efficient iron-making technologies, aiming to cover 80% of all production and achieve significant reductions in coal- and energy-intensive methods of traditional iron-making. Enhance the use of existing technologies such as scrap recovery, along with new technologies and fuels, such as renewable hydrogen.

   Today's good practices:
   - Sustainable production from plant matter, as exemplified in Brazil, where 160 small-scale blast furnaces with combined annual production capacity between 70 000 and 150 000 tonnes are producing up to 6 million tonnes of iron fired with charcoal from eucalyptus trees. Experimental work currently ongoing in other countries shows promising results. In Canada, for instance, a project aims to replace pulverised coal injection with sustainable charcoal to reduce GHG emissions by more than 20%.
   - Production of iron from the direct reduction of ore by using a reducing gas, primarily hydrogen and carbon monoxide. Initial investment and operating costs are lower than integrated steel plants. Moreoever, when hydrogen can be produced from renewable energy sources, it contributes further to emission reductions.

3. **Cement:** By 2050, increase the blending rates of clinker with its substitutes. Supply a higher share of clinker energy needs with biomass and alternative fuels. Reduce the energy demand of clinker production to approach the theoretical limit.

   Today's good practices:
   - Use of pozzolanic material and other materials (e.g. finely ground limestone, silica fume) as clinker substitutes as well as alternative fuels in clinker kilns.
   - Production of new cement types such as geopolymer cements.

4. **Chemicals and petrochemicals:** By 2050, increase the rate of mechanical recycling ten-fold and the share of biomass fuel and feedstocks to cover around a quarter of all energy demand to save on fossil fuel energy and feedstock needs for plastics production.

   Today's good practices:
   - Bioethylene, polylactic acid (PLA) and many other bio-based plastics produced in Europe, Southeast Asia, Brazil and the United States.
   - Carbon capture in nitrogen fertiliser production, as done by companies around the world.

5. **Aluminium:** By 2050, introduce new and emerging primary aluminium smelting technologies. Increase the share of recycling to cover about half of all aluminium supply to save on fuels for alumina (aluminium raw material) and electricity use for primary smelting.

   Today's good practices:

   - Most-efficient Hall Heroult smelting processes in China (in Xinjiang) and in Mozambique. Many aluminium smelters worldwide are located next to hydropower plants to source their electricity needs.
   - An aluminium smelter in Germany used as a battery to deliver up to 1.12 GW of flexible capacity.

6. **Passenger transport electrification:** By 2050, significantly ramp up EV sales to reach a share of around one-third of total passenger car stock. Triple the number of passenger-kilometres travelled by electric railways such as trams, metro and trains.

   Today's good practice:

   - Tesla Model S, BYD E6 and Chevrolet Bolt/Opel Ampera-e with driving ranges of more than 300 kilometres.

7. **Transport biofuels:** By 2050, reduce the cost of biofuels for jet aircraft by at least half with innovation and economies of scale, in order to supply more than one-third of all aviation fuels from such "bio-jet" fuels. Supply one-third of all energy demand for passenger cars and a quarter of all demand for buses from conventional and advanced liquid biofuels and biomethane.

   Today's good practices:

   - Advanced biofuel projects in China, India, Thailand and the United States.
   - Around 100 bio-jet fuel initiatives and the growing number of plants in the United States and rest of the world for production of bio-jet fuels from various routes.

8. **Buildings energy efficiency:** By 2050, utilise the potential from new buildings that will represent about two-thirds of the entire building stock. Ensure all new buildings are fossil fuel-free by 2020. Retrofit non-fossil fuel equipment or replace inefficient equipment in existing buildings in 2050 that will represent the remaining one-third of the building stock. Increase the ownership of efficient appliances and lighting that represent about one-third of buildings emissions.

   Today's good practices:

   - Total Concept method in the European Union for deep renovation of non-residential buildings in a profitable way.
   - Solar district heating/cooling in Austria, Singapore and several other countries.

9. **Buildings renewables use:** By 2050, supply one-third of all heating demand for buildings from solar water heaters. Increase the use of wood chips and pellets by more than 20 times to supply about 800 million tonnes for space and water heating.

   Today's good practice:

   - Solar water heater subsidy programme in Cyprus.

WHERE TO FOCUS INNOVATION

IRENA's analysis shows the required deployment rates for each carbon-reduction technology and sector, as well as where more R&D would be needed. Table 1 below summarises this analysis from the perspective of innovation by categorising each technology against four indicators:

- contribution to total CO_2 emission reductions in 2050 compared to a baseline
- required magnitude of capacity growth for decarbonisation
- status of innovation progress
- opportunities for innovation

Economically scalable solutions exist for two-thirds of global energy use

Questions and answers: Innovation needed for rapid energy decarbonisation

Technologies needed for decarbonisation	How rapidly is innovation progressing?	How much it contributes to decarbonisation in 2050 compared to baseline?[1] [%]	How much capacity needs to grow in 2015-2050?[2] [multiplyer]	What further opportunities exist for innovation?
Power generation				
Hydropower	On track	0.1	1.4	Retrofit existing plant; river basin planning; floating PV
Solar PV	On track	7.6	29	Building integrated PV
Solar CSP	Not viable at current pace	2.3	144	Cost reduction; low cost thermal storage; HT solar thermal applications
Onshore wind	On track	8.8	11	Arctic conditions; on site blade manufacturing; kites
Offshore wind	On track	1.2	33	Floating wind
Biopower	Lagging but viable	0.1	4	Sustainable, reliable, affordable biomass feedstock
Geothermal & OTEC	Lagging but viable	2.3	30	Deep geothermal; resilient and economic wave technologies
CCS for natural gas and biomass	Not viable at current pace	2.1	75	Assessment, coordination and cooperation for CO_2 storage; cost reductions for BECCS
Interconnector capacity	Lagging but viable	Enabling	5	Roll-out ultrahigh voltage; economic underground lines
Ultra high voltage DC	Lagging but viable	Enabling	-	
Smart grids	On track	Enabling	-	Standardised smart meters; equipment responding to price signals
Battery storage [3]	On track	Enabling	>20 000	Cost reduction; seasonal electricity storage
Energy efficiency in end uses	On track	14.1	2	
Demand side response	Lagging but viable	Enabling	-	Better understanding of potentials and their deployment
Various negative emission technologies	Currently not available	-	-	
New materials for advanced battery storage	Currently not available	-	-	

On track
Lagging but viable
Not viable at current pace
Currently not available [5]

Technologies needed for decarbonisation	How rapidly is innovation progressing?	How much it contributes to decarbonisation in 2050 compared to baseline?[1]	How much capacity needs to grow in 2015-2050?[2]	What further opportunities exist for innovation?
		[%]	[multiplyer]	
Industry				
DRI iron making hydrogen		0.3	11	Hydrogen energy systems at scale
DRI iron making gas + CCS		0.1	15	More demonstration plant
Blast furnace iron making +		1.8	-	Demonstration plant
CCS				
Blast furnace iron making biomass		1.2	16	Biomass supply at scale; extend application from small to large capacity blast furnaces
Clinker substitutes		0.9	3	Standards and applications
Clinker kilns + CCS		1.8	100	Demonstration plant
Clinker kilns biomass		0.9	11	Biomass supply at scale
Biomass for chemicals + recycling [4]		7.0	20	Biochemicals economics
Hydrogen ammonia production		0.1	1 000	Hydrogen energy systems at scale
Gas ammonia production + CCS		0.3	100	Economies of scale
Other renewables		2.6	6	Cost reduction for solar water heaters; biomass supply at scale and accessible at low cost
Material efficiency		4.1	2	Standards
Energy management systems ISO 50001		7.0	3	
CO_2 transportation and storage infrastructure		Enabling	-	Acceptance; MRV of retention
Biomass supply at scale		Enabling	-	Sustainable, affordable, reliable
Solar thermal aluminium smelting		-	-	-
Direct conversion of CO_2 to fuels and materials		-	-	-

Technologies needed for decarbonisation	How rapidly is innovation progressing?	How much it contributes to decarbonisation in 2050 compared to baseline?[1]	How much capacity needs to grow in 2015-2050?[2]	What further opportunities exist for innovation?
		[%]	[multiplyer]	
Transport				
EVs		11.2	675	High performance low cost batteries and charging infrastructure
Hydrogen vehicles		1.5		High performance low cost hydrogen vehicles
Conventional biofuels		0.3	4	
Advanced biofuels		1.8	600	Economic jet fuel
Energy efficiency		6.2	2	New power trains and lightweight materials
Railway infrastructure for modal shift		Enabling	-	
Biomass supply at scale		Enabling	-	Sustainable, affordable, reliable
Solar passenger cars		-	-	-
Electric airplanes		-	-	-

On track
Lagging but viable
Not viable at current pace
Currently not available [5]

Technologies needed for decarbonisation	How rapidly is innovation progressing?	How much it contributes to decarbonisation in 2050 compared to baseline?[1]	How much capacity needs to grow in 2015-2050?[2]	What further opportunities exist for innovation?
		[%]	[multiplyer]	
Buildings				
Zero energy buildings		0.6	100	Need for more stringent regulation
Energy renovation and existing stock		1.5	3	
District heating/ cooling with renewables		2.8	6	Strengthen renewable energy component
Clean cooking using renewables		0.6	17	Roll-out at scale; enabling policy frameworks
Solar assisted water/space heating systems		5.6	19	Roll-out at scale; enabling low temperature building energy systems
Heat pumps		1.2	60	Roll-out at scale; enabling low temperature building energy systems
Advanced lightweight materials for construction		-	-	-
New appliance technologies such as magnetic refrigerators, breakthrough materials for insulation and advanced smart heating, cooling and appliance use and control systems		-	-	-

On track

Lagging but viable

Not viable at current pace

Currently not available [5]

Notes: BECCS = bioenergy with carbon capture and storage; CCS = carbon capture and storage; CSP = concentrated solar power; DC = direct current; HT = high-temperature; MRV = measuring, reporting and verification; OTEC = ocean thermal energy conversion; – = not known or not applicable.

[1] This column shows the contribution of each technology to the annual CO_2 emission reductions of 32.5 Gt that needs to be achieved between the baseline (45 Gt) and a scenario which explores technology pathways for deep decarbonisation of the energy sector (12.5 Gt) in 2050. The sum of contributions of all technologies adds up to 100 per cent. The CO_2 emissions include energy-related emissions (fossil fuel, waste, gas flaring) and process emissions from industry. If only fossil fuel combustion related CO_2 emissions were displayed in the table, the savings would be 31 Gt (a reduction from 40.5 Gt to 9.5 Gt in 2050).

[2] This column shows the required growth in capacity (or activity) of each technology between 2015 and 2050.

[3] The total storage capacity from electric vehicles are also included here.

[4] Four technologies are included here: biomass use to generate process heat (5 per cent of all CO_2 emission reductions covered in this category) and as feedstock for production of high value chemicals (ethylene, propylene, butadiene and aromatics) (60 per cent) and better management of plastics end of life by increased deployment of highly-efficient energy recovery (22 per cent) and higher shares of mechanical recycling (13 per cent).

[5] This category of technologies does not include data on abatement potential due to its early development stage.

Several technologies stand out for their importance to CO_2 emission reductions. Energy efficiency technologies represent about 45% of all the emission reductions that are needed. Recent results appear mixed for innovation with energy efficiency technologies. For instance, energy efficiency improvements in appliance use in buildings and motor systems in industry (both covered under "energy efficiency in end uses" category) are on track. By comparison, industrial process heating efficiency improvements and the deployment of energy-efficient buildings lag behind their potential, but have the ability to catch up and therefore can be considered viable.

IRENA's analysis confirms the validity of pursuing energy efficiency first, as "low-hanging fruit" that offers early opportunities to realise considerable potential. The case for renewables is somewhat different.

Today's successful solar PV and on/offshore wind technologies account for just below 20% of the world's total CO_2 emissions-reduction potential. Their current rates of deployment must continue at even higher rates for the next 35 years. The installed generation capacity from these technologies must grow by between 10 and 30 times worldwide from current levels. This will be needed to power a growing number of EVs, which need to grow by nearly 700 times in the same period, contributing another 11% to CO_2 emission reductions. Together with energy efficiency technologies, they constitute three-quarters of the total emission reductions needed. The undertaking will be huge, but IRENA's analysis shows these options are technically and economically feasible to implement.

"Questions and answers" tables on the preceding pages highlight some signicant challenges remaining with several renewable energy technologies. In industry, biomass use as a fuel for process heating and as a raw material for chemicals production could contribute a large share of around 5%, but utilising this potential will not be viable with the current rate of progress. Production of bio-based chemicals must exceed market volume forecasts, overcome technical barriers of system integration and close the price gap with petrochemical counterparts. This is an area that certainly requires greater technological innovation.

More R&D will also be needed for renewables, as well as for enabling technologies. Based on their potential contributions to total emission reductions, renewable hydrogen, liquid biofuels and CSP all require greater research, development and demonstration to overcome barriers. CCS research needs to focus on industry and opportunities for coupling with biomass. All these technologies would cover a further 10% of the total emission reductions needed.

Even if all these technologies are successfully deployed by 2050, accounting for about one-third of the total global energy supply, innovation will still be needed. This is the case not only for new technology options, but also for non-technology strategies. Certain energy-intensive industries and air, maritime and freight transport require particular attention.

» For around two-thirds of the total energy supply, economical and scalable solutions are available.

» The power sector is on track to decarbonise, with vast untapped potential for renewable energy technologies and cost-effective options to reduce the carbon intensity of electricity for end uses to achieve deep emission cuts. These options should be implemented as a priority.

» The share of wind and solar photovoltaic (PV) in power systems can increase significantly to cover half of all generation by 2050. Effective integration of these variable sources will depend on accelerated innovation.

ACCELERATING THE ENERGY TRANSFORMATION THROUGH INNOVATION

Innovation has to go beyond traditional energy technology R&D. Innovation policy frameworks will need to have a balanced focus between support for technologies and for areas beyond technology.

Innovation is needed in sectors where decarbonisation options are limited, to find the solutions needed to mitigate the remaining emissions. The sectors with the lowest progress in innovation for decarbonisation, such as heavy industry as well as freight transport and aviation, are those where proper policy incentives and long-term perspectives are lacking. In industry, it is the production of energy-intensive commodities that poses the main challenge: cement making and the production of chemicals and petrochemicals such as nitrogen fertilisers, plastics and synthetic fibres. In these sectors, international competitiveness and carbon leakage have been major concerns. As a result, they have been largely exempt from ambitious emissions reduction efforts.

Accelerating the deployment of low-carbon technologies requires the creation of a level playing field. This is especially true for technologies that are more expensive than their conventional counterparts. One instrument to improve the economic viability of technologies and correct for market distortions is a carbon price. IRENA's analysis has shown that if a carbon price of USD 60 per tonne of CO_2 was applied to industrial sector technologies, about half of the technologies would still be cost-competitive (IRENA, 2017a). However, it is uncertain whether a uniform global carbon price will be attainable in the near future. Therefore, policy makers and the private sector need to work together to devise politically viable, economic and efficient decarbonisation strategies for the industrial sector. This challenge cannot be addressed by increased R&D investment alone; it also requires global sectoral approaches to help ensure industries remain cost-competitive whilst addressing concerns over carbon leakage from production plants relocating to countries with less stringent policies. Furthermore, these sectors cannot be transformed through national policies due to their global nature. Global agreements for the deployment of technology solutions are indispensable.

In transport, national emissions policies and regulations are aimed at achieving domestic goals (e.g. tighter emissions regulations for internal combustion vehicles that encourage deployment of EVs) and can improve the cost-competitiveness of some costly technologies and increase their deployment. Market instruments, such as correcting for harmful effects of fossil fuels from air pollution externalities that are not priced, are also important (similar to a carbon price). Sectors such as freight and aviation have non-technical barriers to emission reductions. Cross-border regulation of jet fuels in aviation and bunker fuels for maritime transport has yet to be addressed. Governments must find the right balance between focusing on technology solutions and creating an enabling environment for innovation so that the private sector receives the right incentives. Stable and long-term policy objectives are essential to attract private-sector engagement.

To date, the integration of variable renewables has been enabled by flexibility options such as grid reinforcements, demand-side management, energy storage, sector coupling and flexible conventional generation. However, the optimal strategy for integrating shares of VRE higher than 50% on annual basis by 2050 is not yet known. Integrating high shares of renewables requires innovation in all components of the energy system, including new system operations, innovative market design and regulation, out-of-the-box business models, and the enabling infrastructure.

Innovation has been addressed by many organisations, industry associations and increasingly through the establishment of new initiatives. In principle, initiatives are helpful as they develop priorities for sectors to accelerate progress on innovation. In order to ensure initiatives are impactful, they must be aligned with sector-specific innovation needs. The priority areas outlined in this report can also help adjust and complement focus areas suggested by initiatives such as Mission Innovation (MI) or the Breakthrough Coalition. Innovation requires close co ordination with the private sector, where its engagement must be organised more effectively to have a meaningful impact.

A broad understanding of the technology needs for decarbonisation exists. but many pathways will be available to get there. The uncertainty is even greater when the availability of technology and time required for technology deployment are considered. Numerous solutions may already be under consideration by academia, industry and governments, but new breakthroughs will emerge in the future. For instance, in the short and medium term, liquid biofuels and efficient powertrains constitute today's solutions for aviation emission reductions. In the coming decades, however, technologies which do not yet exist, such as electric aircraft, may be developed.

Policy makers need to be informed of all the options that are available today, and which may be commercialised in the future, to make informed decisions. Decarbonisation will therefore increasingly require the creation of enabling frameworks, and innovation efforts will need to expand beyond R&D. Innovation will be needed at the system level to create new business models, develop market design, regulation and policy instruments, and to increase financing. Finally, the decarbonisation of commoditised sectors requires innovation to be accompanied by global sectoral agreements on a clear low-carbon pathway.

» For end-use sectors – transport, industry and buildings – a combination of specific approaches will be required. Deployment rates for renewables in end-use applications need to accelerate in line with the emissions reduction pathway required to decarbonise the energy sector by 2050. In addition, broad and systems-wide electrification offers an immediate option to drive a large proportion of the change needed in end-use sectors.

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