IRENA
International Renewable Energy Agency

INNOVATION LANDSCAPE FOR A RENEWABLE-POWERED FUTURE:

SOLUTIONS TO INTEGRATE VARIABLE RENEWABLES

PREVIEW FOR POLICY MAKERS

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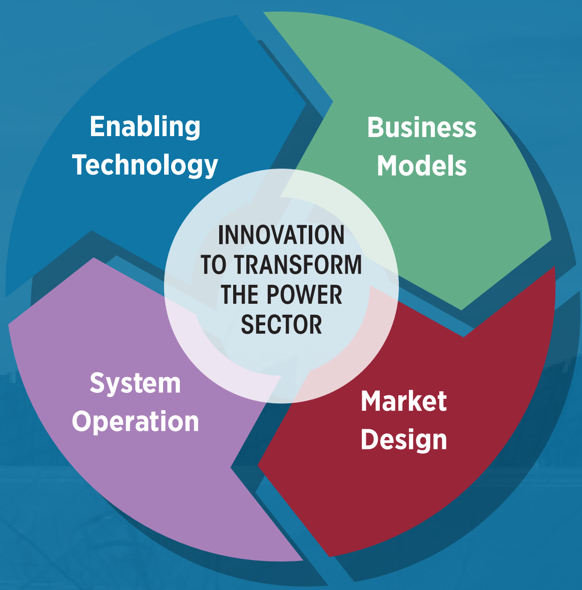
ABOUT THIS PREVIEW

The forthcoming IRENA publication "Innovation landscape for a renewable future: Solutions to integrate variable power sources" brings together key insights on emerging innovations that facilitate a higher share of variable renewable energy (VRE) in the in the power sector. In practice, solutions for the integration of VRE result from the synergies between different innovations across different dimensions. The report analyses the most important innovations and builds links between them – resulting in practical solutions for the integration of VRE in different settings.

This preview for policy makers summarises the findings of the report, which focuses on the flexibility of the power system as the main enabler of renewables integration. The preview outlines the thirty innovations in enabling technologies, market design, business models and system operation identified in the study, which are transforming power sectors with VRE at their core. This document also introduces the resulting solutions for VRE integration, followed by a cost-benefit analysis. An eight-step innovation plan for achieving a renewables-powered future summarises the main recommendations for policy makers.



Transformation requires innovation across the whole power sector

Increased system flexibility

Higher solar and wind share

Reduced total system costs

Innovation is the engine powering the global energy transformation. Moreover, the pace of developing and introducing better, more efficient renewable energy technologies is accelerating around the world. Renewables are becoming the go-to option for many countries in their transition towards a secure, cost-effective and environmentally sustainable energy supply. They underpin continued socio-economic development with jobs and local value creation, while simultaneously combating climate change and local air pollution.

To date, the power sector has led the way, with rapid reductions in the cost of solar and wind technologies resulting in widespread adoption in many countries. Despite the promising progress to date, however, the energy transition needs to significantly pick up the pace. As with market policies, the policies put in place to drive technological innovation should also be continually revisited and updated to keep up with new developments and breakthroughs (IRENA, IEA and REN21, 2018).

The integration of VRE poses specific challenges as its share of power generation rises – in essence, maintaining the balance of supply and demand becomes more of a challenge. More flexible and integrated power systems are needed to maximise the value of low-cost VRE, meaning solar and wind.

In response, policy makers and system operators around the world are adopting a range of measures to maintain an affordable and reliable balance of supply and demand in this evolving landscape. Innovation is focused on fostering the development and deployment of solutions that increase the system flexibility needed to integrate high shares of solar and wind power.

***Flexibility** is the capability of a power system to cope with the variability[1] and uncertainty[2] that VRE generation – such as wind, solar photovoltaic (PV) and run-of-the-river hydropower – introduces into the system at different time scales, from the very short to the long term, avoiding curtailment of VRE and reliably supplying all the demanded energy to customers (IRENA, 2018a).*

1 Variability: The fluctuating nature of solar and wind resources, which translates into possibly rapid changes in electricity generation.
2 Uncertainty: The inability to perfectly predict the future output of solar and wind power sources.

In recent years far-sighted governments and pioneering companies around the world have been creating, trialling and deploying a multitude of innovative solutions that have the potential to radically transform energy systems across the world. The sheer diversity of solutions, coupled with differences between local energy systems, may make for a confusing picture for decision makers, who may struggle to identify and assess the best solutions for each country or context.

The International Renewable Energy Agency (IRENA) has conducted an extensive and detailed analysis of the innovation landscape for the integration of variable renewable power, mapping and categorising the many examples of innovation and innovative solutions. The resulting report (forthcoming), combined with various online resources, aims to give decision makers a clear, easily navigable guide to the diversity of innovations currently under development, or in some cases already in use, in different settings across the globe. These innovations are being combined in a wide range of power systems across the globe. The resulting framework should enable informed judgments on possible solutions for each particular case.

This preview is structured as follows:

- **I** The need to integrate variable renewable energy
- **II** Electrification, decentralisation and digitalisation trends that are changing the power sector paradigm
- **III** The innovation landscape for variable renewable energy integration
- **IV** Innovations to boost flexibility across the power system
- **V** Innovations as building blocks for tailored flexibility solutions
- **VI** Assessing the impact of implementing flexibility solutions
- **VII** Innovations to reduce system costs and maximise benefits
- **VIII** The eight-step innovation plan for power-sector transformation.

I. THE NEED TO INTEGRATE VARIABLE RENEWABLE ENERGY

The world is undergoing a transformation towards a more inclusive, secure, cost-effective, low-carbon and sustainable energy future. One of the critical building blocks is renewable energy. This transformation is fostered by unprecedented public concern followed by policy action to address sustainable development and climate change across the world, as reflected by the United Nations' Sustainable Development Goals and the Paris Agreement on climate change.

The power sector is leading the ongoing energy transition, driven by environmental and health policies and the rapid decline in renewable electricity costs, in particular wind and solar PV generation. The cost of electricity from solar PV fell by almost 75% between 2009 and 2018, and the cost of onshore wind electricity dropped by almost 25% in the same period (IRENA, 2018b).

Renewables accounted for an estimated one-quarter of total global power generation in 2017 (IRENA, 2017a), with impressive growth in the deployment of wind and solar PV technologies. By the end of 2017, the installed capacity of renewables reached 2 337 gigawatts (GW), comprising 34% of total power generating capacity (IEA, 2018). The bulk of this was hydropower (54%), followed by wind power (22%) and solar PV (17%). The share of wind and solar PV is expected to continue increasing at an accelerated rate in years to come (IRENA, 2018c). In some countries the penetration of wind and solar PV is already much higher than the global average.

Denmark and Ireland, for example, are front runners in wind energy integration, with wind power shares of 44% and 27%, respectively, and maximum instantaneous penetration beyond 150% and 60% of demand, respectively (RTE, 2018; EirGrid and SONI, 2018).

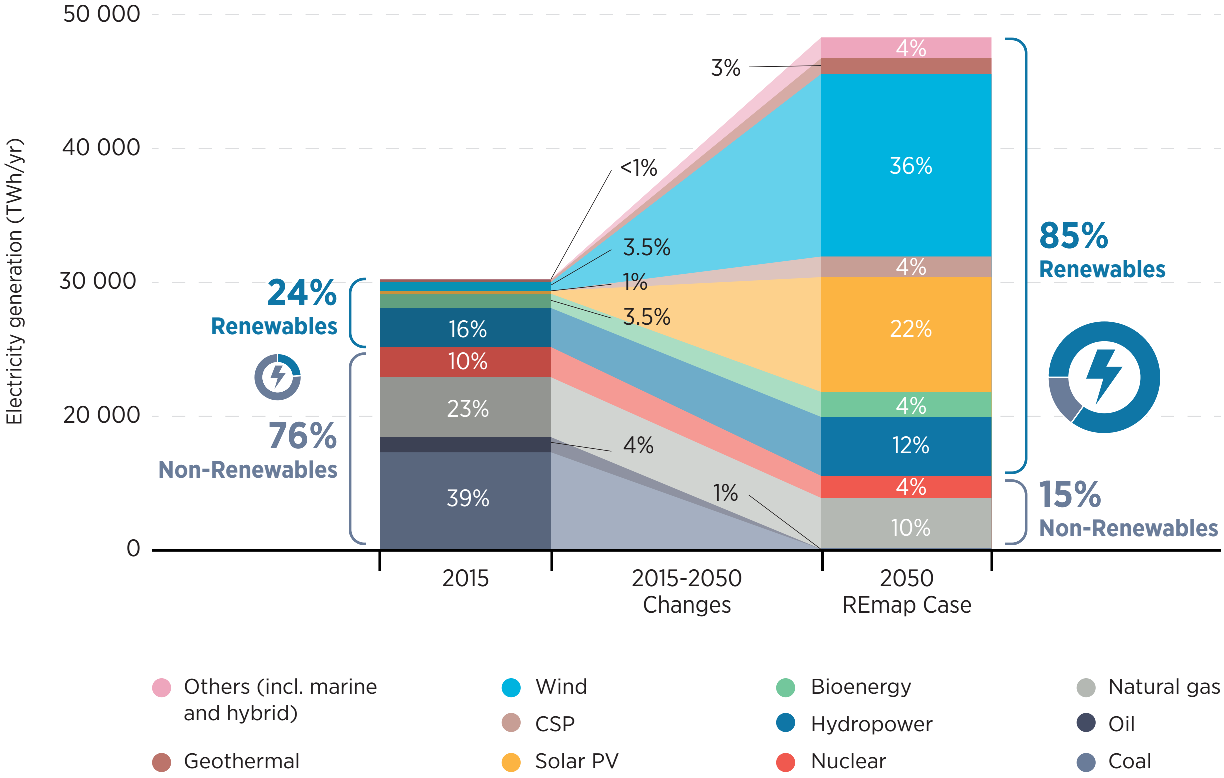
Nonetheless, the energy transition needs a further acceleration of this growth. According to IRENA analysis, decarbonisation of the power sector in line with the climate objectives outlined in the Paris Agreement would require an 85% share of renewable energy in total electricity generation by 2050 (Figure S1) (IRENA, 2018c). Furthermore, the share of electricity in the total energy demand of end-use sectors – industry, transport and buildings – needs to increase from around 20% in 2015 to more than 50% in 2050.

In a scenario compatible with the Paris Agreement, VRE technologies, particularly solar PV and wind power, play a central role in the energy transition. VRE capacity continues to lead, rising from 900 GW today to 13 000 GW in 2050 when it accounts for around 60% of total power generation. This requires a tripling of annual wind capacity additions and a doubling of solar PV capacity additions from 2017 levels.

Innovation is crucial to spur VRE integration and drive the global energy transformation

Therefore, ***innovation for the integration of a high share of VRE in power systems is crucial for the success of the global energy transformation.***[3] The integration of such a high share of VRE has important implications: power systems need to become more flexible; system costs should be contained; and system designs must account for changes resulting from ongoing innovation trends, *i.e.* digitalisation, electrification and decentralisation that are likely to occur with or without the integration of VRE.

Figure S1 Breakdown of electricity generation by source in a Paris Agreement compatible scenario



Notes: CSP = concentrated solar power; TWh = terawatt hour; yr = year.

Source: IRENA (2018c), Global Energy Transformation: A Roadmap to 2050, www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf

3 The full report (forthcoming) contains detailed information on emerging innovations that can support the integration of high shares of VRE, particularly by increasing power system flexibility. The work is based on the analysis of hundreds of innovative projects and initiatives being implemented around the globe and across the entire electricity sector, addressing enabling technologies, market design, business models and system operation. These innovations have been mapped and grouped in categories, resulting in a suite of 30 innovation types.

II. ELECTRIFICATION, DECENTRALISATION AND DIGITALISATION TRENDS THAT ARE CHANGING THE POWER SECTOR PARADIGM

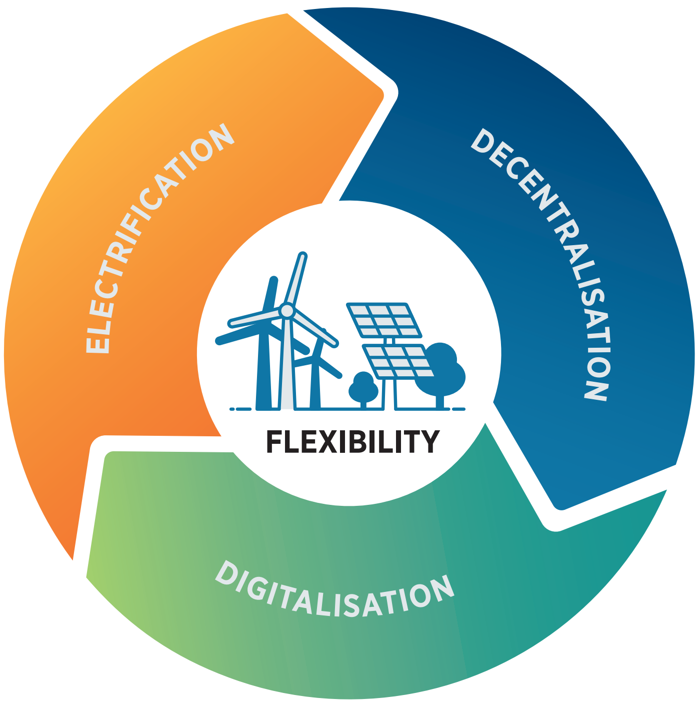
The ongoing power sector transformation is being accelerated by the combination of **electrification**, **decentralisation** and **digitalisation** (Figure S2).

These leading innovation trends are changing paradigms, unlocking system flexibility for high VRE penetration, changing roles and responsibilities and opening doors to new entrants in the sector.

Electrification of end-use sectors

Electrification with renewable power constitutes a cornerstone of decarbonising the end-use sectors –transport, buildings and industry. As a consequence, new electricity loads (*e.g.* electric vehicles [EVs], heat pumps, electric boilers) are being connected to power systems at larger scale, mainly at the distribution level. If not well managed, these new loads can create the need for additional power capacity and can strain the grid, necessitating additional investment to reinforce power infrastructure.

Figure S2 The three trends transforming the power sector



Box 1 Flexibility through smart-charging EVs

EVs are not only transforming the transport industry; they are also on the verge of reshaping the power market by providing a new source of flexibility. Four million electric passenger cars were already on the road in June 2018, 40% of them in China, out of approximately one billion cars worldwide, (BNEF, 2018). EV registrations hit a new record in 2017, with over one million sales worldwide, representing around 1.3% of all car sales.

Many countries and companies are exploring how the charging infrastructure needed for these vehicles can be integrated with power systems. For example, Nissan and Enel partnered to implement an energy management solution that uses vehicle-to-grid (V2G) charging units, and allows car owners who are electricity users to operate as individual energy hubs, able to draw, store and return electricity to the grid. The company Nuvve delivers V2G software solutions to allow settlement between market participants. Pilot projects were launched in Denmark (Parker Project) and in the United Kingdom to test the solution. Throughout 2016, owners of Nissan EVs earned money from sending power to the grid through Enel's bidirectional chargers, and the Danish and UK transmission system operators (TSOs) benefited from primary regulation grid services (Nissan Newsroom Europe, 2016).

Electrification of heat is also growing. Over 10 million heat pumps were thought to be installed in Europe by the end of 2017 (EPHA, 2018). Heat pumps create opportunities for demand-side management applications, such as load shifting and peak shaving. In addition, industrial applications have started using electricity to produce hydrogen, heat and other forms of energy, thus allowing intermittent low-cost renewable energy generation to be absorbed during peak generation time.

Conversely, if done in a smart way, these new loads can themselves become a source of flexibility through demand-side management strategies that can help to integrate more renewables into the power system. Many of these new loads are inherently flexible, as (a) they include batteries (*e.g.* EV batteries) or thermal storage (*e.g.* heat pumps or electric boilers with hot water tanks), and (b) their use can be shifted in time, which helps smooth out the demand pattern to match the availability of generation and the capacity of the distribution grid. ***A smart approach to electrification is crucial*** to harness these benefits, implying the optimal utilisation of electrical equipment and giving customers the incentive to change their use patterns in ways that are consistent with the power system's needs.

Decentralisation of power systems

The emergence of distributed energy resources (DERs) connected at the consumer end are, in effect, decentralising the power system. They include rooftop solar PV, micro wind turbines, behind-the-meter (BtM) battery energy storage systems, heat pumps and plug-in EVs. Electricity generation from wind turbines and solar PV is largely centralised today. However, distributed generation, notably rooftop PV, which at present

Box 2 Better energy access through DERs and digitalisation

Distributed renewable energy in combination with digital technologies is also helping to address the energy access problem. Recently, models such as pay-as-you-go, peer-to-peer (P2P) energy trading and energy communities have grown in popularity in off-grid energy markets. For example, pay-as-you-go models have improved energy access for 83.7 million people globally (GOGLA, 2017). M-KOPA, one of the companies utilising a pay-as-you-go model, supplies solar home systems to households in Kenya and Uganda, using mobile payment systems to collect subscriptions. The company has provided electricity access to over 600 000 homes in these countries, enabling households to have lighting, phone charging and home appliances such as televisions and refrigerators (Quartz Africa, 2018). SOLshare, a start-up in Bangladesh, utilises P2P solar energy trading platforms based on distributed energy technology (SOLshare, 2017). The electricity trading platforms leverage excess generation from solar home systems by selling it to neighbouring households, reducing the annual cost of energy access by at least 25%. The company expects to operate more than 20 000 nano-grids and supply more than one million customers in Bangladesh by 2030 (UNFCCC, 2018).

accounts for around 1% of all electricity generation, is growing at an accelerated pace. Distributed storage has gained momentum too. A BtM storage business model allows customers to store the electricity generated by their rooftop solar panels and use it later when needed or sell it to the grid. ***Decentralisation based on DERs can be an important source of flexibility through, for example, demand response measures and aggregator business models.***

Digitalisation of the power sector

The application of digital monitoring and control technologies in the power generation and transmission domains has been an important trend for several decades, and has recently started penetrating deeper into power systems. Wider usage of smart meters and sensors, the application of the Internet of Things (IoT) and the use of large amounts of data with artificial intelligence have created opportunities to provide new services to the system. Digital technologies support the transformation 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.

Digitalisation is a key amplifier of the energy transformation, enabling the management of large amounts of data and optimising systems with many small generation units. Enhanced communication, control and, in future, automated smart contracts based on blockchain technology, allow distributed energy resources to be bundled by "aggregators".

Box 3 Digital technology facilitates household participation in the market

More than 700 million smart meters have been installed globally according to estimates, with around 400 million in China alone. Moreover, by 2025, 75 billion electrical appliances are expected to be connected through the IoT worldwide, providing a wealth of information to consumers, manufacturers and utility providers (Statista, 2018).

A wide range of companies are exploring how to benefit from the use of such devices in energy applications. For example, Envision Energy, a Chinese smart energy company, is investing in research in advanced renewable energy forecasting in partnership with the European Centre for Medium-Range Weather Forecasts (ECMWF), the Met Office (the UK national weather service) and Aarhus University (BTECH CET). The research is focused on using state-of-the-science data, models, algorithms and supercomputing technologies for enhanced renewable power generation forecasting. Advanced forecasting models would increase the accuracy of energy resource assessments and improve the ability of the grid to plan for renewable energy inputs, resulting in a lower levelised cost of wind and solar energy.[4]

Elia, the Belgian electricity TSO, allows DER capacity to provide grid balancing services. Through a shared IT platform, all consumers and generators connected to the distribution/transmission grid can provide flexibility services to TSOs on a daily basis (Elia, 2018). Moreover, in April 2018 Elia launched a blockchain pilot project, exploring the opportunities offered by this technology as a payment system to address the business side of complex, rapid transactions.

In 2018 the battery solutions company Sonnen in Germany received official certification from the TSO Tennet to provide grid services and participate in the country's electricity balancing market.[5] The grid services are provided by aggregating 30 000 households' networked home storage systems. Together they are currently one of the largest virtual batteries in the world, with a capacity of 300 megawatt hours (MWh). The interconnected solar households are able to take over all the grid services provided by conventional coal-fired power plants, and are estimated to replace an average coal-fired power plant with an installed capacity of 800 megawatts (MW).

4 www.envision-energy.com/2017/12/11/envision-energy-announces-new-strategic-renewable-energy-forecasting-partnership/.
5 www.montelnews.com/en/story/sonnen-balances-german-power-with-home-batteries--report/959924.

Aside from offering a range of useful energy services, distributed generation and enabling technologies have become sources of valuable data. Detailed and real-time information on consumer patterns, load profiles, the performance of components in electricity systems and failures can enable better planning and system operation by grid operators. It also becomes possible to enhance the forecasting of electricity production and consumption by distributed sources on the basis of past behavioural patterns. These developments result in better management of assets and operations, increasing overall system flexibility.

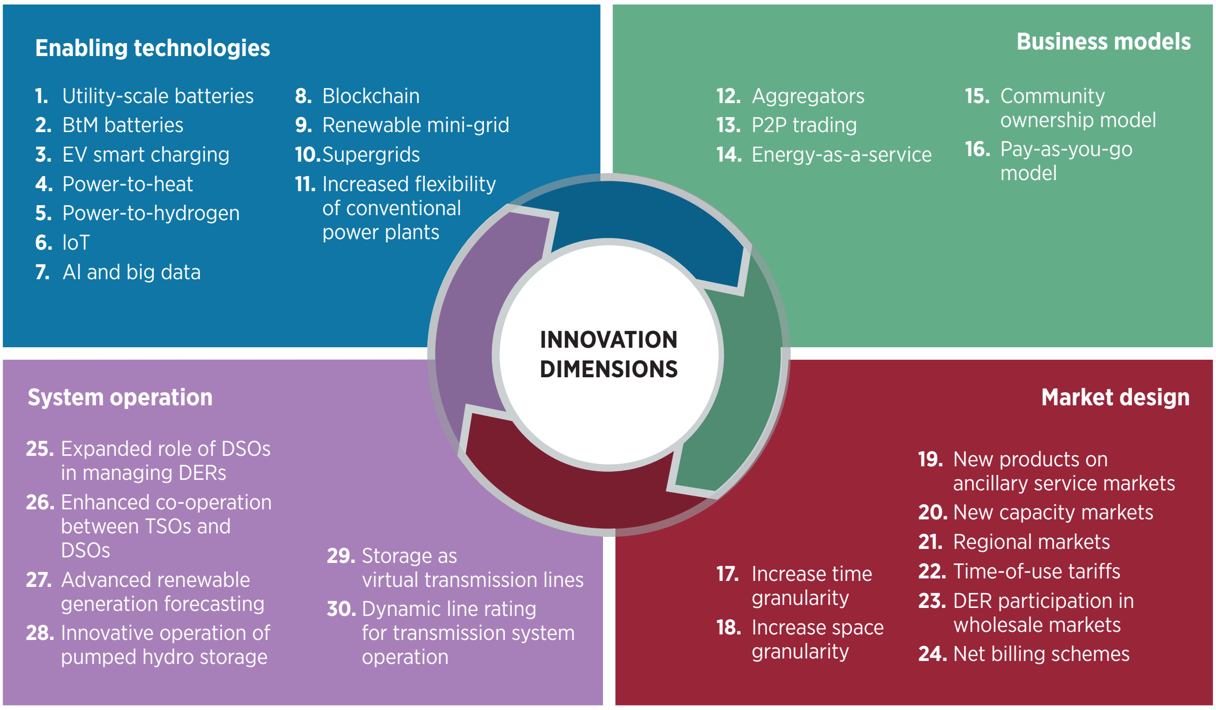
The growing relevance of digitalisation is also due to advancements in decentralisation and electrification. Decentralisation results in large numbers of new small generators, mainly rooftop PV. Electrification of transport and heat involves large quantities of new loads, such as EVs, heat pumps and electric boilers. All those new assets on the supply side (due to decentralisation) and demand side (due to electrification) have an impact on power systems, making monitoring, management and control crucial for the success of the energy transformation.

III. THE INNOVATION LANDSCAPE FOR VARIABLE RENEWABLE ENERGY INTEGRATION

There is no lack of innovation to address the integration of VRE in power systems. IRENA has investigated the landscape of innovations that can facilitate the integration of high shares of VRE. The landscape analysis identified ***30 types of transformative innovations across four dimensions: enabling technologies, business models, market design and system operation***, as depicted in Figure S3.

The energy transformation requires innovations in enabling technologies, business models, market design and system operation

Figure S3 The landscape of innovations for power sector transformation



Notes: AI = artificial intelligence; BtM = behind the meter; DERs = distributed energy resources; DSO = distribution system operator; EV = electric vehicles; IoT = Internet of Things; P2P = peer-to-peer; TSO = transmission system operator.

These innovations and related projects are discussed in detail in a range of innovation briefs (forthcoming) associated with this study.

- **Enabling technologies.** Technologies that enable greater flexibility in power systems play a key role in facilitating the integration of renewable energy. Existing conventional generation technologies, such as coal power plants, are being modernised to become more flexible. Battery storage, demand-side management and digital technologies are changing the power sector, opening doors to new applications that unlock the system's flexibility. Electrification of end-use sectors is emerging as a new market for renewables, but could also provide additional ways of flexing demand, if done in a smart way.

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

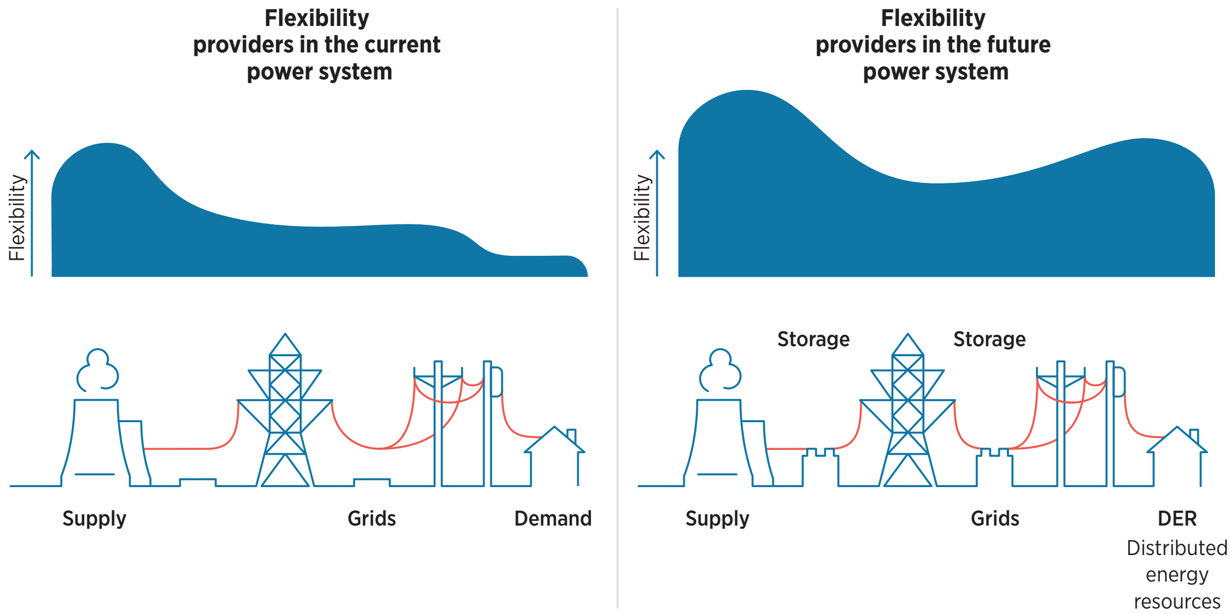
- **Market design.** Adapting market design to the changing paradigm – towards low-carbon power systems with high shares of VRE – is crucial for enabling value creation and adequate revenue streams, as detailed in previous IRENA analysis (IRENA, 2017b). Innovation in both wholesale and retail markets is needed to fully unlock the flexibility potential in the power system.

- **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 DERs.

IV. INNOVATIONS TO BOOST FLEXIBILITY ACROSS THE POWER SYSTEM

Traditionally, in conventional power systems, flexibility has been mainly provided by the supply side, with dispatchable generation adjusting 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 decades towards increasing the flexibility of conventional power plants. The demand side hardly provided any flexibility, since it was largely unresponsive. ***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 systems, 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. Figure S4 below illustrates the transition from a system where generation was the main flexibility source to one where the entire system can be flexible.

Figure S4 New flexibility options across the power sector unlocked by innovation



Opportunities for enhancing flexibility across the power system include the following.

- *Supply-side flexibility:* Greater incentive is needed to increase flexibility from the supply side. More flexible behaviour from existing conventional plants can be provided by lowering minimum operating loads, reducing start-up times and increasing ramp rates.
- *Grid flexibility:* This can be increased through greater network capacity and interconnections in regional markets, which allow electricity to be transported more readily within a larger balancing area, across several control areas or even continent-wide. Distribution grid capacity and management are also important for integrating more renewable energy from sources connected at the distribution level.
- *Demand-side flexibility:* On the demand side, the emergence of DERs, combined with a market design that allows their participation in the market, has the potential to greatly increase system flexibility. By becoming active participants in the electricity network, DERs respond to system conditions and provide services to the grid.
- *System-wide storage flexibility:* Energy storage technologies are key flexibility providers that can be connected across the entire electricity system. Utility-scale batteries and Power-to-X applications (such as power-to-hydrogen) can increase flexibility on the supply side by storing excess VRE generation, and on the demand side though smart electrification of end-use sectors. They can also increase grid flexibility by reducing network congestion

V. INNOVATIONS AS BUILDING BLOCKS FOR TAILORED FLEXIBILITY SOLUTIONS

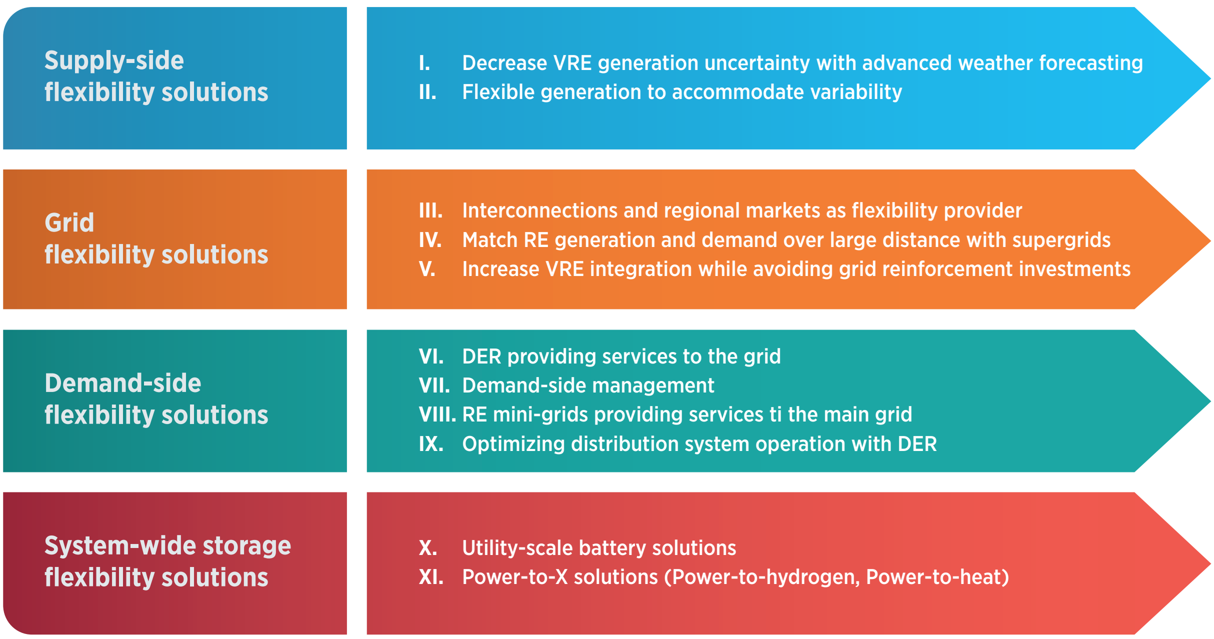
This study highlights 11 solutions for the integration of VRE based on their relevance and increasingly widespread use, each combining several innovations. The list, though not exhaustive, aims to show how countries can pursue VRE integration by combining different innovations to suit each context. Figure S5 lists the flexibility solutions discussed in the report.

Innovations are not implemented in isolation. Synergies between different innovations across all dimensions can offer solutions for VRE integration.

The design of an optimal strategy for integrating high shares of VRE and the implementation of different innovations depend on the country context. And different solutions offer increased flexibility in different segments of the power system, from generators to consumers.

Figure S6 shows the link between the 30 innovations and the 11 flexibility solutions examined in this study. The different innovations were used as building blocks to create solutions for the integration of VRE.

Figure S5 Solutions for unlocking flexibility in the power system



Note: RE = renewable energy.

Box 4 **Examples of flexibility solutions being implemented in different countries**

Supply-side flexibility (Germany): Alongside conventional generators, renewable energy generators, battery storage systems and industrial loads have also been allowed to participate in Germany's balancing markets since 2009. In the period from 2009 to 2015, the size of the balancing market in gigawatts decreased by 20% and TSO ancillary service procurement costs decreased by 70%. In the same period, system stability increased and the installed capacity of VRE increased by 200%. This indicates that allowing alternative energy resources to participate in ancillary service markets can help increase system stability while reducing costs (Wang, 2017).

Grid flexibility (Denmark): High wind penetration is due in large part to strong grid interconnection. Denmark mostly exports any wind energy surplus to the other Nordic nations that can use these imports to displace their hydro generation and conserve water in their reservoirs. Denmark's internal transmission grid is robust, and its interconnector capacity with the rest of Scandinavia and Germany is almost equal to the peak load of 6.5 GW (import capacity from Germany 2.2 GW, Sweden 2 GW and Norway 1.6 GW).

Demand-side flexibility (United States): Con Edison, a utility in New York, offers a rebate to customers for enrolling in its demand response programme. The customer allows the utility to adjust their thermostat a maximum of 10 times each year (Con Edison, 2016). Similarly, STEM, a US-based company, helps commercial and industrial customers reduce their energy bills by using energy stored in their batteries during periods of peak demand. The company combines battery storage with cloud-based analytics systems to identify the best time to draw energy from battery storage (Colthorpe, 2017). STEM uses its artificial intelligence-enabled technology (Pickerel, 2018).

System-wide storage flexibility (Australia): The US company Tesla recently commissioned a lithium-ion battery storage facility with a capacity of 100 MW/129 MWh at the 315 MW Hornsdale Wind Farm in South Australia. The facility was installed to firm up the power generated from the wind farm and simultaneously provide ancillary services to the grid in southern Australia grid (McConnell, 2017). A further example of storage flexibility is the HyStock project developed in the Netherlands, which consists of a 1 MW electrolyser and a 1 MW solar field that will supply part of the electricity required to generate hydrogen. The project is located close to a salt cavern that can be used as a buffer to store the hydrogen being produced by the electrolyser after its compression. This hydrogen can be then inserted into storage cylinders and transported to end users. The project is further investigating how this electrolyser could also provide benefits to the power sector by, for instance, providing ancillary services to the grid (EnergyStock, 2018).

Figure S6 11 Flexibility solutions created by combining innovations in enabling technologies, business models, market design and system operation

SUPPLY-SIDE FLEXIBILITY SOLUTIONS

I Decrease VRE uncertainty with advanced generation forecasting

- IoT / AI and Big Data
- Increase time granularity/ Increase space granularity in electricity markets
- Advanced RE generation forecasting

II Flexible generation to accommodate variability

- Increased flexibility of conventional power plants + IoT / AI & Big Data / Blockchain
- Increase time granularity in electricity markets / New products on ancillary service market / New capacity markets
- Innovative operation of PHS

GRID FLEXIBILITY SOLUTIONS

III Interconnections and regional markets as flexibility providers

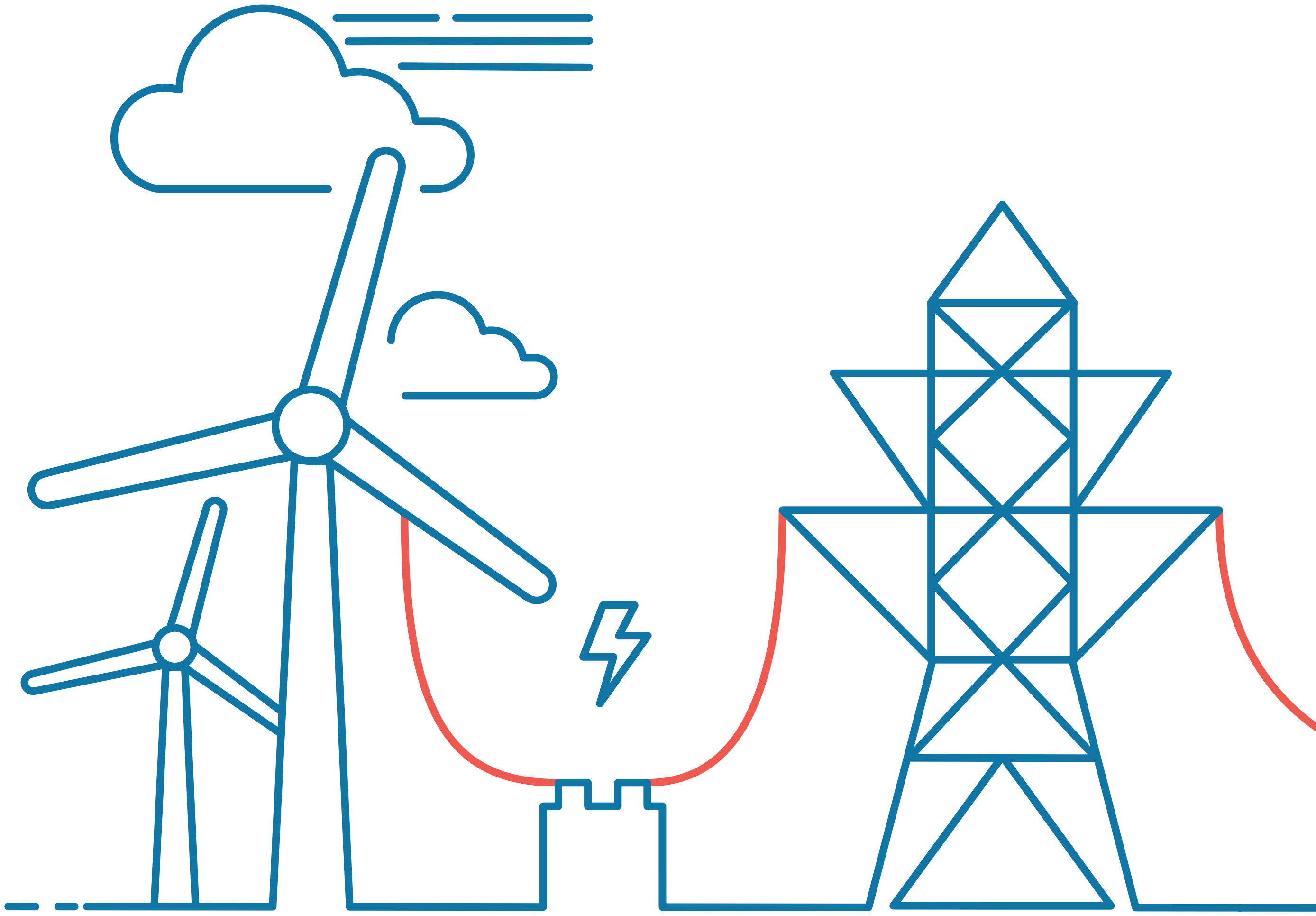
- IoT / AI & Big Data / Blockchain
- Regional markets / Increase time granularity in electricity markets

IV Match RE generation and demand over large distances, with Supergrids

- Supergrids + IoT / AI & Big Data
- Regional markets

V Increase VRE integration while avoiding grid reinforcements investments

- Utility-scale battery storage / Power-to-hydrogen / Power-to-heat + IoT / AI & Big Data
- Virtual power lines / Dynamic line rating



Note: PHS = pumped hydro storage.

DEMAND-SIDE FLEXIBILITY SOLUTIONS

VI DER providing services to the grid

- BtM batteries / Smart Charging for EVs / Power-to-heat + IoT / AI & Big Data / Blockchain
- Aggregators
- DER participation in wholesale market / New products on ancillary service market
- DSO-TSO co-operation

VII Demand side management

- BtM batteries / Smart Charging for EVs / Power-to-heat + IoT / AI and Big Data
- Energy-as-a-Service
- Time-of-use tariffs / Net billing schemes
- Advanced RE generation forecasting

VIII RE mini-grids provide services to the main grid

- RE mini-grids +BtM batteries / Smart Charging for EVs / Power-to-heat + IoT / AI & Big Data / Blockchain
- P2P energy trading + Community ownership model DER participation in wholesale market

IX Optimising distribution system operation with DER

- BtM batteries / Smart Charging for EVs + IoT / AI and Big Data
- Aggregators
- Net billing schemes
- Expanded role of DSO in managing DERs / Virtual power lines

SYSTEM-WIDE STORAGE FLEXIBILITY SOLUTIONS

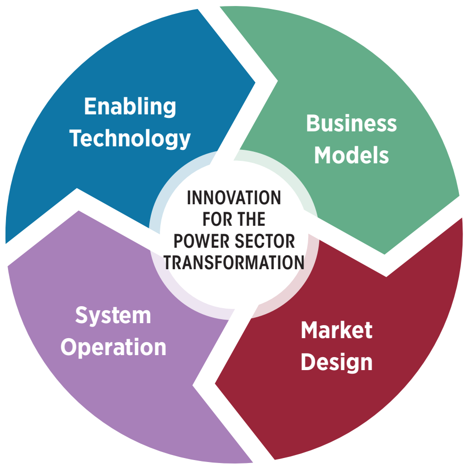
X Utility-scale battery solutions

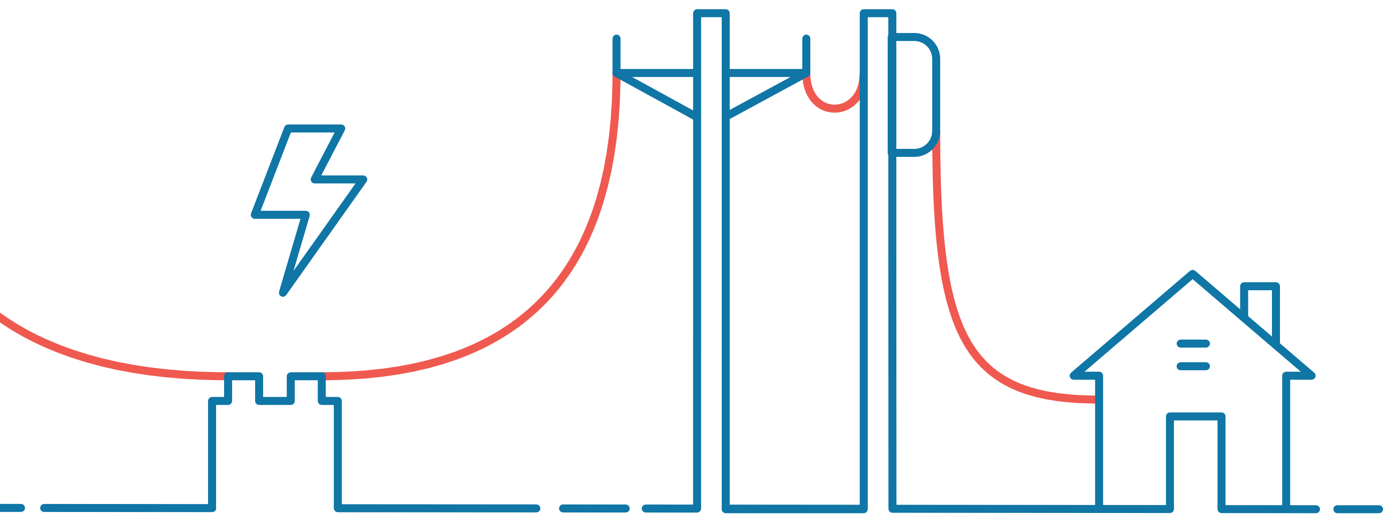
- Utility-scale batteries + IoT / AI & Big Data
- New products on ancillary service market / Increase time granularity/ Increase space granularity in electricity markets /New capacity markets
- Virtual power lines

XI Power-to-X solutions

- Power-to-hydrogen / power-to-heat +IoT / AI & Big Data
- New products on ancillary service market
- Virtual power lines

Legend





VI. ASSESSING THE IMPACT OF IMPLEMENTING FLEXIBILITY SOLUTIONS

Policy makers need to recognise that the implementation of different solutions poses different challenges, such as the need for investment in technology and infrastructure development, regulatory challenges, complexity in the coordination of multiple stakeholders and possible changes in the roles of the main actors.

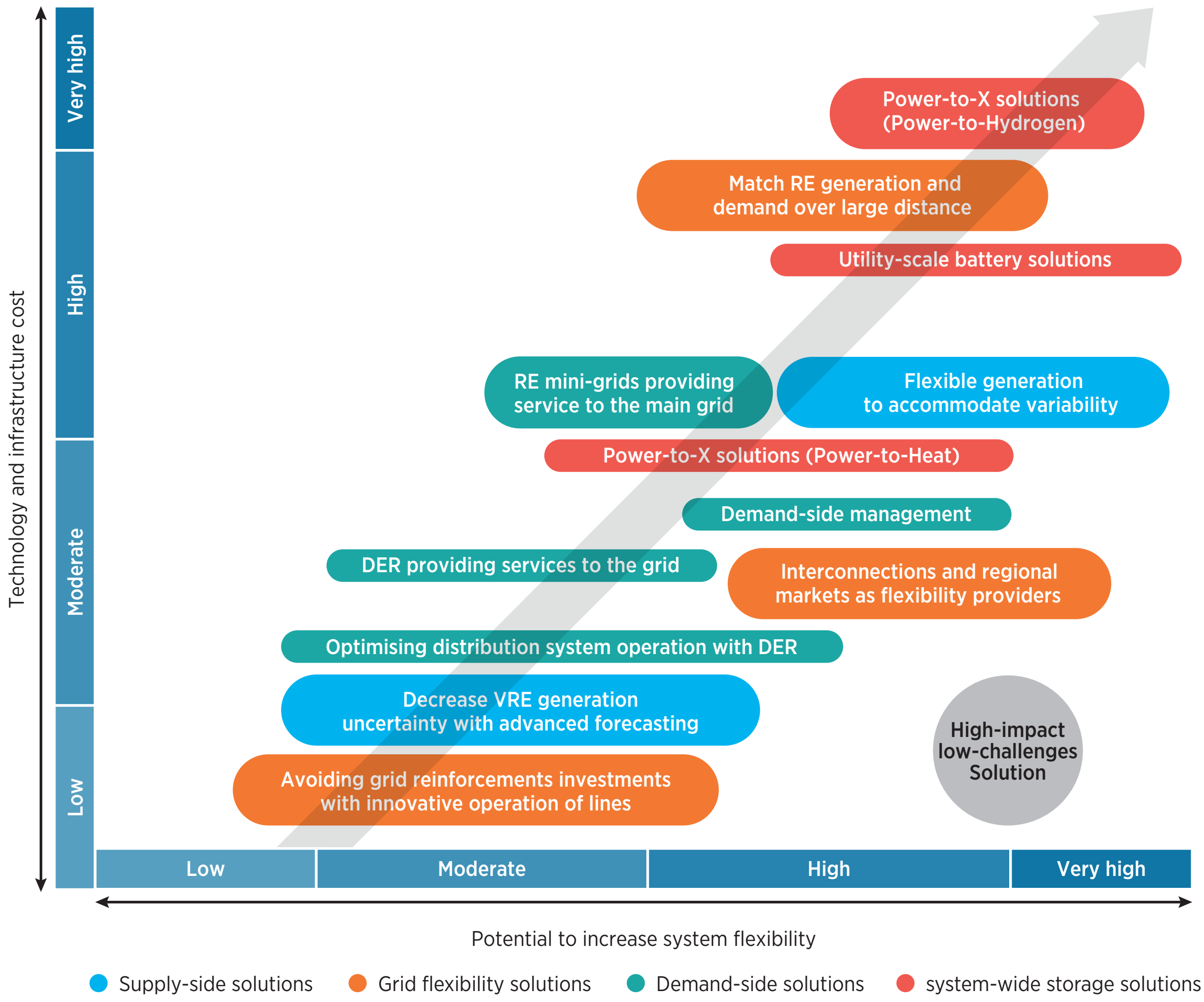
Generally, the solutions that need the least investment in technology or infrastructure are the ones based primarily on innovations in system operation and market design. These can incentivise existing and new actors to respond effectively to new system conditions based on existing assets. Table 1 below illustrates the high-level challenges that may accompany different solutions and innovations.

As the complexity of implementing different solutions varies, so does the impact of each solution in enabling a high share of VRE. Figure S7 compares the solutions in terms of their flexibility potential and cost, while Figure S8 compares them in terms of the non-technological challenges, for example the need to change policy or regulatory frameworks, the engagement of several actors in the energy sector, and public acceptance. There is no "silver bullet" solution that has a very high impact with low cost and few challenges – as Figure S7 shows, the investment required by a solution is generally directly proportional to the potential flexibility it offers. However, the exact same proportionality is not observed for the non-technical challenges, as illustrated by Figure S8.

Table 1 Challenges to the implementation of innovations

Innovation dimension	Investment required	Significant challenges
Enabling technologies	High	· Operation of the enabling technologies
Business models	Moderate	· Possible need for changes in regulation
Market design	Low	· Changes in regulatory framework · Political challenges · Possible need for international co-operation · Co-ordination between many different stakeholders · Changing roles of actors in the power sector
System operation	Moderate	· Possible need for changes in regulation · Data management handling · Engagement with more actors in the power sector

Figure S7 Solution flexibility potential vs technology cost



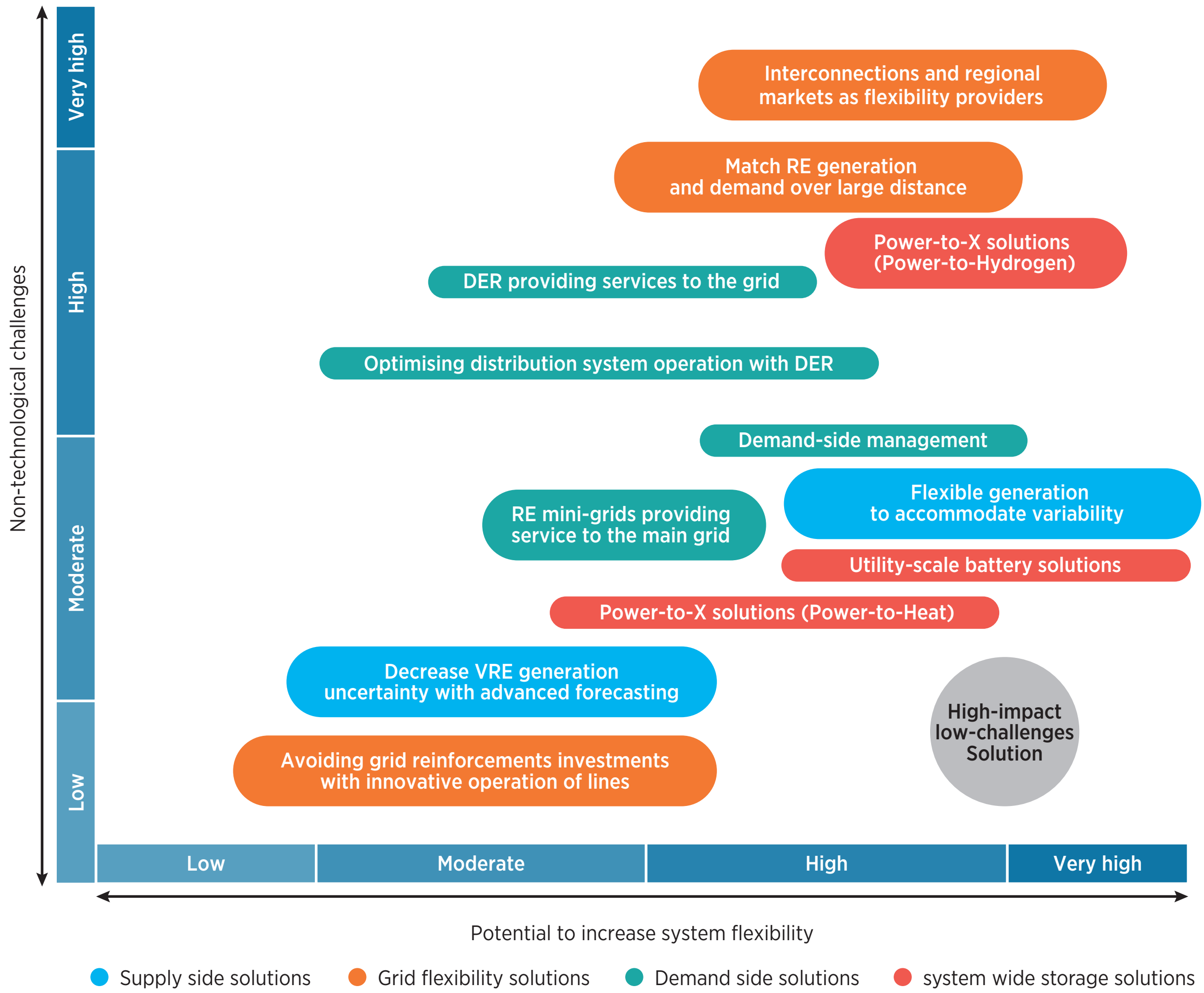
This is because each solution has diverse challenges and it becomes difficult to compare one against another in an absolute way. In each of them, the challenges are influenced by the specifics of the geopolitical and power system context.

Figure S7 shows that large-scale batteries, supergrids and electrolysers for power-to-hydrogen applications are costly technologies, but are solutions with high and very high flexibility impacts. However, many other solutions offer significant flexibility at lower cost. Each system needs its own assessment of the level of flexibility required and the synergies that can be created within its context.

There are, however, potential synergies between the solutions, which would result in a lower investment requirement when implemented together. For example, investment in digital technologies to enable DERs to provide services to the grid would also help in providing demand-side management. Investment in power-to-heat solutions, such as residential heat pumps, would increase the impact of demand-side solutions, making demand-side management more efficient, providing services to the grid and enabling DSOs to better optimise the operation of the system.

An important challenge that arises for many innovative solutions, considered in the non-technological challenges in Figure S8, is the changing role and responsibility of the actors involved. For example, demand-side flexibility solutions involve changing the role of consumers and altering consumption patterns.

Figure S8 Solution flexibility potential vs non-technological challenges



Note: Non-technological challenges include required regulatory changes, required changes in the role of actors, and other challenges.

For integration of DERs and allowing them to unlock demand-side flexibility, changes in the role of the TSO and, more importantly, that of the DSO are required. Changing the role of actors in the system is a significant challenge, as the right incentives and business models are needed to accomplish the shift. In other cases, the political set-up and international environment are often a particular challenge when it comes to external cooperation, setting cross-system roles and responsibilities, and putting the regional benefit ahead of the national. These are perhaps the most significant obstacles to establishing well-functioning regional markets or agreements through interconnections.

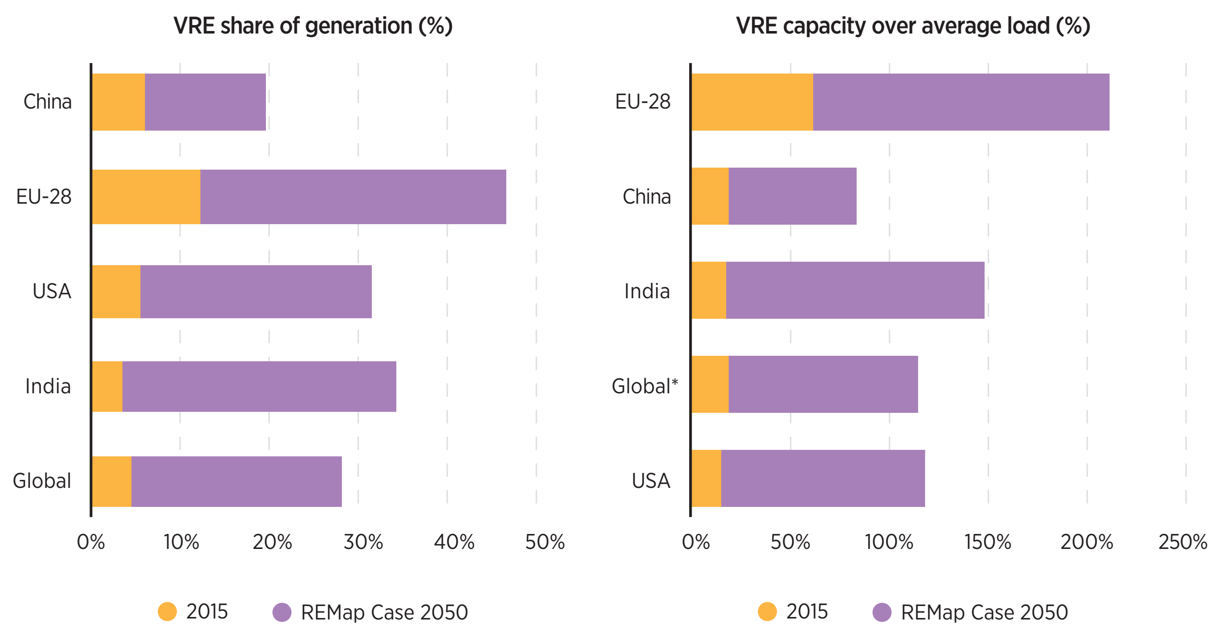
More generally, Figures S7 and S8 above show that ***solutions focused on the demand side and based on market design innovations have lower costs*** and a moderate to high impact on VRE integration. This makes them an attractive option in many countries and therefore a good starting point. Solutions with more intensive use of ***enabling technologies, such as grids, storage and Power-to-X innovations, require higher investment, but may also have a higher impact on integrating VRE***. This makes them more suited to advanced stages where countries are reaching a significant penetration of VRE in their power systems. Policy frameworks, however, must anticipate the regulatory and infrastructure planning aspects that are essential for success in implementing these solutions at a later stage.

VII. INNOVATIONS TO REDUCE SYSTEM COSTS AND MAXIMISE BENEFITS

Globally, in a scenario compatible with the Paris Agreement the share of VRE in electricity generation reaches more than 60% by 2050, with several countries having an even higher share, as shown in Figure S9. A more important aspect for power systems is that during times of peak VRE generation, electricity supply could significantly exceed electricity system load in many countries. Flexible systems and smart approaches can assist in using such renewable electricity surplus whilst minimising additional challenges to the infrastructure and operation of power systems.

With the objective of achieving a cost-effective global transformation that results in a low-carbon, sustainable, reliable and inclusive energy system, strategies need to minimise the costs related to the integration of VRE while maximising the associated benefits.

Figure S9 Share of VRE in total power generation and VRE capacity over average load, for selected countries in 2015 and 2050 in a Paris Agreement compatible scenario



Source: IRENA based on REmap data.

Lack of proper planning for VRE integration in power systems may result in tight constraints that increase system costs. Sound planning that anticipates system requirements and emerging flexibility solutions will increase the benefits of low-cost VRE generation (IRENA, 2017c), as depicted in Figure S10.

IRENA analysis concludes that the level of investment 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 energy 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 (IRENA, 2018c). This underlines the importance of innovation to decrease the cost while increasing the benefits of integrating a high share of VRE in power systems.

The report (forthcoming) shows that ***power system innovation can decrease the cost of VRE integration with solutions that increase the flexibility of the system.*** This concept is illustrated in Figure S11. The reference is a system with a low share of VRE currently and significant constraints to increasing this share. The implementation of flexibility solutions helps to move the cost curves to the right of the chart, meaning that, for the same level of investment, a higher share of VRE can be achieved as solutions are put in place. Market design and system operation solutions have lower implementation costs and are a good opportunity to start with. Other solutions based on new business models and enabling technologies require the engagement of more actors and higher investment, but unlock greater flexibility in power systems.

As noted, however, a combination of innovation in market design, system operation, business models and enabling technologies is needed to achieve high levels of VRE integration.

Figure S10 Innovation maximising system benefits

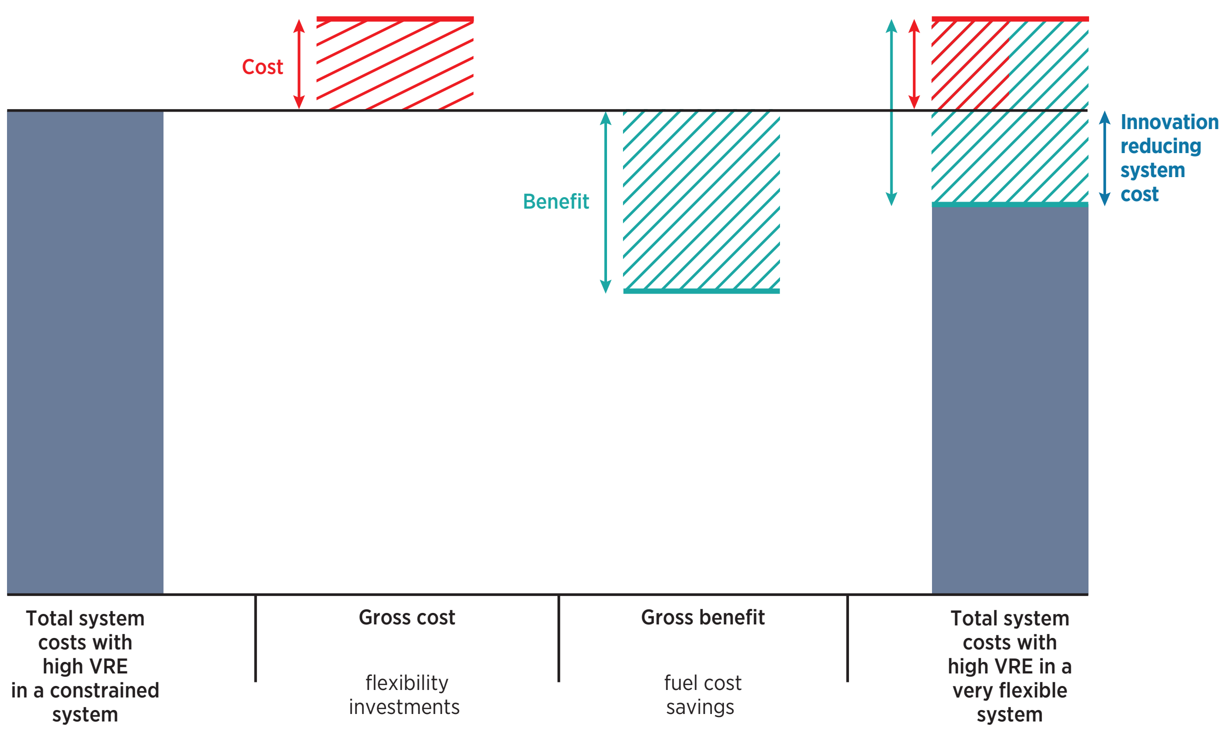
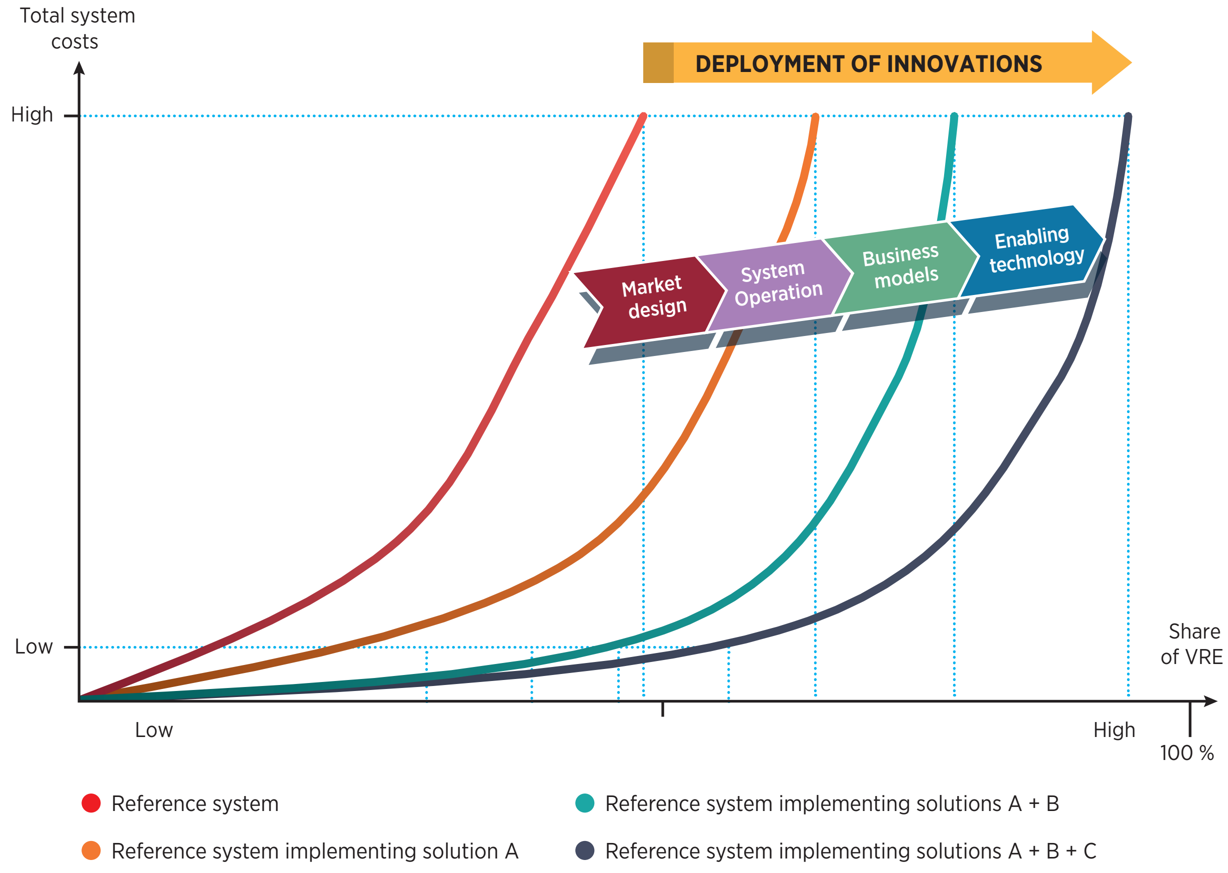
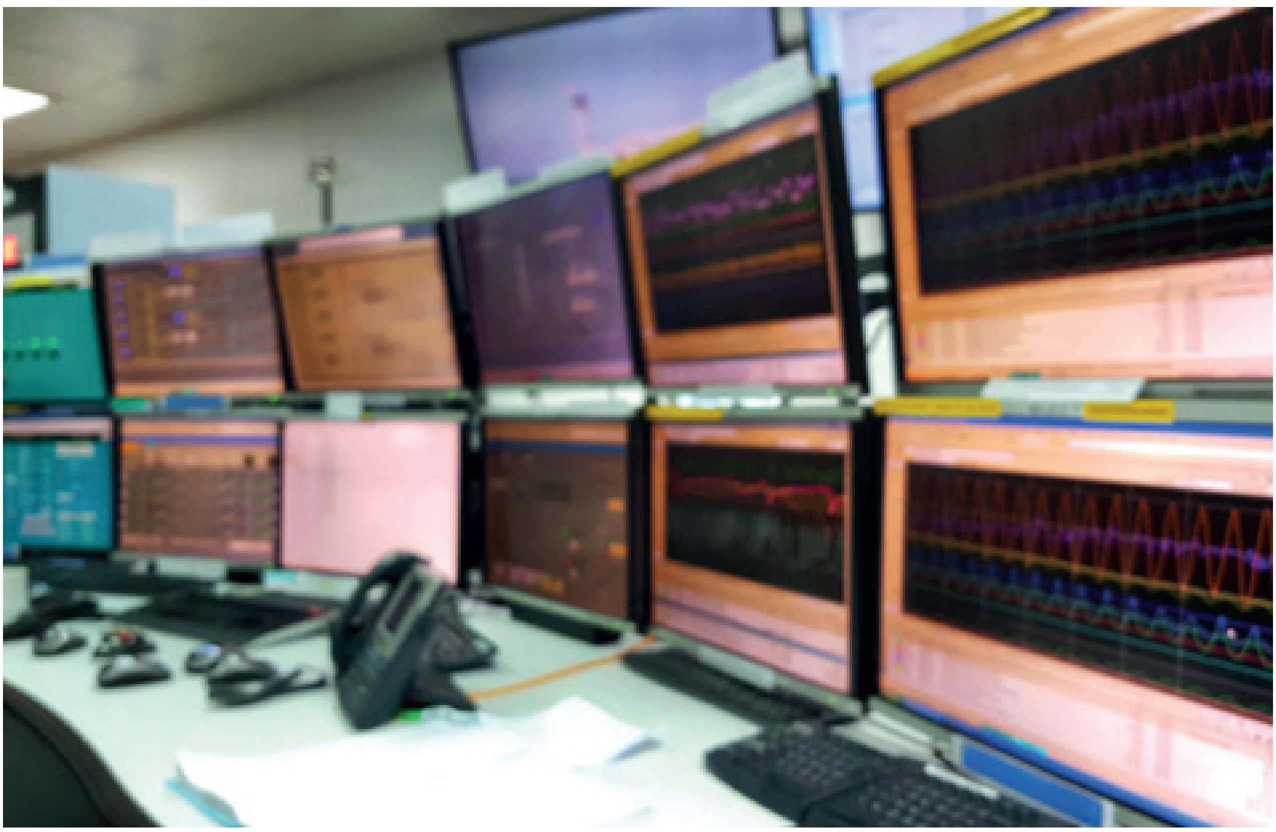


Figure S11 Concept of innovation reducing total system costs with high shares of VR





VIII. THE EIGHT-STEP INNOVATION PLAN FOR POWER SECTOR TRANSFORMATION

Power systems are changing due to policy imperatives and accelerating innovation. The strong business case for VRE technologies, such as wind and solar PV, is positioning them at the core of the transformation. Innovations being trialled in leading countries show that power systems can operate with very high shares of VRE in a reliable and economic way. However, a large gap exists between the leaders and the majority of followers in integrating VRE. While the private sector will continue to come up with new solutions to speed up the energy transformation, governments have a crucial role to play in facilitating and guiding the sector in line with national socio-economic objectives. To bridge the gap, the following recommended actions should be implemented by countries wishing the maximise the benefits of renewable energy for their economies (Figure S12).

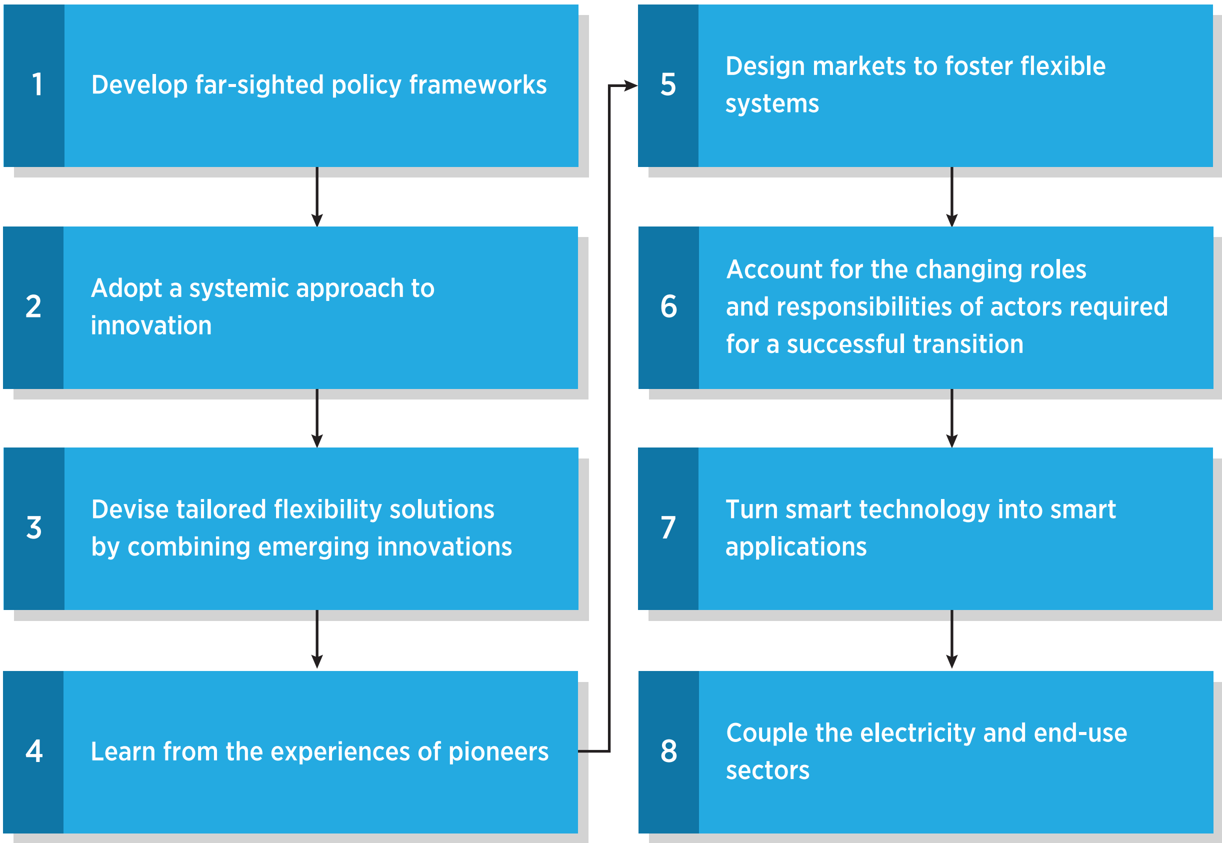
1 **Develop far-sighted policy frameworks.** Ensuring the cost-effective integration of VRE at scale requires the balancing of present needs (a focus on deployment of renewable generation technologies) with future needs (a focus on integrating high shares of VRE). There are difficult trade-offs between quick wins, such as achieving small increases in VRE by adding back-up capacity, and a comprehensive plan to meet future market needs, such as a long-term strategy. In targeting high levels of renewable deployment and integration, policy makers should not look at the quick wins in isolation. They need to look ahead to a time when renewable energy deployment has been successful and should design the markets and systems around this future.

2 **Adopt a systemic approach to innovation.** Leveraging synergies between innovations across all sectors and components of the system, and involving all actors, is crucial. Innovations in technology , business models, market design and system operation should be pursued alongside innovations in finance instruments and policy frameworks.

3 **Devise tailored flexibility solutions by combining emerging innovations.** Solutions can be tailored to the context and needs of a specific country by combining innovations in enabling technologies, market design, system operation and business models. Implementing them to unlock flexibility across the whole power sector results in lower costs to integrate VRE and so support the energy transformation. Potential synergies between the different solutions also exist, which can lower investment needs when implemented together.

4 **Learn from the experiences of pioneers.** Knowledge and experience should be more widely shared. Insights from trials and pilots should be more fully and systematically captured and more widely disseminated. Increased international collaboration can help ensure learning is quickly spread and efforts are not unnecessarily duplicated.

Figure S12 The eight-step innovation plan for power sector transformation



5 **Design markets to foster flexible systems.** Market design solutions for VRE have been shown to have high impact at low cost, making them a likely first option on which to focus effort. Certain energy markets and regulations are showing how markets can be adapted to reflect the needs of power systems with higher shares of VRE. Market operators are observing that value is moving from providing kilowatt hours to providing flexibility to accommodate more low-cost VRE. Pricing energy and grid services properly and remunerating all actors that are able to provide flexibility adequately are key components of market designs that accelerate the energy transformation. Proper planning that accounts for the energy transformation results in holistic and cost-effective market designs. Conversely, solutions based on quick wins and a patch-up approach result in high system costs in the long run.

6 **Account for the changing roles and responsibilities of actors required for a successful transition.** The increasing penetration of decentralised energy resources and the emergence of new market players, such as prosumers and active consumers, is ushering in a new era. Governments and companies need to gather better insights into consumer and community needs and expectations and their willingness to adopt innovations – and should then 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, DSOs will have to adjust their current role and transform their business model, transitioning from just a network planner to a system operator. Greater cooperation with TSOs is needed to increase the visibility of the newly connected DERs that can provide services to the system.

7 **Turn smart technology into smart applications.** Digital innovations (such as artificial intelligence, the IoT and blockchain) are starting to have a significant impact on power systems in many different ways. The implications for established models and actors – and the risks – 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. Many more pilots and deployments of digitally enabled solutions are needed in a wider range of circumstances.

8 **Couple the electricity and end-use sectors.** There are valuable synergies between the integration of VRE in power systems 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 consideration of wider societal changes.

The report (forthcoming) shows that a multitude of innovations that can facilitate the integration of VRE are now being implemented or trialled around the globe. Such solutions, furthermore, can be tailored to suit the needs and circumstances of almost any country. Policy frameworks that embrace and support the uptake of innovative solutions are crucial to fully realise the benefits of low-cost renewable power.

A successful energy transformation requires innovation to be part of comprehensive policy mix that includes policies related to education and training, industry, labour and investment, among others. Armed with knowledge of the options available, energy system planners and decision makers can, with confidence, envisage and pave the way for a renewables-powered future.

ACRONYMS AND ABBREVIATIONS

AI	artificial intelligence
BtM	behind-the-meter
CSP	concentrated solar power
DERs	distributed energy resources
DSO	distribution system operator
EV	electric vehicle
IoT	Internet of Things
IRENA	International Renewable Energy Agency
PHS	pumped hydro storage
PV	photovoltaic
P2P	peer-to-peer
RE	renewable energy
TSO	transmission system operator
VRE	variable renewable energy
V2G	vehicle-to-grid

UNITS OF MEASUREMENT

GW	gigawatt
MW	megawatt
MWh	megawatt hour
TWh	terawatt hour
yr	year

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INNOVATION LANDSCAPE FOR A RENEWABLE-POWERED FUTURE:

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