SOLUTIONS TO INTEGRATE HIGH SHARES OF **VARIABLE RENEWABLE ENERGY**

A report from the International Renewable Energy Agency (IRENA)
to the G20 Energy Transitions Working Group (ETWG)

JUNE 2019

ISBN: 978-92-9260-135-5

Citation: IRENA (2019), *Solutions to integrate high shares of variable renewable energy* (Report to the G20 Energy Transitions Working Group (ETWG)), International Renewable Energy Agency, Abu Dhabi.

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

www.irena.org

Acknowledgements

Valuable external review was provided from G20 economies as part of the G20 Energy Transitions Working Group, including the Governments of Japan and the Republic of Germany. The report was prepared by Dolf Gielen, Asami Miketa, Emanuele Taibi, Francisco Boshell, Raul Miranda and Sean Ratka at IRENA.

Available for download: **www.irena.org/publications**

For further information or to provide feedback: **info@irena.org**

Disclaimer

CONTENTS

FIGURES

1. BACKGROUND

IRENA's ongoing work with the G20

Over the past five years, the International Renewable Energy Agency (IRENA) has been committed to supporting the work of the G20 by providing guidance on how to effectively, and substantially, increase the share of renewables in electricity systems to accelerate the ongoing energy transition. Most recently, the 2019 Japanese G20 presidency requested that IRENA draft a report summarising the current state and outlook of solutions to integrate high shares of variable renewable energy (VRE) – namely solar PV and wind power – in electricity systems.

IRENA has engaged with the G20 on the subject of the energy transition since 2015 when, during the Turkish presidency, IRENA was selected as the central co-ordinator of the G20 Toolkit for Renewable Energy Deployment, in co-operation with other international organisations. At the 2016 meeting in Beijing, presided over by the Chinese G20 presidency, energy ministers reviewed the progress made since the implementation of the Toolkit and adopted the G20 Voluntary Action Plan on Renewable Energy with the aim of substantially increasing the share of renewable energy by 2030.

During the German presidency in 2017, IRENA was requested to analyse options for decarbonising the energy sector to meet the objectives of the Paris Agreement, and to explore related investment implications. The Climate and Energy Action Plan for Growth attached to the 2017 G20 Leaders' Declaration also called upon IRENA to support the G20's efforts by providing a regular update on the energy sector's global transition and further investment needs.

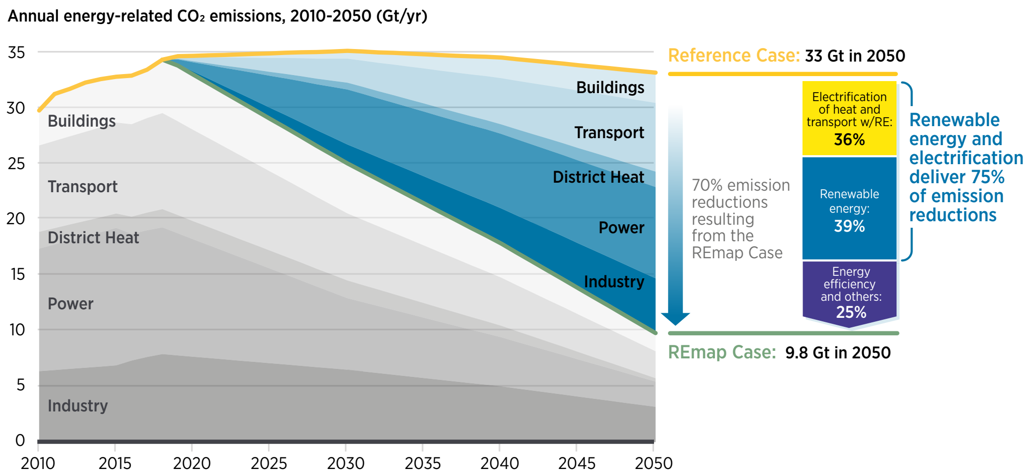
The 2018 Argentinian presidency highlighted the commitment of the G20 to working towards lower greenhouse gas (GHG) emissions and increased innovation in the field of cleaner, more sustainable energy systems. As part of active support of the G20 and the ongoing analysis of options for decarbonising the energy sector, IRENA produced an analytical report for the Argentinian presidency, Opportunities to accelerate national energy transitions through advanced deployment of renewables (IRENA, 2018a), that highlighted the importance of accelerated VRE power system integration.

This present report, requested by the 2019 Japanese G20 presidency, aims to summarise the most up-to-date information on a select range of innovative solutions to integrate VRE in power systems, drawing on IRENA's recent and extensive analysis on the topic.

The energy transition

To mitigate climate change, the global energy system must undergo a profound transformation from one that is largely based on fossil fuels to one that enhances efficiency, is based on renewable energy and pursues extensive electrification while increasing system flexibility. Renewables and energy efficiency, boosted by electrification, can provide 90% of the necessary reductions in energy-related carbon emissions to limit the global rise in temperature to well below 2°C by 2050 (Figure 1). Indeed, renewables and electrification alone would provide 75% of the reductions needed.

Figure 1: Annual energy-related CO_2 emissions in the reference case and reductions in the REmap Case, with the contribution by sector, 2010–2050 (Gt/yr)

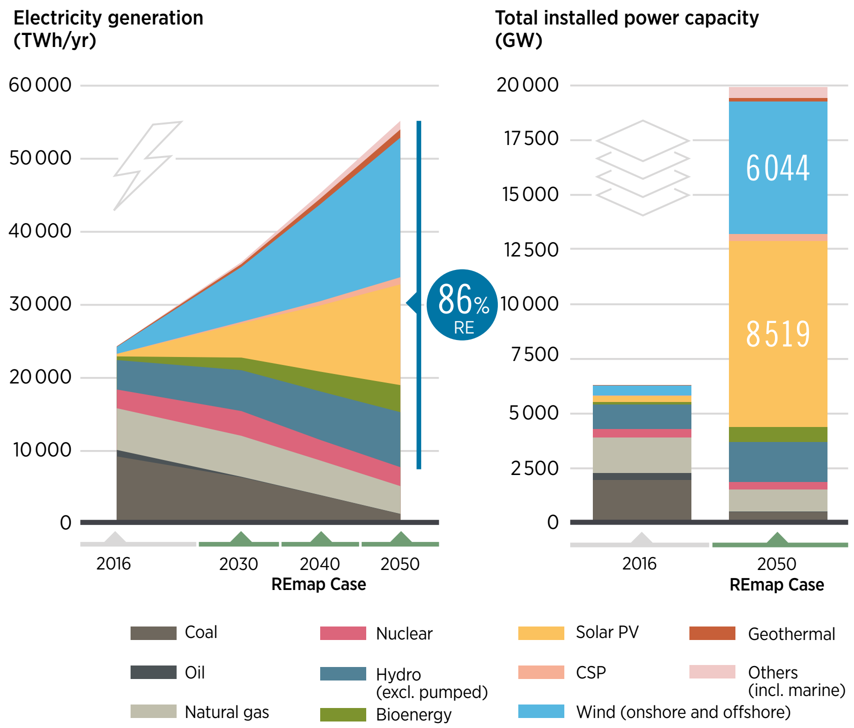


Source: IRENA (2019a).

Note: "Renewables" implies deployment of renewable technologies in the power sector (wind, solar PV, etc.) and end-use direct applications (solar thermal, geothermal, biomass). "Energy efficiency" includes efficiency measures deployed in end-use applications in the industrial, buildings and transport sectors (e.g., improving insulation of buildings or installing more efficient appliances and equipment). "Electrification" denotes electrification of heat and transport applications, such as deploying heat pumps and electric vehicles (EVs).

The energy transition is being driven by new technological innovation, coupled with policy imperatives relating to sustainable development and the need to combat climate change. Clean electricity will be the principal source of power, combined with "smart" digital technologies that make it possible to take full advantage of the growing amounts of low-cost renewable power. This vision unlocks the potential synergies between major increases in the use of electricity and renewable power generation by co-ordinating their deployment and use across key sectors – power, transport, industry and buildings. In a highly digitalised future with strong global climate policies, electrification of energy services will be pervasive. Electric or fuel cell vehicles would largely replace fossil-fuelled cars and trucks, and heat pumps and electric boilers would substitute for oil and gas furnaces in buildings and industry. Electricity from renewables could also be used to make hydrogen, synthetic gas or liquids for applications where direct electrification is difficult.

Figure 2: Electricity generation mix (TWh/yr) and power generation installed capacity (GW) by fuel, REmap Case, 2016–2050



Source: IRENA (2019a).

Note: 24% of electricity consumption in 2016 and 86% in 2050 is sourced from renewable sources. CSP refers to concentrated solar power.

Transforming our energy system into one dominated by renewable power comes with some challenges, as high variable renewable energy (VRE) shares increase system requirements for balancing supply and demand. Wind and solar PV energy are expected to substantially increase by 2050, from their current shares of 7% and 3%, to 35% and 25%, respectively (IRENA, 2019a). Figure 2 illustrates how, under the REmap case [1], wind and solar power will dominate growth in renewable-based electricity generation.

By 2050, solar power, with 8 500 GW installed capacity, and wind, with 6 000 GW, would account for three-fifths of global electricity generation. These are variable energy sources with fluctuating generation; therefore, addressing resource variability is crucial for their sustainable and cost-effective deployment, for which system innovations are required to achieve the requisite flexibility.

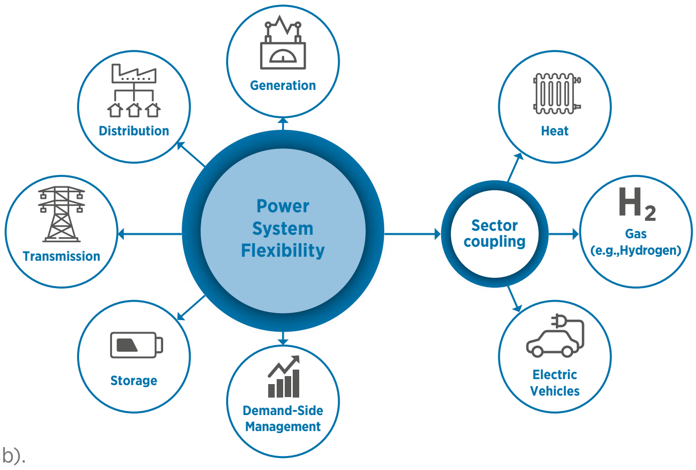
More about the ongoing energy transformation can be found in IRENA's recently released 2019 edition of **Global Energy Transformation: A roadmap to 2050** (IRENA, 2019a).

1 The Renewable Energy Roadmap (REmap) case is a scenario which includes the deployment of low-carbon technologies, based largely on renewable energy and energy efficiency, to achieve a transformation of the global energy system that limits the rise in global temperature to well below 2 degrees Celsius above pre-industrial levels. The scenario is focused on energy-related carbon dioxide emissions, which make up around two-thirds of global greenhouse gas emissions.

2. POWER-SYSTEM FLEXIBILITY: LEARNING FROM FRONT RUNNERS

To effectively manage large-scale VRE, flexibility must be harnessed in all sectors of the energy system, from power generation to transmission and distribution systems, storage (both electrical and thermal) and, increasingly, flexible demand (demand-side management and sector coupling); (Figure 3).

Figure 3: Power system flexibility enablers in the energy sector



Source: IRENA (2018b).

In conventional power systems, flexibility has mainly been provided by generation, with dispatchable generators adjusting their output to follow demand and, if available, pumped hydro dealing with inflexible baseload and reducing the need for power plants to cover peak demand. Important progress has been made in recent years towards increasing the flexibility of conventional power plants, as the demand side was largely unresponsive and provided very little flexibility. Emerging innovations are not only further increasing flexibility on the supply side but are now also widening the availability of flexibility to all segments of the power system, including grids and the demand side. They offer a broader portfolio of solutions that can be combined and optimised to reduce costs and maximise system benefits.

Various effective measures exist to integrate renewables at low costs by improving operational practice and electricity market design, as seen in a number of different countries. At a certain stage in the transition, more capital-intensive measures will be needed. These experiences have also revealed that challenges related to VRE integration (e.g. increasing curtailment levels and reserve requirements) do not emerge if the right procedures are proactively put in place. Technical solutions to VRE integration challenges almost always exist, so the limitation is largely economic rather than technical. Therefore, economically speaking, the maximum ideal level of VRE integration (economic carrying capacity) is the one at which any additional cost outweighs the benefits of the additional VRE unit and, therefore, no additional VRE capacity is economically desirable (NREL, 2015).

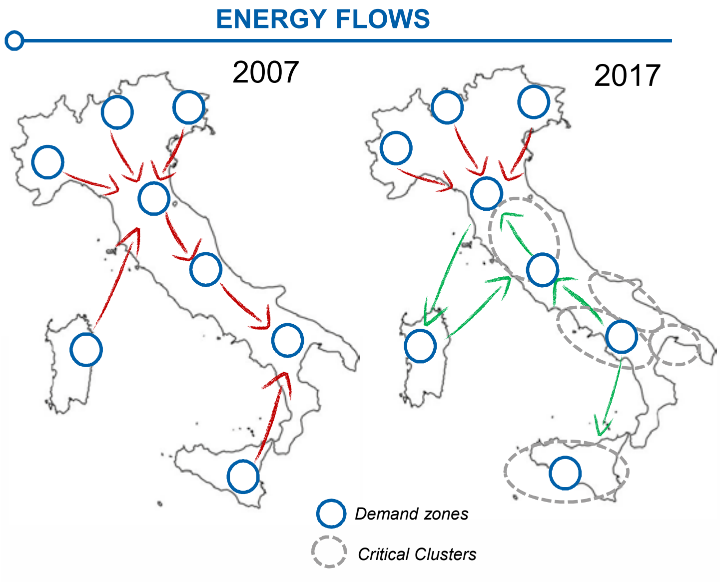
The IRENA FlexTool is a detailed but user-friendly tool developed by IRENA to address Member States' power system flexibility needs at a national or regional level. The IRENA FlexTool analyses system operations and assesses whether the power system is sufficiently flexible. If not, the FlexTool can identify a least-cost mix of flexibility investments. The tool has already been successfully applied to four different countries: Colombia, Panama, Thailand and Uruguay[2].

2 The IRENA FlexTool can be freely downloaded from the IRENA website along with a user manual and an overview for policy makers (IRENA, 2018b).

Experience in Italy

Initial measures usually comprise better operational practices and grid code improvements. This has been the case in Italy, for instance, which began developing solar PV and wind projects in the early 2000s. VRE capacity rose from roughly 1 GW to almost 5 GW within five years (2004–2009) – largely installed in southern regions while main load centres remain in mid-northern cities. This changed energy flow patterns (Figure 4) and led initially to energy congestion and curtailment (Figure 5). In 2018, solar PV and wind installed capacity in Italy eclipsed 20 GW and 10 GW, respectively.

Figure 4: Energy flow dominant paths in Italy



Source: Carlini (2018).

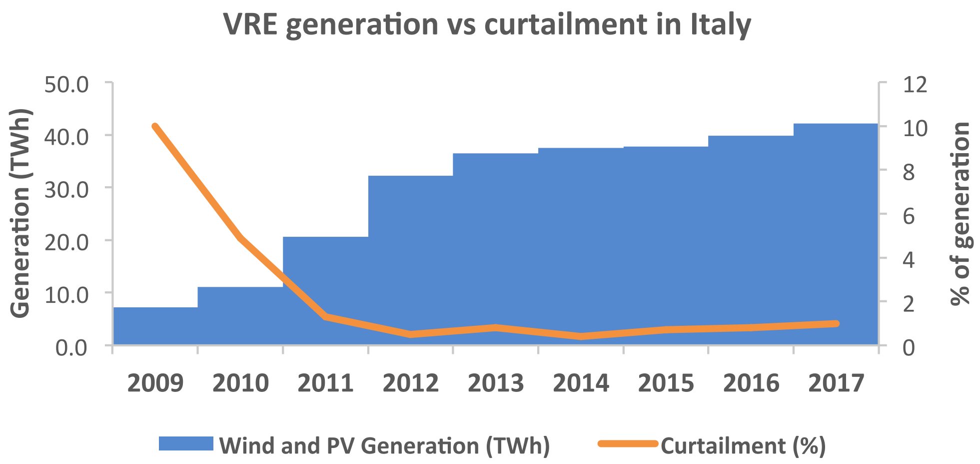
Note: Green lines represent transmission assets that had their dominant paths altered in the period 2007–2017; red lines in 2017 remain unchanged from 2007.

Disclaimer: Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

Since then, a set of measures has been applied in the country, with Dynamic Line Rating (DLR)[3] contributing greatly to easing curtailment due to transmission constraints. DLR is a relatively low-cost measure with a short lead-time that has been instrumental in significantly reducing curtailment levels down to 1-2% in Italy in a very short period. Such levels have remained almost unchanged since then, with the help of other measures that have followed, such as transmission expansion and the current development of smart grids in the region of Puglia. Besides supporting increasing amounts of distributed solar PV generation, which requires active management of the network, the smart grid project should also allow for the near-term phasing out of a large coal power plant that has remained in operation to control voltage in the region (e-distribuzione, 2019). Within this context, synchronous compensators have reduced the number of plants considered essential for the security of the grid in Sardinia, saving millions of euros.

3 Dynamic Line Rating refers to the activity of dynamically adjusting current capacity of transmission lines based on environmental conditions such as local temperature, solar irradiation and wind speed and direction. As a general illustration, line capacities tend to be higher under low-temperature environments and decrease as temperature increases. It opposes static line rating in which the capacity to transmit energy is based on average-static environmental conditions and remains flat irrespective of current weather conditions. This approach is largely considered when setting line parameters.

Figure 5: Variable renewable generation and curtailment in Italy

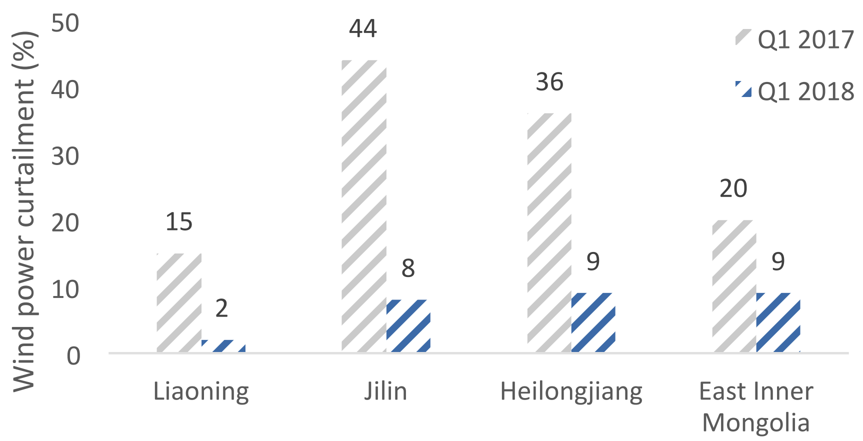


Source: Carlini (2018).

Experience in China

High curtailment has been reported in China in parallel with rapid VRE deployment over the past decade[4]. However, a set of actions has helped to accommodate increasing shares of solar and wind, substantially decreasing curtailment levels as a result (Figure 6). Like many other countries, wind projects are located far from load centres. Besides, in the same region where wind has been deployed the rest of the power generation is comprised of inflexible coal power plants, with a significant share of combined heat and power (CHP). These units are critical in supplying heat during winter and therefore run at high operating levels during the season (minimum load of 70%). Curtailment levels at wind farms dropped to 7% in 2018 from 13% in the previous year, while in solar PV plants it dropped to 3% from 5.8% over the same period.

Figure 6: Wind curtailment in north-eastern Chinese provinces in the first quarters of 2017 and 2018



Source: CEM (2018).

4 China added roughly 290 GW of wind and solar PV projects in the period 2007–2017 (IRENA, 2018c).

The inflexibility of coal power plants leaves very limited room for VRE generation. Because of this, the Chinese government has retrofitted old coal plants to reduce minimum load levels. This turned out to be the most feasible approach to add flexibility in the short-term due to lower lead-times[5] and lower costs compared to investing in open-cycle gas turbines or pumped storage, among other options (CEM, 2018). Furthermore, financial enablers have provided power plants with incentives to go flexible, such as the release of ancillary services and spot market pilot projects. These new revenue streams have also been important in offsetting revenue losses due to lower operating hours[6].

Grid reinforcements and other actions to improve the use of grid assets – such as establishing reserve sharing mechanisms for regional power grids, real time balancing and power trading centres at the national and provincial level – have also supported VRE development in China. Besides giving priority of dispatch to VRE projects since 2016, China has also launched a dynamic (yearly) risk alert system[7] to prevent further wind deployment in grid-constrained locations until necessary measures are put in place (Figure 6), redirecting investments where the grid is ready to accommodate additional variable generation.

Figure 7: Investment alert platform for wind farms in 2018

Source: NDRC and CNREC (2018).
Disclaimer: Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

5 A coal power plant retrofit takes around 3 months, while a new pumped storage project may take 5–6 years to complete and the construction of a natural gas plant would require 2–3 years.

6 Chinese coal power plants have been granted flat rates for operating above a minimum number of hours on a yearly basis.

7 The warning system categorises risk levels by green, orange and red. Regions will be given a red alert if VRE operation had been below certain predefined values in the previous year or if curtailment levels had been above 20%.

Experience in Germany

The German experience has shown that greater co-operation amongst grid areas reduces reserve requirements. Previously, reserves were procured separately by the four German TSOs, eventually resulting in reserves simultaneously being activated in opposite directions (positive/negative). German grid protocol co-operation solved the issue, leading to a common market for control reserve where bidders can offer their products to all TSO areas. Together with shorter market intervals (down to 15 minutes on the spot market), reserve requirements and price have decreased between 2008 and 2014, while VRE increased by almost 50 GW in the same period (Hirth and Ziegenhagen, 2015).

In addition, adjustments to the country's grid code have allowed for the integration of more renewables while maintaining grid reliability. Due to the large number of PV projects in the distributed network (70% of total), there are specific provisions in the German grid code regarding reactive power capabilities in low-voltage distribution as well as over frequency events that might trigger a snowball effect by disconnecting all PV systems at once (the notorious 50.2 Hz problem) (BMWi, 2019). In this regard, incentives were provided to retrofit older units (IRENA, 2016).

The participation of renewables in the German power system has been increasing and 65% of demand was met by renewables for an entire week recently, following a record year in 2018 during which 40% of demand was met by renewables. In addition, renewables accounted for 90% of all power consumption on 3 March 2019 – a particularly windy Sunday (Agora Energiewende, 2019). Such strong growth, however, has put pressure on the grid.

The German power system has been balanced by conventional power units in addition to exports to neighbouring countries. Still, redispatch events have taken place due to energy and voltage imbalances resulting from bottlenecks in the German transmission network. These events have increased year by year and essentially occur at moments of congestion in the north–south direction, when power plants in the south and west must ramp up to meet the region's demand, previously scheduled to be met by wind from the north. Due to grid expansion delays and the temporary decommissioning of grid assets, as well as higher electricity exports to southern neighbouring Austria and the shutdown of a nuclear power plant ahead of schedule, redispatching events in 2015 were common (Tennet, 2016).

In 2015, redispatching costs reached EUR 412 million, roughly three times higher than the costs in 2010. More recently, redispatching costs fell from EUR 391 million in 2017 to EUR 351 million in 2018, and a further decrease is expected when new transmission lines come online (BNetzA, 2019). The Federal net expansion law stipulates 7 700 km of grid extension and reinforcement measures. So far 1800 km have been approved and 1 100 km have been realised (BNetzA, 2019). Increments in new lines from 150 to 1 100 km have had a positive impact on the German power system. For instance, bottleneck-management costs within the area of TSO 50 Hertz decreased from 346 million euros in 2015 to 187 million euros in 2017. This progress relates to the commission of a southwest interconnector in 2017 and additional 5 GW of transmission capacity in the southern direction, also important for a further phasing out of nuclear plants in the south. Although improvements have been achieved, the grid still requires further improvement.

While generally effective as a means to support renewable energy integration, a stronger integrated European market that increases cross-border trade may also increase redispatch costs in the German case. This may happen once the market clearance in European day-ahead markets considers Germany as a single node, not accounting for internal grid constraints. The German strategy also includes sector coupling by means of electric vehicles (EVs), electrification of heat, and power to hydrogen.

IRENA's Knowledge Framework

The challenges to accommodating renewables tend to increase as the share of VRE increases. Yet, countries are quite diverse, hence challenges and related measures are dependent on many other characteristics. This means that power sector transition should be approached in a multi-dimensional way. Although no two countries are alike, and thus follow diverse pathways in their power system transitions, successful actions already in place may be a perfect match to countries sharing specific characteristics.

The IRENA Knowledge Framework for power sector transition intends to help countries identify next steps on their pathways to power system decarbonisation by identifying applicable measures to consider when moving forward with the deployment of renewables. The key goal is to gather useful information and best practices from front runners, essentially by capturing the learning-by-doing pathway observed in these countries. The Framework includes a country database with profiles and measures applied. From this, IRENA has also developed over twenty indicators allocated in the following macro-sectors: flexibility; transmission; demand response and storage; interconnectors; operation; and markets.

The Knowledge Framework can provide potential solutions to address specific power sector transition challenges in any given country. In this respect, IRENA regularly organises workshops to exchange experiences and best practices and to discuss their applicability elsewhere based on enabling conditions and means of implementation.

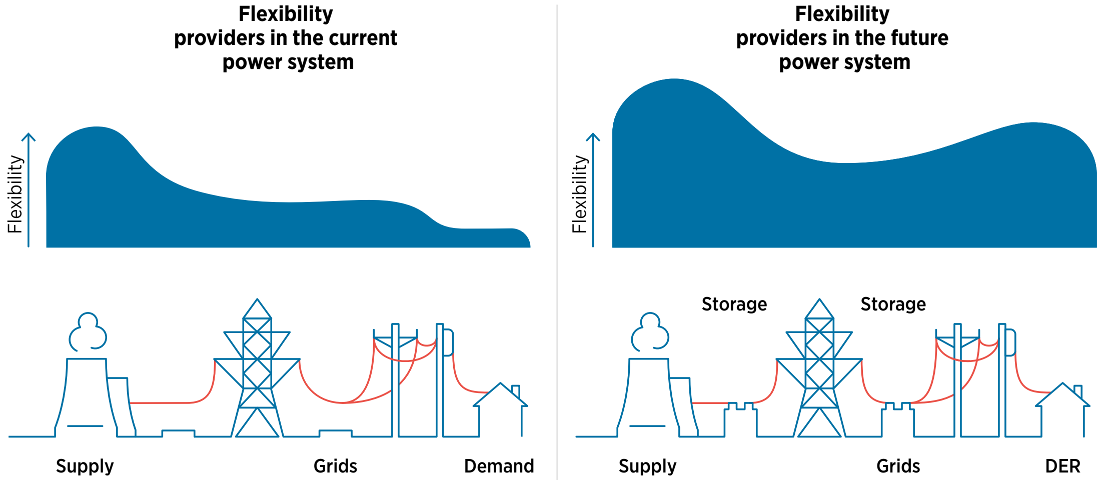
*More about IRENA's flexibility work can be found on IRENA's website (***www.irena.org***).*

3. THE NEXT STAGE: UNLOCKING FURTHER FLEXIBILITY THROUGH INNOVATION

In January 2019, Ministers and CEOs from the energy industry gathered to discuss the transition of the power sector during a Ministerial Roundtable at IRENA's 9th Assembly in Abu Dhabi. There was widespread recognition among the Ministers present that innovation is a key driver for the energy transition and that countries must keep abreast of the latest developments to create solutions tailored to their needs and contexts.

Rapidly falling costs and rising shares of renewable power generation in the global energy mix have shifted attention to those costs related to the integration of VRE – particularly in terms of cost–benefit calculations related to the transition. Fortunately, power system flexibility is not static. Innovation can increase power system flexibility across the whole value chain – including supply, transmission, distribution and demand – while reducing total system costs.

Figure 8: Flexibility in current and future power systems



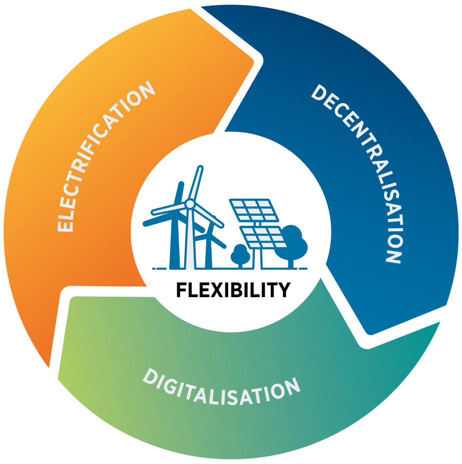
Source: IRENA (2019b).

IRENA's comprehensive study, *Innovation landscape for a renewable-powered future* (IRENA, 2019b), contains the most comprehensive analysis available to date on innovations to integrate VRE. It shows that we are not lacking innovation – on the contrary, we need to find ways to make sense of recent innovations and announcements. The purpose of this report is to make this complex topic more easily accessible and to guide members toward the innovation that can help them most. It identified 30 types of innovation and 11 practical solutions that build on these innovations. It also identified and analysed more than 200 real-world projects and applications. The result is not a blueprint, but rather a toolbox, as the realities of each power system must be considered when these innovations are applied.

Three innovation trends

IRENA sees three major trends driving the energy transition: digitalisation, decentralisation and electrification of end-use energy sectors. These trends are driven by strong economic and social benefits. Together they can transform the energy sector as we know it.

Figure 9: Three innovation trends combining to increase flexibility



Source: IRENA (2019b).

Electrification of end-use sectors

Discussed in detail in the previous section, electrification with renewable power constitutes a cornerstone of decarbonising end-use sectors (transport, buildings and industry). Electric vehicles (EVs), for example, provide a new source of flexibility, and 5.6 million electric passenger cars were already on the road at the beginning of 2019 (IRENA, 2019c). China and the United States formed the largest markets, with 2.6 and 1.1 million EVs, respectively, out of the approximately one billion total vehicles worldwide (IRENA, 2019c, BNEF, 2018). Electrification of heat is also growing. More than 10 million heat pumps were estimated to be installed in Europe by the end of 2017 (EPHA, 2018).

Decentralisation of power systems

The emergence of distributed energy resources (DERs) connected at the consumer end are decentralising the power system. They include rooftop solar PV, micro wind turbines, behind-the-meter battery energy storage systems, heat pumps and plug-in EVs. Notably, rooftop PV, which currently accounts for around 1% of global electricity generation, is growing at an accelerated pace. Decentralisation based on DERs can be an important source of flexibility through, for example, demand response measures. Firms in Africa, for example, utilise a pay-as-you-go model to supply solar home systems to households in Kenya and Uganda. Mobile payment systems are used to collect payments. Electricity access has been provided to over 600 000 homes in these countries, enabling households to have lighting, phone charging and home appliances such as televisions and refrigerators.

Digitalisation of the power sector

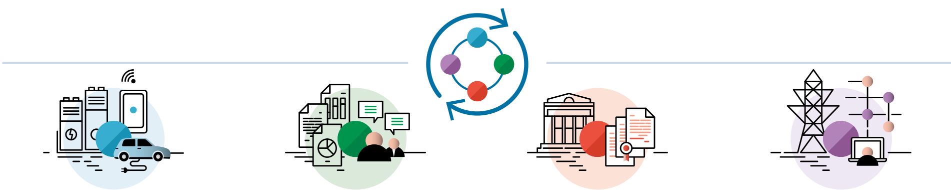
Digitalisation is a key amplifier of the energy transition, enabling the management of large amounts of data and optimising systems with many small generation units. Enhanced communication, control and automated smart contracts based on blockchain technology allow distributed energy resources to be bundled by "aggregators". Wider usage of smart meters and sensors, the application of the Internet of Things (IoT) and the management of large amounts of data via artificial intelligence have created opportunities to provide new services to the system.

Digital technologies support the transition of the power sector in several ways, including: better monitoring of assets and their performance; more refined operations and control closer to real time; implementation of new market designs; and the emergence of new business models. More than 700 million smart meters have been installed globally, according to estimates (IRENA, 2019b), with around 400 million in China alone. By 2025, 75 billion electrical appliances are expected to be connected through the IoT worldwide (Statista, 2019), providing a wealth of information to consumers, manufacturers and utility providers. In 2018 the battery solutions company Sonnen in Germany, for example, provided grid services and participated in the country's electricity balancing market. The grid services are provided by aggregating 30 000 households' networked home storage systems.

Four dimensions of innovation

As IRENA's work confirms, there is no single game-changing innovation. No innovation in isolation may have a significant impact but rather needs to be accompanied by innovations in all the segments of the power sector. IRENA has investigated the landscape of abundant innovations that can facilitate the integration of high shares of VRE into the power system, identifying and clustering 30 transformative innovations across four dimensions: enabling technologies, business models, market design and system operation.

Figure 10: Four dimensions of innovation



ENABLING TECHNOLOGIES

1 Utility-scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

Source: IRENA (2019b).

Enabling technologies: battery storage, demand-side management and digital technologies are changing the power sector, opening doors to new applications that unlock system flexibility. Electrification of end-use sectors is emerging as a new market for renewables but could also provide additional ways of flexing demand, if applied in a smart way (further elaborated in section 4).

Business models: innovative business models are key to monetising the new value created by these technologies and therefore enable their uptake. At the consumer end, numerous innovative business models are emerging, alongside innovative schemes that enable renewable electricity supply in places with limited options, such as off-grid or densely populated areas.

Market design: adapting market design to the changing paradigm – towards low-carbon power systems with high shares of VRE – is crucial for enabling value creation and adequate revenue streams.

System operation: with new technologies and sound market design in place, innovations in system operation are also needed and are emerging in response to the integration of higher shares of VRE in the grid. These include innovations that accommodate uncertainty and the innovative operation of the system to integrate distributed energy resources (DER).

Innovation for a cost-effective transition

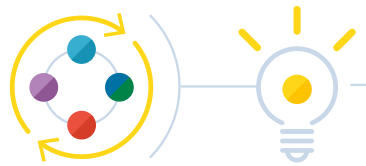
Innovation has driven the cost of RE technologies down significantly in the last decade, as illustrated by the cost of electricity from solar PV which fell by almost 75% between 2009 and 2018, or the cost of onshore wind electricity which dropped by almost 25% in the same period (IRENA, 2018c). As a result, the business case of RE power generation is very strong today. From now on, the focus should move to reducing the cost of integration for these technologies.

According to IRENA's analysis, the level of investment to achieve deep decarbonisation between 2015 and 2050, in reinforcement of grid infrastructure, storage and flexible conventional generation for VRE integration, is of a similar order of magnitude to the total investment required in additional renewable power-generation technologies. These investments are estimated to add up to USD 18 trillion for the period between 2015 and 2050 in a scenario in line with the Paris Agreement, assuming limited flexibility options are implemented.

This estimation underlines the importance of innovation in increasing flexibility in the power system. One example where innovation could reduce such costs is given by the City of Hamburg in Germany where, following a massive adoption of EVs, the grid is faced with bottlenecks. To accommodate the required load during periods of high demand, such as simultaneous charging of thousands of EVs or during emergency load conditions – such as when an adjacent line is taken out of service – an investment of approximately EUR 20 million for the reinforcement of approximately 10 000 km of 0.4 kV cable lines would be needed. As an alternative, Stromnetz Hamburg partnered with Siemens in an attempt to decrease the number of EVs that are charged at the same time on the same local grid by testing a smart solution using digital technologies. The cost of this solution, which includes the installation of 30 control units and the monitoring of private charging infrastructure loads, is estimated at EUR 2 million, which is just 10% of the cost of the conventional solution of reinforcing the grid (IRENA, 2019c).

This example shows that real-world solutions, with real impacts, come from the combination of innovations. The right mix and the best solutions may be different for each country, but many will have elements in common. Solutions born of combining innovations in these four dimensions result in reduced electricity system costs. IRENA has elaborated on 11 solutions to increase flexibility in power systems to illustrate how combining innovations results in tailored approaches to VRE integration.

Figure 11: Flexibility solutions



SUPPLY-SIDE FLEXIBILITY SOLUTIONS	GRID FLEXIBILITY SOLUTIONS	DEMAND-SIDE FLEXIBILITY SOLUTIONS	SYSTEM-WIDE STORAGE FLEXIBILITY SOLUTIONS
I Decreasing VRE generation uncertainty with advanced generation forecasting	III Interconnections and regional markets as flexibility providers	VI Aggregating distributed energy resources for grid services	X Utility-scale battery solutions
II Flexible generation to accommodate variability	IV Matching RE generation and demand over large distances with Supergrids	VII Demand-side management	XI Power-to-X solutions
	V Large-scale storage and new grid operation to defer grid reinforcements investments	VIII RE mini-grids providing services to the main grid	
		IX Optimising distribution system operation with with distributed energy resources	

Source: IRENA (2019b).

More about innovations to integrate increased shares of VRE can be found in IRENA's **Innovation landscape for a renewable-powered future** (IRENA, 2019b).

4. RENEWABLE ELECTRIFICATION: DRIVING THE TRANSITION OF ENERGY SERVICES

IRENA and the world's largest utility, the State Grid Corporation of China (SGCC), have joined forces to analyse the potential to electrify end-use sectors through renewable power and the implications for the energy sector. The analysis identifies key areas for further work to better understand the implications and economic impacts of various electrification pathways. This chapter summarises the key findings of the joint study.

The electrification of end uses is one of the key innovation trends mentioned in section 3 and covered in IRENA's report, Innovation landscape for a renewable-powered future (IRENA, 2019b). With increased grid flexibility comes the potential for widespread electrification via renewables. At the same time, electrification via renewable energy (RE-electrification) can make power systems even more flexible and resilient, while making the wider energy system more secure and less reliant on fossil fuels. RE-electrification offers significant efficiency gains in primary energy use and reduces pollution, leading to improved health. The modern automation and control systems that are an integral part of RE-electrification can also boost economic productivity and improve the quality of living conditions.

Unlocking synergies between electrification and renewables

A common, yet outdated, view of electricity system operation – one that does not acknowledge the many innovations now available – is that electricity demand is variable but relatively inflexible and predictable. Small variations can be covered by operational reserves at fossil fuel or hydro generators. Most flexibility to meet variable demand comes from the supply side, where dispatchable power plants can be ramped up and down.

RE-electrification creates a very different system. Overall demand for electricity will rise significantly in transport, buildings and industry, which creates new markets. Solar and wind will be key suppliers to these new markets. At the same time, the electricity they generate can vary depending on prevailing weather conditions, and having a high share of such variable renewable energy (VRE) in a power system poses increased operational challenges.

RE-electrification strategies meet emerging operational challenges by looking beyond the generation side of the power system and tapping all available sources of flexibility. This is particularly evident in the flexibility of demand over a wide range of time scales. To take just one example, the charging of electric vehicles (EVs) can be ramped up or down within milliseconds or shifted by several hours.

To deliver this new system in a cost-effective manner, simply switching to electricity in end uses and building new renewable generation is not sufficient, however. RE-electrification strategies also require smart devices and other information technologies that offer much more flexibility and control over demand and the delivery and use of renewable electricity. The integration of smart approaches in combination with digitalisation is key to reducing the risk of rising peak loads, to expand opportunities for renewable power utilisation and to avoid the need for massive investment in building new grid infrastructure. Smart electrification with renewables thus creates a virtuous cycle, where electrification drives new uses and markets for renewables, which then accelerates the switch to electricity for end uses, creating more flexibility and thus driving further renewable energy growth and technological innovation. Growth and innovation also reduce costs and create additional investment and business opportunities.

Challenges ahead

Such a major transition is not trivial. Energy systems are both complex and highly integrated, making them difficult to change. On the policy side, they are highly dependent on entrenched regulations, taxes and subsidies, which require considerable political will to adjust. Even where there is political will, transforming markets and supply chains – e.g., the global car industry to EVs or home heating to heat pumps – may still take many years. People replace heating equipment and cars every 10-15 years, and in some parts of the world the building stock is being renovated at a rate of less than 1% per year (IRENA, 2019d). Any transition also creates winners and losers, and those who do not benefit may resist change. The distribution of costs and benefits needs to be fair and just in order to achieve broad acceptance.

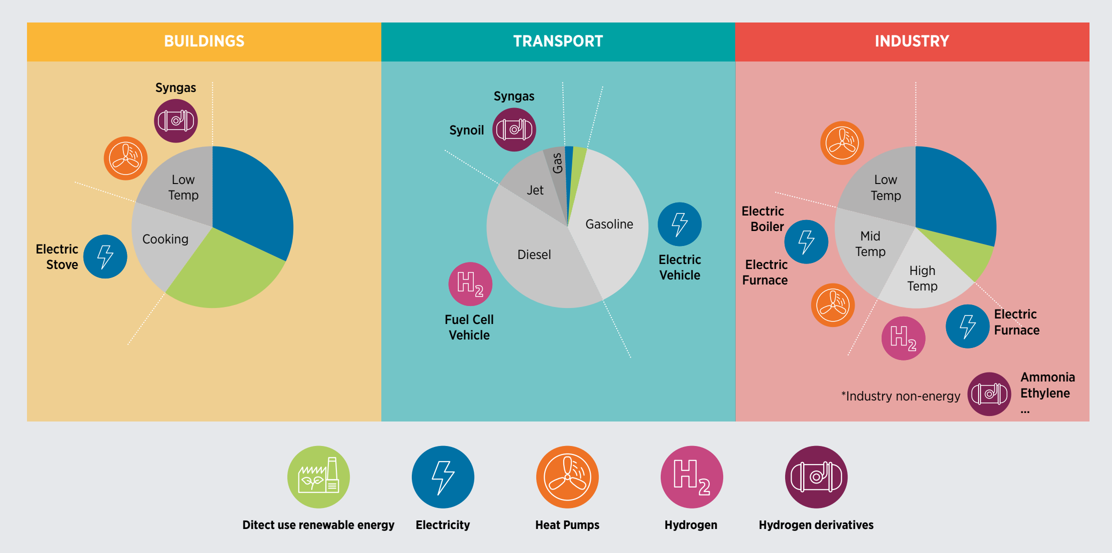
On the technical side, a transition to the widespread use of renewable electricity also has considerable challenges. It requires integrating large amounts of VRE into the grid, which involves matching supply and demand in the face of varying generation and peak production that may not match peak demand. It requires improved co-ordination between sectors of the economy, both in planning and operation. In addition, new infrastructure must be built or expanded for, inter alia, the power grid, EV charging networks and hydrogen or synthetic gas production facilities.

The basic technologies needed for the transition already exist. Still, innovation remains critical. Innovation in technologies needs to go hand-in-hand with improvements in new hardware, software and services. Together, these innovations can accelerate the energy transition and lower its overall cost (innovations to unlock increased flexibility are discussed in Section 4).

RE-electrification is a particularly powerful strategy because it takes advantage of potential synergies between electrification and renewable energy, and between sectors of the economy. At the same time, however, it is a very complex undertaking, since steps taken in one sector can have major impacts on other sectors and their infrastructure requirements. The impacts will be seen not only in the power grid, but also in gas and thermal network infrastructures, as well as in building stocks, recharging stations for EVs and other end-user infrastructure.

Each of the three major areas of the economy would play a significant role in achieving the RE-electrification transition, both through major growth in their use of electricity as a fuel, and in offering opportunities for significantly increasing the flexibility of that use. Potential future RE-electrification options are summarised in Figure 12.

Figure 12: Electrification of end-use sectors



Source: IRENA (2019d).

Implications for network investment

To deliver electrification at scale, investment will clearly be needed to build or upgrade key infrastructure. This includes the production of electricity (and hydrogen), energy transmission and distribution networks (such as the electricity grid and gas and thermal pipelines) and end-user infrastructure (such as information and communications technology (ICT) devices, retrofits and distribution stations).

RE-electrification strategies could bring significant cost reductions by reducing investment needs in peak-load infrastructure, achieving higher utilisation rates of power generated by VRE and reducing the need for investment in additional flexibility measures, such as storage.

Multiple RE-electrification technology pathways exist for any given sector. Often the best strategy involves a combination of technology pathways that balances the need for different infrastructure requirements across sectors, with a particular focus on avoiding excessive new investment in power distribution. There is no global study that comprehensively assesses the infrastructure implications of alternative combinations of RE-electrification pathways, but various pilot projects, case studies and energy system modelling studies do offer some insights. These are used here to illustrate four important implications of RE-electrification for network investment:

1. Smart RE-electrification reduces peak-load grid costs.
2. Smart grid investment pays off beyond peak-load savings.
3. Transmission investment needs depend on resource location.
4. The economic case for hydrogen production infrastructure still needs to be established.

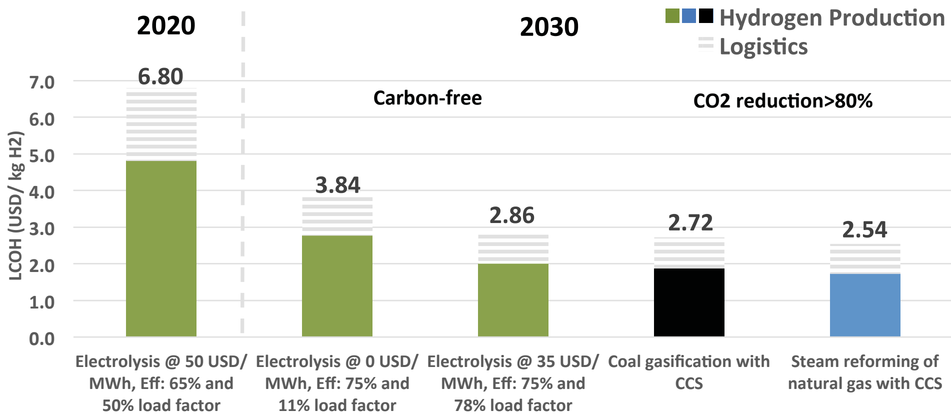
Renewable hydrogen

During the G20 Energy Transitions Working Group meeting that took place on 13 February 2019 in Tokyo, IRENA was invited by the G20 presidency to present key findings on the role of hydrogen in the energy transition (IRENA, 2018d). One of the main findings was that the costs associated with producing hydrogen from renewable electricity are comparable to the costs of producing hydrogen from fossil fuel with CCS. Figure 13 illustrates hydrogen total supply costs under various conditions.

Hydrogen and electricity, as energy carriers, are complementary in a world dominated by renewable energy. Fuel cell EVs can help decarbonise transport as they complement battery EVs and offer similar performance to internal-combustion-engine vehicles. Hydrogen produced from renewables can also help decarbonise industry by replacing fossil-produced hydrogen and fossil-based feedstocks. The gas grid can also be decarbonised via renewable hydrogen by taking advantage of low electricity prices, providing seasonal storage for solar and wind, and providing grid services from electrolysers.

More on the RE-electrification approach can be found in IRENA's **Electrification with renewables report preview** (IRENA, 2019d).

Figure 13: Total supply costs for hydrogen: Production, storage and shipping



Source: IRENA analysis
Note: Figure 13 assumptions: wind + PV 2030 free-electricity and 1 000 h/year; wind + PV 2030 USD 35/MWh and 6 840 h/year; coal price USD 2/GJ and 10.3 MJ/kg; natural gas price USD 5/million BTU.

5. WAY FORWARD: EIGHT-STEP POLICY PLAN

The strong business case for VRE technologies such as wind and solar PV has positioned these technologies at the core of the transition. Innovations being trialled in front-running countries show that power systems can be operated with very high shares of VRE in a reliable and economical way. However, a large gap remains between front runners and countries at early stages of VRE integration. To bridge the gap, the following recommended actions, identified in IRENA (2019b), could be implemented by countries.

1. ***Develop far-sighted policy frameworks:*** Countries should anticipate future power system needs. Ensuring cost-effective integration of VRE at scale requires balancing present needs (a focus on deployment of renewable generation technologies) with future needs (a focus on integrating high shares of VRE). Difficult trade-offs exist between quick wins and long-term strategies. In targeting high levels of renewable deployment and integration, policy makers should not focus on quick wins alone. They need to look ahead to a time when renewable energy deployment is already ubiquitous and design the markets and systems around this future. Unlocking existing flexibility is the first action to be taken; the restructuring of markets and operations is key. Regulation can be a barrier and requires attention.

2. ***Adopt a systemic approach:*** The integration of high shares of VRE requires a systemic approach which includes enabling policies; regulations and measures; and new technologies and business models. Solutions come from combining innovations in technology, markets, business and operation. Leveraging synergies among innovations across all sectors and components of the system, and involving all actors, is crucial. The innovative solutions mapped in Figure 10 show that those tailored to national contexts and needs can be built by combining innovations in enabling technologies, market design, system operation and business models. The implementation of such innovations to unlock flexibility across the whole power sector would result in lower costs to integrate VRE and therefore support the energy transition. Potential synergies among the different solutions also exist that can result in lower investments when implementing them together. A system-specific, least-cost mix of investments in transmission and distribution, storage, distributed energy resources and digitalisation will eventually be needed to increase flexibility.

3. ***Foster learning by doing:*** This means supporting trial and demonstration. Early planning is key to limiting integration costs and allows for learning-by-doing; we cannot predict a unique archetype of the power system of the future. Innovation necessarily involves failure, but energy systems cannot fail – the lights must stay on, and we need to understand which solutions work and do not work in each country context. This makes learning by doing – through trial and demonstration – of paramount importance to mitigate risk. The capacity of different actors to take risks varies: start-ups (for example, new entrants) can take higher risks and have more space to fail. Therefore, an open innovation approach is important to enable start-ups to solve problems and devise solutions. There is a need for a regulatory space that will allow levels of experimentation; one example is creating regulatory sandboxes that allow actors to experiment and test innovations without being restricted by the regulatory environment.

4. ***Change key roles and responsibilities to ensure success:*** The increasing penetration of decentralised energy resources and the emergence of new market players, such as prosumers and active consumers, will usher in a new era. Governments and companies need to gather better insights into consumers' and communities' needs and expectations and their willingness to adopt innovations and should tailor solutions accordingly. Some consumers are likely to be willing to play an active role in the energy system, but the benefits must be clear, and automation is needed to make responses simple. Furthermore, distribution system operators will have to adjust their current role and transform their business model, transitioning from just network planners to system operators. Greater co-operation with transmission system operators is needed to increase the visibility of the new distributed energy resources that are connected and that could provide services to the system.

5. ***Make market design innovation a priority:*** This can foster flexibility at low implementation cost. Market design solutions for VRE have been shown to be very impactful, low-cost solutions, making them a first option on which to focus efforts. Some energy markets and regulations are showing how markets can be adapted to reflect the needs of power systems with higher shares of VRE and to respond to the trends of digitalisation, decentralisation and electrification. Markets are observing that value is moving from providing kilowatt-hours to also providing flexibility in order to accommodate more low-cost VRE. The glue that holds this together is a market that prices energy and balances services properly and that remunerates all actors that are able to provide flexibility. Proper planning, accounting for the energy transition, would result in holistic and cost-effective market designs. Otherwise, solutions based on quick wins and temporary patches would result in high system costs in the long run. Gradual improvement of energy market pricing is critical regardless of any short-term patches that might be adopted.

6. ***Couple the electricity and end-use sectors:*** Create synergies between renewable power supply and electric mobility, heating and cooling. Valuable synergies exist between renewable power and the decarbonisation of end-use sectors that must be harnessed. Electrification strategies must be planned carefully and delivered intelligently, with close connections to strategies for the accelerated roll-out of renewable energy and with consideration of wider societal changes.

7. ***Turn smart innovations into smart solutions:*** The potential of digital technologies is only starting to be understood. Digital innovations (such as artificial intelligence, the Internet of Things, blockchain, etc.) are beginning to significantly impact power systems in multiple ways. The risks and implications for established models and actors are not yet fully understood. Technologies exist but smart applications are still limited. Energy systems should make far more use of the "smartness" that digital innovations enable. How other industrial sectors have applied digital technologies to their full potential (or close to it) also needs to be learned, with this knowledge then transferred to the power sector. Many more pilots and deployments of digitally enabled solutions are needed in a wider range of circumstances.

8. ***Adopt an open and co-operative approach to innovation:*** Innovation needs to engage different actors from both the public and private sectors and across developed and developing countries. Knowledge and experience should be shared more widely. There is ample opportunity to learn more from other sectors and from different players. Interplay with industrial segments that are not considered part of the energy sector could bring great opportunities to harness synergies. Innovation should be coupled with a sustainable and inclusive approach. G20 countries could benefit from a better-structured exchange of best practices and experiences on how to cost-effectively enhance energy system flexibility.

REFERENCES

- **Agora Energiewende (2019),** "Recent Electricity Data: Power Generation and Consumption", Berlin, www.agora-energiewende.de/en/service/recent-electricity-data/chart/power_generation/03.03.2019/03.03.2019/.

- **BMWi (2019)**, "System security: Grid-related ancillary services", Federal Ministry for Economic Affairs and Energy, Germany, www.bmwi.de/Redaktion/EN/Artikel/Energy/system-security.html/.

- **BNEF (2018)**, "Cumulative global EV sales hit 4 million", Bloomberg New Energy Finance blog, https://about.bnef.com/blog/cumulative-global-ev-sales-hit-4-million/.

- **BNetzA (2019)**, "Quarterly Report on Network and System security measures: Full year and fourth quarter of 2018" (translation), Bundesnetzagentur, Bonn, www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Allgemeines/Bundesnetzagentur/Publikationen/Berichte/2019/Quartalsbericht_Q4_2018.pdf?__blob=publicationFile&v=4.

- **Carlini, E.M. (2018)**, "Terna's experience on wind and solar energy integration" (PowerPoint Presentation), Terna S.p.A.

- **CEM (2018)**, "Thermal Power Plant Flexibility - A Publication under the Clean Energy Ministerial Campaign", Clean Energy Ministerial campaign, Paris.

- **e-distribuzione (2019)**, "Puglia Active Network: the project that will make Puglia the first 'Smart Region' in Italy", e-distribuzione SpA, www.e-distribuzione.it/it/progetti-e-innovazioni/PAN.html/.

- **EPHA (2018)**, "Press release: Ongoing growth: heat pump sector continues its positive contribution to Europe's energy and climate targets", European Heat Pump Association, www.ehpa.org/about/news/article/press-release-ongoing-growth-heat-pump-sector-continues-its-positive-contribution-to-europes-ene/.

- **Hirth, L., Ziegenhagen, I., (2015)**, "Balancing power and variable renewables: Three links", Renewable and Sustainable Energy Reviews 50, 1035–1051.

- **IRENA (2019a)**, "Global energy transformation: A roadmap to 2050" (2019 edition), International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition.

- **IRENA (2019b)**, "Innovation landscape for a renewable-powered future", International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2019/Feb/Innovation-landscape-for-a-renewable-powered-future.

» **IRENA (2019c)**, "Innovation outlook: Smart charging for electric vehicles", International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2019/May/Innovation-Outlook-Smart-Charging.

» **IRENA (2019d)**, "Electrification with renewables: Driving the transformation of energy services" (preview for policy makers), International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2019/Jan/Electrification-with-Renewables.

» **IRENA (2018a)**, "Opportunities to accelerate national energy transitions through advanced deployment of renewables" (Report to the G20 Energy Transitions Working Group), International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2018/Nov/Opportunities-to-accelerate-national-energy-transitions-through-advanced-deployment-of-renewables.

» **IRENA (2018b)**, "Power system flexibility for the energy transition, part 1: Overview for policy makers", International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2018/Nov/Power-system-flexibility-for-the-energy-transition.

» **IRENA (2018c)**, "Renewable power generation costs in 2017", International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017.

» **IRENA (2018d)**, "Hydrogen from renewable power: Technology outlook for the energy transition", International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2018/Sep/Hydrogen-from-renewable-power.

» **IRENA (2016)**, "Scaling up variable renewable power: The role of grid codes", International Renewable Energy Agency, Abu Dhabi, www.irena.org/publications/2016/May/Scaling-up-Variable-Renewable-Power-The-Role-of-Grid-Codes.

» **NDRC and CNREC (2018)**, "China Renewable Energy Outlook 2018 – Executive Summary", Energy Research Institute of Academy of Macroeconomic Research, China Renewable Energy Research Centre.

» **NREL (2015)**, "Grid Integration and the Carrying Capacity of the U.S. Grid to Incorporate Variable Renewable Energy (No. NREL/TP-6A20-62607)", National Renewable Energy Laboratory, Golden, CO (United States), www.osti.gov/biblio/1215010-grid-integration-carrying-capacity-grid-incorporate-variable-renewable-energyhttps://doi.org/10.2172/1215010.

» **Statista (2019)**, "Internet of Things (IoT) connected devices installed base worldwide from 2015 to 2025 (in billions)", Statista, www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/.

» **Tennet (2016)**, "Market Review 2015 – Electricity market insights", Tennet, Arnhem, Netherlands.

IRENA
International Renewable Energy Agency

www.irena.org