

INNOVATION LANDSCAPE FOR A RENEWABLE-POWERED FUTURE: SOLUTIONS TO INTEGRATE VARIABLE RENEWABLES



© IRENA 2019

Unless otherwise stated, material in this publication may be freely used, shared, copied, reproduced, printed and/or stored, provided that appropriate acknowledgement is given of IRENA as the source and copyright holder. Material in this publication that is attributed to third parties may be subject to separate terms of use and restrictions, and appropriate permissions from these third parties may need to be secured before any use of such material.

ISBN 978-92-9260-111-9

Citation: IRENA (2019), *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*. International Renewable Energy Agency, Abu Dhabi.

ACKNOWLEDGEMENTS

This report benefited from input and review of experts: Konstantin Staschus (Ecofys – A Navigant Company); Deger Saygin (SHURA Energy Transition Centre); Mark Van Stiphout, Ruud Kempener (European Commission); Luiz Augusto Barroso (PSR); Tomas Baeza (CORFO); Maher Chebbo, Vlad Duboviks (GE Power); Stephen Woodhouse (Poyry); Wolfram Sparber (EURAC); Mackay Miller (National Grid); Jan Vorrink (Tennet); Ioannis Theologitis, Norela Constantinescu (ENTSO-E); Koen Noyens, Helene Lavray (Eurelectric); Guy Vekemans (Vito); Tiago Mouras (EDP); Nilmini Silva-Send (EPIC); David Butler (Hydro Tasmania); Mika Ohbayashi (Renewable Energy Institute); James Watson, Thomas Döring (Solar Power Europe); Lei Xianzhang, Wang Caixia, Wand Feng (SGCC); Jia Hongjie, Wang Chengshan (Tianjin University); Zhou Yue (Cardiff University); Gerard Wynn, Tim Buckley (IEEFA); Marko Vainikka, Saara Kujala (Wärtsilä); Peter Stratmann, Yvonne Finger (Federal Network Agency for Electricity); Varun Sivaram (Council on Foreign Relations); Doug Arent (NREL); Pablo Mastropietro (Comillas Pontifical University); Josh Roberts (REScoop); François Moisan, Olivier Chazal (ADEME); Anna Darmani (Innoenergy); Ilja Rudyk (EPO); Karoliina Auvinen (Aalto University); Florence Couillet (Clarion Energy); Arthur Petersen, Iman Jamall (UCL); Ahmed Abdel-Latif, Hameed Safiullah, Emanuele Bianco, Paul Komor, Emanuele Taibi, Carlos Fernandez, Raul Miranda, Harold Anuta, Elena Ocenic (IRENA).

The report was authored by Francisco Boshell, Arina Anisie, Roland Roesch, Paul Durrant, Sean Ratka, Alessandra Salgado, Javier Sesma (IRENA). The study was supervised by Dolf Gielen.

Report available online: www.irena.org/publications

For questions or to provide feedback: publications@irena.org

DISCLAIMER

This publication and the material herein are provided “as is”. All reasonable precautions have been taken by IRENA to verify the reliability of the material in this publication. However, neither IRENA nor any of its officials, agents, data or other third-party content providers provides a warranty of any kind, either expressed or implied, and they accept no responsibility or liability for any consequence of use of the publication or material herein.

The information contained herein does not necessarily represent the views of the Members of IRENA. The mention of specific companies or certain projects or products does not imply that they are endorsed or recommended by IRENA in preference to others of a similar nature that are not mentioned. The designations employed and the presentation of material herein do not imply the expression of any opinion on the part of IRENA concerning the legal status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Photographs are from Shutterstock unless otherwise indicated.



FOREWORD



Innovation is the engine that powers the ongoing transformation of the global energy system. A multitude of innovative solutions have been key to making renewables into the competitive energy option that they are today.

The pace of renewable energy innovation, meanwhile, keeps accelerating, with power generation solutions at the forefront. Rapid cost reductions for solar and wind power have put these technologies at the core of the energy transformation. To maximise their share while maintaining low electricity costs, more flexible power systems are needed.

Innovation programmes in leading markets, therefore, are focusing on solutions to achieve maximum power system flexibility. The increasing electrification of transport, buildings and industry can also facilitate solar and wind uptake if smart approaches are adopted. As many of these new loads will be flexible, their inclusion in the power system can also help to integrate more renewables through demand-side management strategies.

Many of the solutions to address such challenges are ready for commercialisation. With pioneering companies creating, trialling and deploying a swathe of potentially transformative innovations, the key trends of digitalisation, decentralisation and electrification are moving ahead faster than anyone expected. Yet timely, focused government action remains essential to support innovation and integrate emerging solutions.

In each context, decision makers need to identify the optimal combination of solutions. Determining a suitable, tailored innovation mix for each country requires a systemic approach – combining innovations in technology with those in market design, business models and systems operation. But the sheer diversity of solutions available, coupled with the diversity of power systems around the world, can pose significant challenges in decision-making.

The present Innovation Landscape study, prepared by the International Renewable Energy Agency (IRENA), aims to provide a clear and comprehensive guide to such solutions. It seeks to support informed decision-making, assist in the creation of enabling policy frameworks, help nurture targeted innovation and, ultimately, facilitate the accelerated transition to renewables.

The present report maps and categorises examples of the innovations being developed and implemented globally to facilitate the large-scale integration of variable renewable power. This main report will be augmented by technology briefs and online resources which will permit closer examination of each innovation type.

The study highlights the broad range of innovations available that could not just accelerate renewable energy deployment to meet demand, but could also help to ensure that the energy transformation is global and inclusive. IRENA will continue to work with its Members on fostering renewable energy innovation and deployment, in line with their national economic, social and environmental goals as well as with global climate and sustainable development objectives.

Adnan Z. Amin

Director-General
International Renewable
Energy Agency

CONTENTS

Executive Summary	8
Innovation Landscape Briefs: Innovations for a renewable-powered future.	10
Synthesis report: Solutions to integrate variable renewables	12
Figures	14
Tables	15
Abbreviations	16
1 Power sector transformation	18
1.1 Towards a low-carbon, reliable, affordable and secure energy system	19
1.2 Increasing system flexibility for the integration of VRE	21
1.3 Showcasing innovation.	23
1.4 Innovation trends and changing roles in future power systems.	29
· Digitalisation of the power sector.	31
· Decentralisation of power systems.	34
· Electrification of end-use sectors.	36
2 The landscape of innovations for variable renewable power integration	38
● 2.1 Enabling technologies	41
· Electricity storage	42
· Electrification of end-use sectors.	43
· Digital technologies.	45
· New grids	46
· Dispatchable generation.	47
● 2.2 Business models	48
· Empowering the consumer	49
· Enabling renewable energy supply	50
● 2.3 Market design	51
· Innovative wholesale market design	52
· Innovative retail market design.	54
● 2.4 System operation	55
· Operation of distributed energy resources.	56
· Accommodating uncertainty.	57
· Grid reinforcement deferral.	58

3	Innovations creating solutions for a renewable-powered future	60
3.1	Supply-side flexibility solutions	66
	Solution I: Decreasing VRE generation uncertainty with advanced weather forecasting	67
	Solution II: Flexible generation to accommodate variability	71
3.2	Grid flexibility solutions	78
	Solution III: Interconnections and regional markets as flexibility providers	79
	Solution IV: Matching renewable power generation and demand over large distances with supergrids	84
	Solution V: Large-scale storage and new grid operation to defer grid reinforcements investments	87
3.3	Demand-side flexibility solutions	92
	Solution VI: Distributed energy resources providing services to the grid	93
	Solution VII: Demand-side management	99
	Solution VIII: Renewable energy mini-grids providing services to the main grid	104
	Solution IX: Optimising distribution system operation with distributed energy resources	108
3.4	System-wide flexibility solutions	113
	Solution X: Utility-scale battery solutions	114
	Solution XI: Power-to-X solutions	120
4	Impact assessment of solutions	128
4.1	Key solutions: Implementation challenges versus flexibility potential	132
4.2	Indicators on the suitability of solutions	142
5	Summing up: Eight-step innovation plan	148
	References	154

ES EXECUTIVE SUMMARY

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

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 pace of the energy transition needs to pick up significantly. As with market policies, the policies put in place to drive technological

innovation should be continually revisited and updated to keep up with new developments and breakthroughs (IRENA, IEA and REN21, 2018).

The integration of variable renewable energy (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: *The capability of a power system to cope with the variability and uncertainty that solar and wind energy introduce at different time scales, from the very short to the long term, avoiding curtailment of power from these variable renewable energy (VRE) sources and reliably supplying all customer energy demand (IRENA, 2018c).*

Variability: *The fluctuating nature of solar and wind resources, which translates into potentially rapid changes in electricity output*

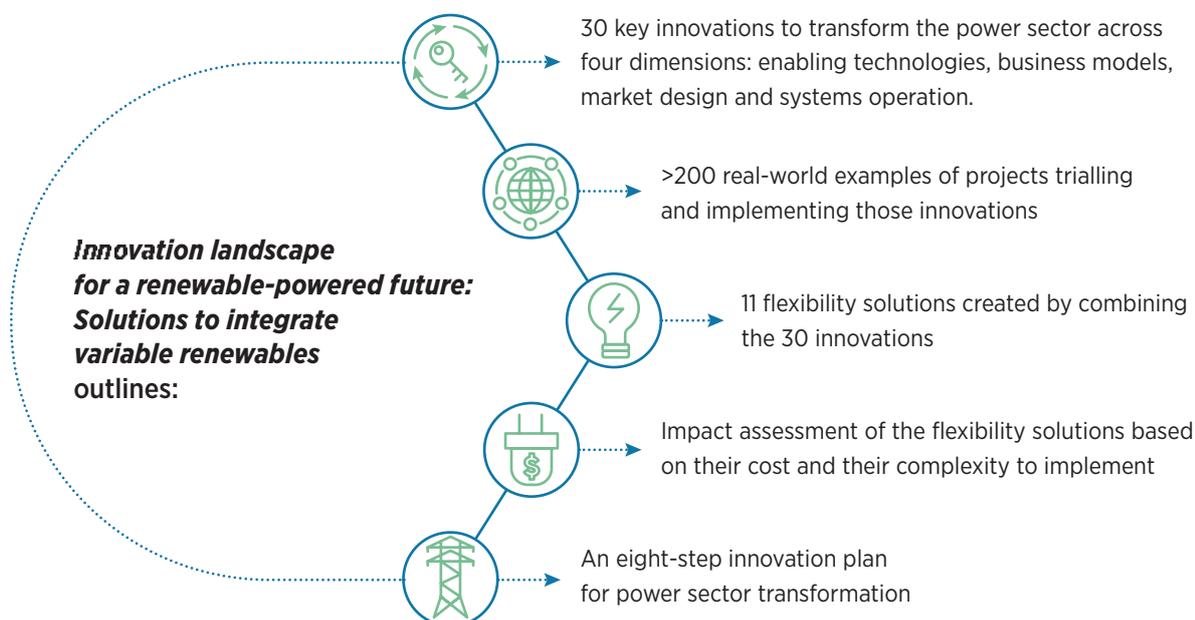
Uncertainty: *The inability to predict perfectly the future output of solar and wind power sources*



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. This report, 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 worldwide. The resulting framework should enable informed judgments on possible solutions for each particular case.



INNOVATIONS TO FACILITATE VARIABLE RENEWABLE ENERGY INTEGRATION

A large number of innovations that can be used to integrate high VRE shares are emerging and are being implemented worldwide. IRENA's Innovation Landscape study maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of VRE into power systems as a result of implementing these innovations.

The Innovation Landscape is based on analysis of hundreds of innovative projects and initiatives being implemented around the globe. These innovations have been grouped and mapped in categories, resulting in a suite of 30 innovations (see Table 1).

The analysis also demonstrates that innovations are emerging across four key dimensions of the world's power systems:

- **Enabling technologies:** Technologies that play a key role in facilitating the integration of renewable energy.
- **Business models:** Innovative models that create the business case for new services, enhancing the system's flexibility and incentivising further integration of renewable energy technologies.
- **Market design:** New market structures and changes in the regulatory framework to encourage flexibility and value services needed in a renewable-based power energy system, stimulating new business opportunities.
- **System operation:** Innovative ways of operating the electricity system, allowing the integration of higher shares of variable renewable power generation.

Based on the experiences of pioneering countries and companies in piloting and applying these innovations, each of the 30 innovation types has been analysed in detail. A series of briefs accompanying this report aims to help readers assess the benefits, risks and suitability of each innovation for any specific context.

Each of the Innovation Briefs contains:

- I **Description:** what the innovation is and how it works.
- II **Contribution to power sector transformation:** how the innovation, through the services and the benefits provided to power systems, could support the integration of VRE.
- III **Key factors to enable deployment:** overview of the risks and challenges, and how to overcome them, for the implementation of the innovation.
- IV **Current status and examples of initiatives:** indicators to track the current progress of the innovation, and examples of ongoing initiatives and projects implementing the innovation around the world.
- V **Implementation requirements:** checklist an easy-to-use tool for policy makers, listing the items that need to be in place to implement the innovation.

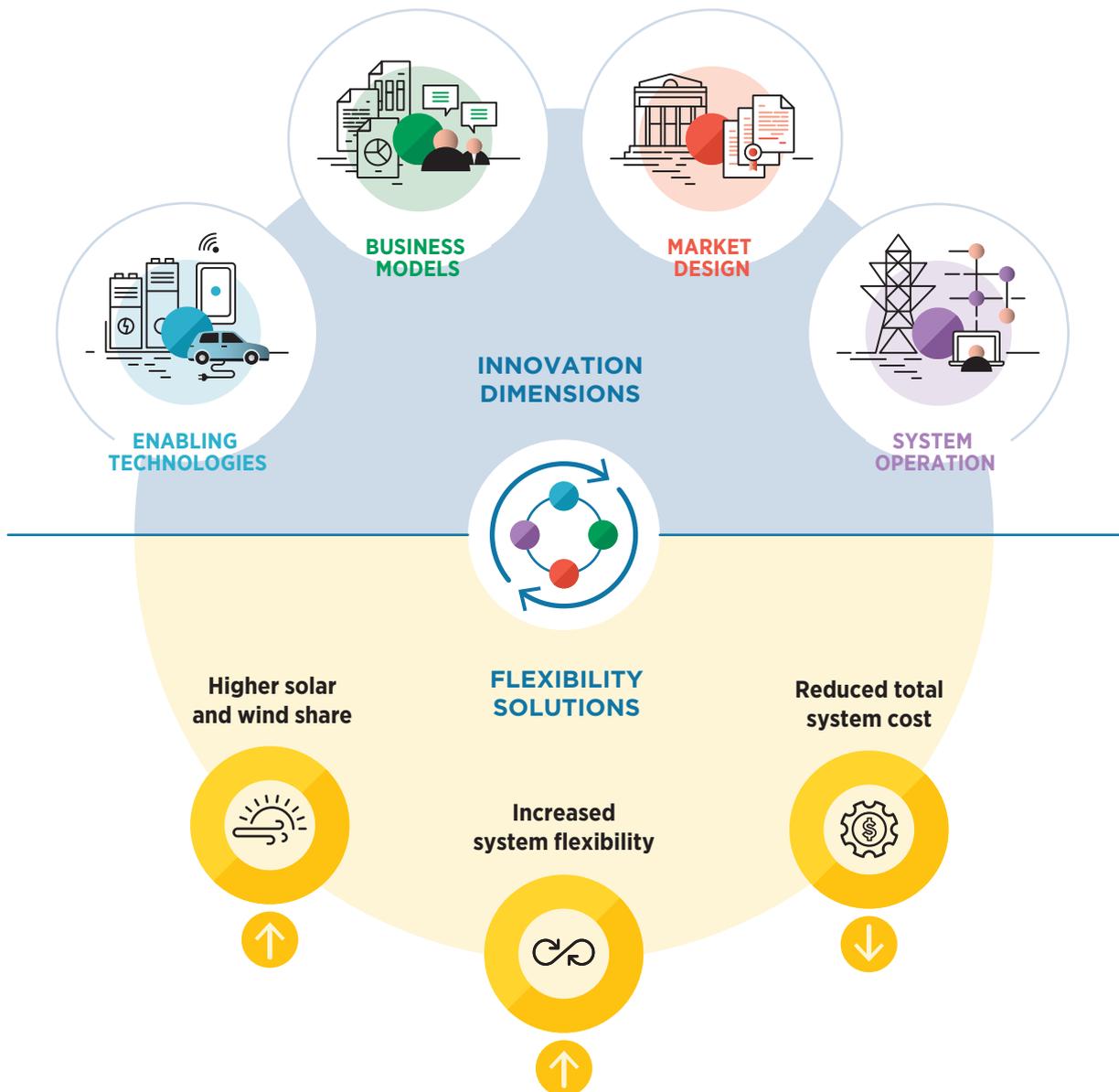
Table 1 Overview of the Innovation Briefs

	OVERVIEW	INNOVATION BRIEFS
Enabling technologies 	<ul style="list-style-type: none"> Battery storage technologies, able to back up the variability of renewables and provide various services to the grid. 	<ol style="list-style-type: none"> Utility-scale batteries Behind-the-meter batteries
	<ul style="list-style-type: none"> Technologies that enable electrification of other sectors, opening doors to new markets for renewable generation as well as new ways to store the generation surplus. 	<ol style="list-style-type: none"> Electric-vehicle smart charging Renewable power-to-heat Renewable power-to-hydrogen
	<ul style="list-style-type: none"> Digital technologies that are introducing new applications in the power sector, changing the boundaries and dynamics of the industry and helping to optimise renewables assets. 	<ol style="list-style-type: none"> Internet of things Artificial intelligence and big data Blockchain
	<ul style="list-style-type: none"> New and smart grids, both large and small scale, that complement each other and enable new ways to manage VRE generation. 	<ol style="list-style-type: none"> Renewable mini-grids Supergrids
	<ul style="list-style-type: none"> Refurbishment of existing assets, to adapt to the new conditions and to the needs of the system. 	<ol style="list-style-type: none"> Flexibility in conventional power plants
Business models 	<ul style="list-style-type: none"> Business models that empower consumers, turning them into active participants. 	<ol style="list-style-type: none"> Aggregators Peer-to-peer electricity trading Energy-as-a-service
	<ul style="list-style-type: none"> Innovative schemes that enable renewable energy supply, in both off-grid and connected areas. 	<ol style="list-style-type: none"> Community-ownership models Pay-as-you-go models
Market design 	<ul style="list-style-type: none"> New regulations in the wholesale markets that encourage flexibility from market participants, better signal firming power supply's value, and properly remunerate their grid support services. 	<ol style="list-style-type: none"> Increasing time granularity in electricity markets Increasing space granularity in electricity markets Innovative ancillary services Re-designing capacity markets Regional markets
	<ul style="list-style-type: none"> Design and regulatory changes in the retail market that stimulate flexibility on the consumer / prosumer side. 	<ol style="list-style-type: none"> Time-of-use tariffs Market integration of distributed energy resources Net billing schemes
System operation 	<ul style="list-style-type: none"> Distributed generation deployment requires new ways of operating the distribution grid and market facilitation for distributed generation. 	<ol style="list-style-type: none"> Future role of distribution system operators Co-operation between transmission and distribution system operators
	<ul style="list-style-type: none"> New operation procedures that enhance electricity system flexibility. 	<ol style="list-style-type: none"> Advanced forecasting of variable renewable power generation Innovative operation of pumped hydropower storage
	<ul style="list-style-type: none"> New ways to operate the grid that reduce VRE curtailment due to grid congestion. 	<ol style="list-style-type: none"> Virtual power lines Dynamic line rating

SOLUTIONS TO INTEGRATE VARIABLE RENEWABLES

This synthesis report brings together the key insights from the innovations identified in the Innovation Landscape, illustrating that innovations do not emerge in isolation. On the ground, implemented solutions for the integration of VRE come from the synergies of different innovations across different dimensions, such as technology, market design, business models and systems operation. This is called **systemic Innovation**.

This stand-alone report synthesises the information contained in the underlying Innovation Briefs and builds links among the various innovations. The details of each of the innovations, discussed in the synthesis report, are presented in the Innovation Briefs.



The synthesis report is structured in four chapters:

Chapter 1: Power sector transformation portrays the big picture, explaining the importance of a future renewable-powered system for a low-carbon, reliable, affordable and secure energy system. It also highlights the main challenges that lie ahead and identifies innovation trends that are helping to overcome the challenges. The changing roles and responsibilities of actors in the power sector, as well as new actors entering the scene, are highlighted.

Chapter 2: The landscape of innovations for variable renewable power integration presents an overview of the 30 mapped innovation types.

Chapter 3: Innovations creating solutions for a renewable-powered future explains the relation and synergies among the innovation types and the four dimensions and formulates possible solutions from such innovation synergies, or what it is called systemic innovation. Systemic innovation refers to matching and leveraging synergies in innovations in all components of the power system and including all actors.

Chapter 4: Impact assessment of solutions provides brief guidance on which solutions could be low-hanging fruit for increasing the flexibility in the system, and which solutions might be relevant for the context of different systems.

Chapter 5: Final remarks: Eight-step innovation plan closes the report with recommended actions for a renewable-powered future.

Power systems are changing due to policy imperatives and accelerating innovation. The strong business case for VRE energy technologies, such as wind and solar PV, is positioning these technologies at the core of the transformation. Innovations being trialled in front-running countries show that power systems can operate with very high shares of VRE in a reliable and economical way. However, a large gap remains between the front runners and the majority of followers in integrating VRE. While the private sector will continue to come up with new solutions to speed 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 could be implemented by countries wishing to maximise the benefits of renewable energy for their economies.

FIGURES

Figure 1. Towards a low-carbon, reliable, affordable and secure energy system . . .	20	Figure 19. Costs and benefits of nodal pricing	74
Figure 2. New flexibility options across the power sector unlocked by innovation . . .	22	Figure 20. Power generation from nuclear, hard coal and lignite power plants and demand in Germany, 23 to 30 March 2016	75
Figure 3. Innovations taking place in the electricity supply chain	30	Figure 21. Flexibility requirements in Germany. Example load curves for two weeks during winter in Germany	76
Figure 4. Innovation trends.	31	Figure 22. Key characteristics of the design of the Nordic market.	77
Figure 5. Emerging digital applications in the power system	32	Figure 23. Synergies between innovations for unlocking flexibility through interconnections and regional markets . .	79
Figure 6. Internet of Things-connected devices worldwide (billions), 2015-2020	33	Figure 24. Synergies between innovations for matching renewable energy generation and demand using supergrids.	84
Figure 7. Distributed energy resources	34	Figure 25. Synergies between innovations for investments in transmission grid reinforcement	87
Figure 8. Landscape of innovations.	39	Figure 26. Illustrative structure of the Surf ‘n’ Turf initiative	89
Figure 9. Enabling technologies innovations	41	Figure 27. Synergies between innovations that permit grid services based on distributed energy resources.	93
Figure 10. Business model innovations	48	Figure 28. Synergies between innovations for enabling demand-side management	99
Figure 11. Market design innovations	51	Figure 29. Synergies between innovations for enabling mini-grids to provide services to the main grid	104
Figure 12. System operation innovations.	55	Figure 30. Synergies between innovations for optimising distribution system operation with distributed energy resources	108
Figure 13. The innovation landscape for variable renewable power integration.	59	Figure 31. Synergies between innovations with utility-scale batteries	114
Figure 14. Systemic innovation for power sector transformation	61		
Figure 15. Traditional flexibility providers (left) versus emerging flexibility providers (right)	63		
Figure 16. Solutions created by combining innovations in enabling technologies, business models, market design and system operation. . .	64		
Figure 17. Synergies between innovations for decreasing uncertainty of VRE generation with advanced forecasting . .	67		
Figure 18. Synergies between innovations for increased flexible generation	71		

TABLES

Figure 32. PJM regulation services signal and battery response	118	Table 1. Overview of the Innovation Briefs	11
Figure 33. Synergies between innovations for power-to-X solutions.	120	Table 2. Suitability of various battery technologies for different grid applications.	115
Figure 34. Integration of VRE into end-uses by means of hydrogen	121	Table 3. Flexibility needs addressed by the solutions	132
Figure 35. Use of electrolyser for fast frequency response	123	Table 4. Challenges for implementing different innovations and solutions.	133
Figure 36. Innovation that maximises system benefits	129	Table 5. Summary table.	140
Figure 37. Innovation reducing total system costs for high shares of VRE	130		
Figure 38. Solutions that unlock the system's flexibility	131		
Figure 39. Solutions' flexibility potential versus technology costs needed.	134		
Figure 40. Solutions' flexibility potential versus non-technological challenges	135		
Figure 41. Solutions guide according to population density in cities	143		
Figure 42. Solutions guide according to seasonality	144		
Figure 43. Solutions guide according to interconnection possibilities	145		
Figure 44. Solutions guide according to the distance between VRE resources and demand centres	145		
Figure 45. Solutions guide according to the net load profile.	146		
Figure 46. Solutions for all contexts	146		
Figure 47. The eight-step innovation plan for power sector transformation.	150		

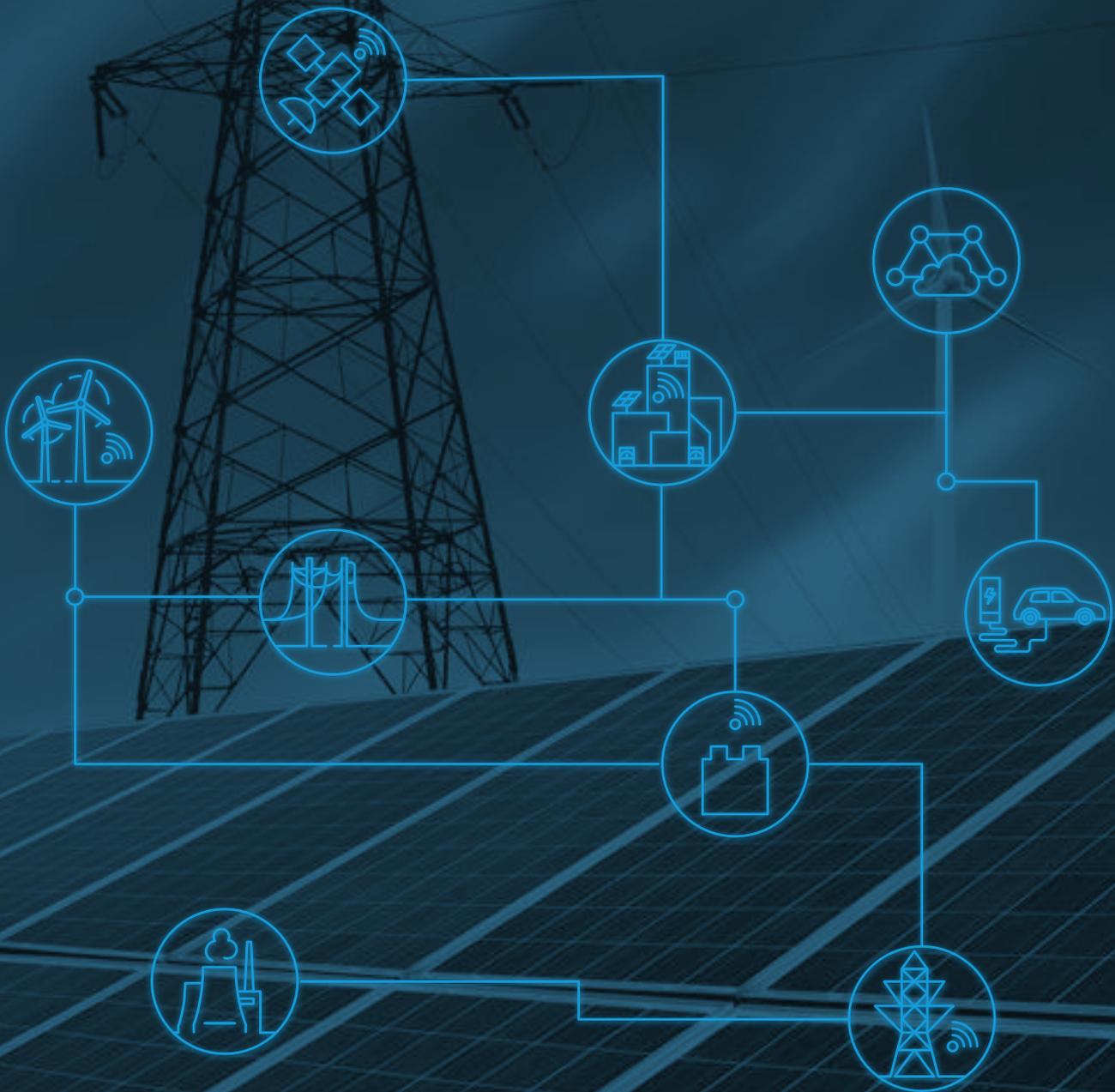
ABBREVIATIONS

AC	Alternating current	IoT	Internet of Things
AI	Artificial intelligence	ISO-NE	Independent System Operator – New England
APS	Arizona Public Service Company	IT	Information technology
AUD	Australian dollar	IRENA	International Renewable Energy Agency
BMWi	Germany Federal Ministry for Economic Affairs and Energy	kg	Kilogram
CAISO	California Independent System Operator	kV	Kilovolt
CHP	Combined heat and power	kW	Kilowatt
CO	Community ownership	kWh	Kilowatt-hour
CREZ	Competitive renewable energy zone	MISO	Midcontinent Independent System Operator
DC	Direct current	MW	Megawatt
DLR	Dynamic line rating	MWh	Megawatt-hour
DUoS	Distributed use of system	NEM	National Electricity Market
EaaS	Energy as a service	NYISO	New York Independent System Operator
EIM	Energy Imbalance Market	P2P	Peer-to-peer
ENTSO-E	European Network of Transmission System Operators	PAYG	Pay as you go
ERCOT	Electricity Reliability Council of Texas	PEM	Proton exchange membrane
EU	European Union	PG&E	Pacific Gas and Electric
EUR	Euro	PJM	Pennsylvania – New Jersey – Maryland Interconnection
EV	Electric vehicle	PV	Photovoltaic
FCAS	Frequency Control Ancillary Services	SAPP	Southern African Power Pool
FERC	Federal Energy Regulatory Commission	SIDE	Smart Integrated Decentralised Energy
GBP	British pound	TWh	Terawatt-hour
GW	Gigawatt	UHV DC	Ultra-high-voltage direct current
GWh	Gigawatt-hour	UK	United Kingdom
HVAC	Heating, ventilation and air conditioning	US	United States
HVDC	High-voltage direct current	USD	United States dollar
Hz	Hertz	VPP	Virtual power plant
ICT	Information and communications technology	VRE	Variable renewable energy



1

POWER SECTOR TRANSFORMATION



1.1 TOWARDS A LOW-CARBON, RELIABLE, AFFORDABLE AND SECURE ENERGY SYSTEM

The world is undergoing an energy sector transition towards a more inclusive, secure, cost-effective, low-carbon and sustainable future. One of the critical building blocks is renewable energy. This transition is fostered by unprecedented public pressure and policy action, triggered by the United Nations' Sustainable Development Goals, rising air pollution and water stress, as well as by increasing concerns about climate change, which led to the 2015 Paris Agreement, and the urgency and importance of which are disclosed in the recent report from the Intergovernmental Panel on Climate Change (IPCC, 2018). The energy transition is now evolving further with innovation as an additional key driver.

The power sector is leading the ongoing energy transition, driven by the rapid decline in renewable electricity costs, particularly for wind and solar generation. Between 2009 and 2018 the price of solar photovoltaic (PV) modules dropped more than 80%, and the cost of electricity from solar PV fell nearly 75%. The price per unit of wind power fell by about 50% (depending on the market) over the same period, and the costs of onshore wind power dropped nearly 25% between 2010 and 2018, with further dramatic declines expected in the coming decade (IRENA, 2018a).

Renewable power generation accounted for an estimated one-quarter of total global power generation in 2017, with impressive growth in recent years in variable renewable energy (VRE), particularly wind and solar PV technologies. By the end of 2017 the installed capacity of renewables reached 2 337 gigawatts (GW), comprising 34% of the total power-generating capacity (IEA, 2018a). The bulk of this was from hydropower (54%), followed by wind power (22%) and solar power (mostly solar PV, at almost 17%). Between 2005 and 2016 the global installed capacity of solar PV increased more than seven-fold, and the capacity of onshore wind increased nearly three-fold. An additional 98 GW of solar PV and 48 GW of wind power was installed in 2017 alone.

Nonetheless, this energy transition needs further acceleration of this growth. According to analysis from IRENA (2018b) a 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. By that time solar and wind power capacity would rise from 900 GW today to 13 000 GW and would account for 60% of the total power generated. This requires a tripling of annual wind capacity additions and a doubling of solar PV capacity additions from 2017 levels.

Furthermore, the share of electricity consumption in the total energy demand of the three primary end-use sectors – industry, buildings and transport – needs to double from around 20% in 2015 to 40% in 2050. The progress in renewable power

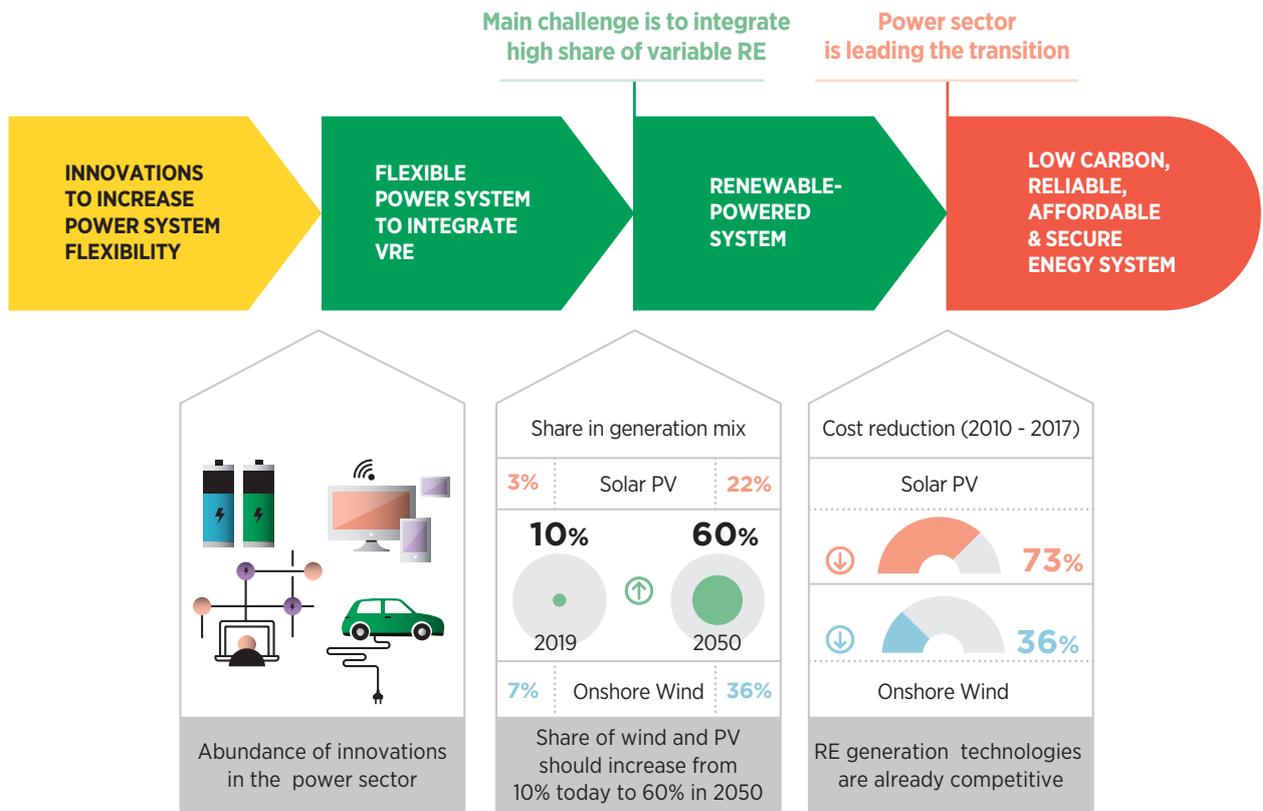
1

generation technologies brings opportunities to use renewable electricity as a vector to decarbonise the end-use sectors. Smart electrification approaches, based on innovative business models and market designs, are crucial to realise these synergies and to take advantage of the potential flexibility provided by the new loads.

Further innovation in renewable energy technologies is needed to increase efficiency, to better adapt these technologies to specific weather conditions,

to better integrate them into the living environment (for example innovations in building-integrated PV systems) and to further decrease costs. However, in addition to innovation in renewable power generation technologies, innovation in grid integration strategies has become crucial in increasing the share of VRE in the power system, enhancing the system's flexibility in a cost-effective manner. Figure 1 summarizes the path towards a cleaner, reliable and secure energy system.

Figure 1 Towards a low-carbon, reliable, affordable and secure energy system



1.2 INCREASING SYSTEM FLEXIBILITY FOR THE INTEGRATION OF VRE

In an age of low-cost renewable power generation, the success of the energy transition will be underpinned by the implementation of strategies to integrate high shares of VRE into power systems at the lowest possible cost. At present the share of VRE in electricity generation in G20 countries is about 10%. Some countries, particularly in Europe, have achieved significantly higher VRE shares: in 2017 the VRE share in Denmark reached 53%, in South Australia 48%, and in Lithuania, Ireland, Spain and Germany greater than 20%.

The three largest power systems in the world – China, India and the United States (US) – are expected to double their VRE shares to more than 10% of annual generation by 2022 (IRENA, IEA and REN21, 2018). India, for example, covered 7.7% of its load with VRE generation between 2017 and 2018 and is on track to reach 9% VRE generation by 2019. In the US 7.6% of electricity came from wind and solar sources in 2017 (EIA, 2018a).

However, the share of solar PV and wind power in global electricity generation will need to grow from 4.5% in 2015 to nearly 60% by 2050 (IRENA, 2018b). Given the variability and uncertainty of wind and solar energy sources, innovative solutions are needed to provide the necessary flexibility and adequacy to power systems. Between 2015 and 2050 investments similar to those needed for additional renewable energy generation technologies could be required for grid infrastructure reinforcement and other flexibility options for VRE integration. Grid and flexibility investment needs for this period would rise from USD 9 trillion without this additional VRE to about USD 18 trillion (IRENA, 2018b). These investments need to underline the importance of putting greater effort into addressing flexibility, as VRE grid integration may become the technical or economic bottleneck of a global energy sector transformation.

The next step, therefore, is to focus innovation efforts on integrating high shares of VRE in power systems and to lower the costs of this integration through solutions that increase flexibility in the system. Flexibility – defined as the ability of a system to respond to changes in load and

generation – has always been part of operating a power system because the normal demand for electricity varies greatly on a daily and a seasonal basis (IRENA, 2018c). With increasing shares of VRE, the flexibility of the operating power system is also directly related to its ability to accommodate variable generation while maintaining a reliable balance of supply and demand at the lowest possible cost.

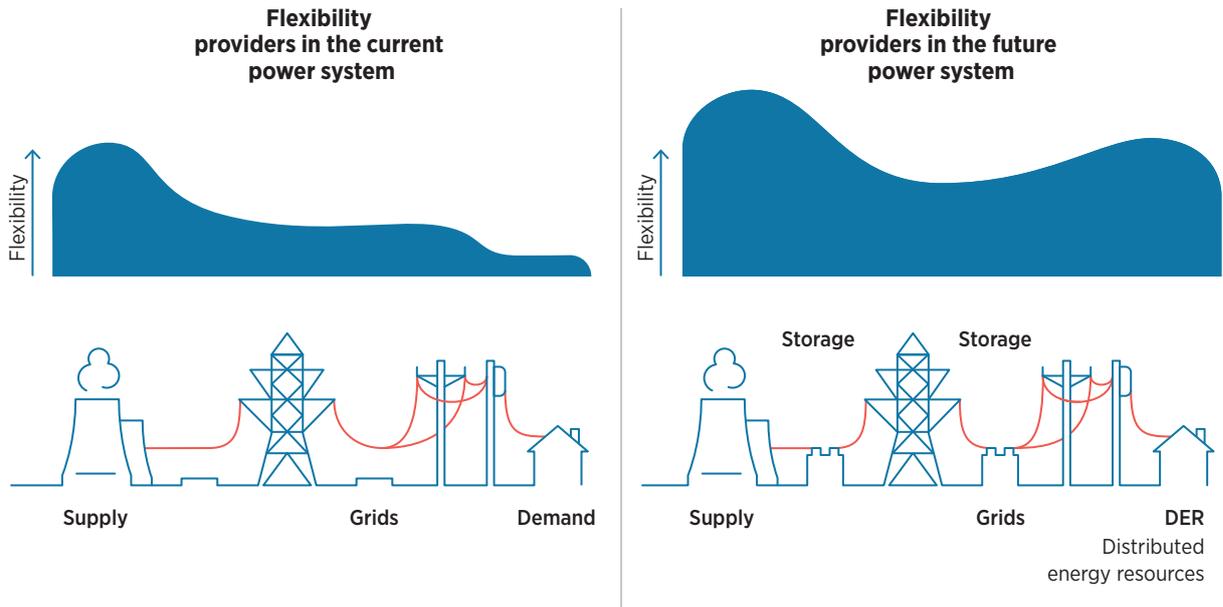
Insufficient flexibility could lead to load shedding (if the system cannot ramp up sufficient firm capacity during periods of low VRE generation) or to VRE curtailment (if the system cannot ramp down during periods of high VRE production). It therefore can result in a reduced operational value of incremental new VRE and in increased operations costs due to the need for additional firm capacity to meet reserves or peak demand. Therefore, in this context, flexibility is the capability of a power system to cope with the variability and uncertainty that VRE generation introduces into the system in different time scales, from the very short term to the long term, avoiding curtailment of VRE and reliably supplying all of the demanded energy to customers (IRENA, 2018c).

Traditionally, in conventional power systems, the supply side provided flexibility by adjusting the generation to follow demand. The demand side provided very little flexibility because it was largely unresponsive. Emerging innovations not only further increase supply-side flexibility, but also make provisions for such flexibility in all segments of the power system. Figure 2 illustrates the transition towards a flexible system and away from a system in which generation is the only flexibility source.

- **Supply-side flexibility:** Higher flexibility from the supply side needs to be further incentivised, with more flexible behaviour both from existing conventional plants and from renewable energy generators (to the extent of their capabilities).
- **Grid flexibility:** Grid flexibility is provided by greater network capacity and by the establishment of regional markets, which allows electricity to be transported more readily within a larger balancing area, across several control areas or even continent-wide. Thus, a wider geographic diversity of resources can be

1

Figure 2 New flexibility options across the power sector unlocked by innovation



used to balance supply and demand by taking advantage of weather and resource diversity. Distribution grid capacity and management is also important for integrating more renewable energy, which is connected at the distribution grid.

- **Demand-side flexibility:** On the demand side the emergence of distributed energy resources – such as rooftop solar PV, micro wind turbines, battery energy storage systems, mini-grids, plug-in electric vehicles, etc. – have the potential to greatly increase system flexibility by becoming active participants in the electricity network. The electrification of end-use sectors such as transport, buildings and industry – by using a smart approach to managing these new loads through demand-response programmes, price elasticity and sector coupling – opens new flexibility opportunities for integrating VRE into the grid. Digital technologies are emerging to support distributed energy resources in responding to system conditions and providing services to the grid, turning them into flexibility providers.

- **System-wide storage flexibility:** Energy storage technologies are flexibility providers across the energy sector that have huge potential to enable high VRE shares in the system. On the supply side utility-scale batteries and “power-to-X” applications (e.g., power-to-heat, power-to-hydrogen) can increase flexibility when connected to a VRE plant and storing its excess generation. On the demand side they can provide significant flexibility through direct or indirect electrification of end-use sectors if the load is well managed, or they could help increase grid flexibility and reduce network congestion when connected to the grid for such purposes.

The optimal strategy for increasing flexibility in a system and integrating higher shares of VRE is not certain. Also, strategies are country- and context-specific, depending on the rate of electricity demand growth, the level of existing grid interconnectivity and the spread of domestic natural resources, among others. Different sets of innovation are already being deployed in different power systems.

Innovation is crucial to create and implement the solutions to increase the flexibility of power systems and to reduce the cost of integration of VRE – tailored to different power system contexts – and to create new value streams for the different actors in the power value chain, from generators to consumers.

1.3 SHOWCASING INNOVATION

Countries such as Denmark, Germany, Portugal, Spain and Uruguay have proven the feasibility of managing annual VRE shares higher than 25% in power systems. An increasing number of sub-regions and even entire countries have managed

VRE shares close to 100% for short periods of time (IRENA, 2018a). The tables below summarise the innovations that different power systems are implementing to increase system flexibility and VRE share.

DENMARK

VRE penetration:	Challenges:
<p>More than 40% since 2014, reaching 53% in 2017 (IEEFA, 2018), with most of it coming from wind energy.</p> <p>Target:</p> <p>100% renewables in the energy sector by 2050, with 50% wind electricity.</p>	<ul style="list-style-type: none"> • Balancing supply and demand, ensuring that sufficient baseload power is available when there is no wind. • Keeping wind power valuable during high wind production, as currently large wind power quantities are sold at low or negative prices (Zaman, 2018).
Innovations implemented and planned:	
<ul style="list-style-type: none"> • Denmark's high wind penetration is a result of its strong grid interconnection. The country mostly exports surplus wind energy to Nordic nations that can use the imports to displace their hydropower generation and conserve water in reservoirs. Denmark's internal transmission grid is strong, and its interconnector capacity with the rest of Scandinavia and Germany is nearly equal to the peak load of 6.5 GW (import capacity from Germany is 2.2 GW, from Sweden is 2 GW and from Norway is 1.6 GW). • The top priorities of the Danish transmission system operator are developing demand-side response measures, electrification of heating sectors, smart grids and compressed air energy storage (SEDC, 2017). • The market design has been adjusted to encourage flexible behaviour of conventional generation and to re-define the balancing products to better counteract variability in generation. Coal power plants have been refurbished to become more flexible and to decrease their minimum load from 50% to 20%. • Advanced weather forecasting has been implemented in power system operations, allowing more accurate and updated forecasts every five minutes. 	



1

REPUBLIC OF IRELAND AND NORTHERN IRELAND

VRE penetration:	Challenges:
<p>VRE accounted for 29.7% of electricity demand in 2017, with wind providing the vast majority (26.4%). In January 2015 Ireland experienced a maximum instantaneous wind penetration of 66.2%.</p> <p>Target: 40% renewable energy penetration by 2020, mostly from wind.</p>	<ul style="list-style-type: none"> • Limited interconnections make the system almost like an isolated grid. • Wind power is curtailed to maintain system stability, due to maximum non-synchronous penetration levels and other grid constraints. Curtailment reached 4% of total wind generation in 2017.

Innovations implemented and planned:

- Re-designing of the ancillary service market by defining a suite of ancillary services to support the increasing levels of VRE generation (non-synchronous response) (Zaman, 2018).
- Enforcing grid infrastructure: Ireland developed a transmission plan to develop stronger network grid integration with the United Kingdom (UK). Northern Ireland-to-Scotland and Ireland-to-Wales links are now in place.
- Demand-side management and battery storage projects are expected to ensure reliable operation of the power system (EirGrid, 2016).

ELECTRIC RELIABILITY COUNCIL OF TEXAS (ERCOT)

VRE penetration:	Challenges:
<p>Texas is the leading US state for wind capacity, with wind accounting for 14.8% of the generation mix in 2017 (US DOE, 2018). Solar accounted for 1% of ERCOT's generation mix in 2016 (Seel et al., 2018). ERCOT is expected to see 9 GW of planned additions in 2018/19, increasing total VRE 40% to 29 GW by end-2019.</p>	<ul style="list-style-type: none"> • Limited interconnections make ERCOT almost like an isolated system. • Transmission constraints and inflexible generation lead to wind curtailment, in order to maintain a reliable and secure power system. • Areas with the highest potential for wind and solar are located far from load centres, with very limited connections available.

Innovations implemented and planned:

- Extensive transmission planning, with the building of new transmission lines as well as the reinforcement of existing ones.
- The Public Utility Commission of Texas, in consultation with ERCOT, created five competitive renewable energy zones (CREZs), which helped to develop a transmission plan to deliver renewable power from CREZs to customers while maintaining reliability and economics. The implementation of CREZs has helped to enable the addition of more than 18 GW of wind generation capacity to Texas's power system while overcoming technical issues such as curtailment and transmission congestion (ACEG, 2017).
- Market design changes that allow more resources, including wind, to participate in the day-ahead and real-time markets, making all parties responsible for addressing variabilities in loads and resources.
- To minimise forecasting errors, the real-time balancing market has been shortened from 15 minutes to 5 minutes. The solution also included a continuous fine-tuning of the procured ancillary service amounts, requiring renewable energy generators to provide primary frequency response services (Du et al., 2017).

CALIFORNIA

VRE penetration:

Almost 20% of the generation mix was from wind and solar in 2017 (CEC, 2018). There is a large share of distributed renewable resources in the grid, with 5 900 megawatts (MW) of rooftop solar PV capacity.

Target:

33% renewable energy generation by 2020, 50% by 2026 and 60% by 2030 (Roberts, 2018).

Challenges:

- Oversupply of renewables and congestion in the grid, leading to curtailment.
- Steep morning and evening ramps created by increasing distributed solar generation.

Innovations implemented and planned:

- Market design: The system operator has been developing a flexible ramping product to tackle the steep evening ramps. This will allow generators to be paid for some of their capacity to remain on stand-by during low-ramp periods, so that they are available to be used during high-ramp periods at the system operator's request (dispatch) (Zaman, 2018).
- Energy storage: As a part of the flexibility solution, California has enacted policies to achieve a target of 1 325 GW of storage procurement by the end of 2020, across transmission and distribution grid and on the customer-side. Four Pacific Gas & Electric energy storage projects were approved by the California Public Utilities Commission in November 2018, totalling 567 MW/2 270 megawatt-hours (MWh) of storage (Bade, 2018), the largest storage contract globally to-date.
- Regional Energy Imbalance Market: In 2014 the system operator began implementing a regional Energy Imbalance Market that would allow neighbouring balancing authorities to share reserves and integrate renewable resources across a larger geographic region. This is expected to help the regional market mitigate over-supply events, potentially reducing curtailments in California and its neighbouring balancing markets (PacifiCorp, 2018).



1

SOUTH AUSTRALIA* (AUSTRALIA)

VRE penetration:	Challenges:
<p>In 2017 48.4% of power generation came from wind and solar sources, with wind accounting for 39.2% and rooftop solar for 9.2%. More than 30% of households have a PV system installed, for a total of 781 MW.</p> <p>Target: 50% renewables in the generation mix by 2020, 75% by 2025 (Morton, 2018).</p>	<p>Synchronous power generation provides adequate levels of system reliability and inertia, required to secure a power system. In 2016 South Australia experienced an extreme weather event where a wind storm knocked down part of the grid, triggering a cascading event and a major blackout.</p>

Innovations implemented and planned:

- Energy storage: In 2017 South Australia installed a 100 MW /129 MWh battery storage system that is charged using renewable energy from the Hornsdale Wind Farm. The storage system then delivers electricity during peak hours, helping to maintain the reliable operation of South Australia’s electrical infrastructure and materially lowering ancillary service grid costs to consumers.
- Among other recent actions to increase grid flexibility options, 1 000 MW of demand-side management was contracted and 833 MW of existing flexible gas-power generators were returned to the market together with the construction of a flexible solar thermal plant with up to 10 hours of storage capacity.
- A significant increase in grid interconnection capacity is planned (with plans to add a new South Australia-to-New South Wales link to more than double the current South Australia-to-Victoria interconnection).

**South Australia’s system is one of five sub-systems comprising the Australian National Electricity Market (the others are Queensland, New South Wales, Victoria and Tasmania).*

URUGUAY

VRE penetration:	Challenges:
<p>In 2017 48.4% of power generation came from 28% wind and solar generation in 2017. Together with hydropower and biomass, total renewable generation accounted for 98%.</p> <p>Target:</p> <ul style="list-style-type: none"> • Flexible hydropower generation • Complementary generation profiles for hydropower and wind. 	<ul style="list-style-type: none"> • With a steep, eight-fold jump in wind generation from 2013 to 2014, Uruguay’s main challenge was to maintain the reliability of the system, given the increased variability in the short term. • A big challenge is VRE curtailment, because biomass runs as baseload throughout the year and wind penetration exceeds minimum demand. The excess generation could be exported through the 2.57 GW interconnection with Argentina and Brazil; however, no active cross-border market is in place with neighbouring countries

Innovations implemented and planned:

- The transmission system operator invested in automated generation control components to manage short-term intermittency and balancing needs.
- Power-to-X alternatives are being explored, especially power-to-heat, in order to increase electricity demand and reduce curtailment.

GERMANY

VRE penetration:	Challenges:
<p>Variable wind and solar generation was 25% in 2017. Total renewable energy generation (hydropower, wind, solar and biomass) was up 15% year-on-year to 210 terawatt-hours (TWh), or 38.2% of the 2017 total (Fraunhofer ISE, 2018)..</p> <p>Target: 65% renewables in electricity by 2030.</p>	<ul style="list-style-type: none"> • A key challenge is wind curtailment to maintain grid stability and to solve the bottlenecks in the transmission grid. Curtailment is especially high in the north, where most of the wind plants are located, mostly because of the grid congestion between the north and south. Renewable energy generators are compensated for lost revenue during most curtailments. Network operators are required to re-dispatch the power plants in the south and increase their output to meet the increased power demand, while the interconnection with the north remains congested. Additional operating costs caused by the re-dispatching are subject to financial compensations, which make the procedure very costly for the system. • In 2017 Germany had a record 144 hours of day-ahead negative wholesale electricity prices.
Innovations implemented and planned:	
<ul style="list-style-type: none"> • Grid strengthening, in particular new transmission capacity between north and south; 8 GW of new north-south direct current transmission lines are planned to avoid curtailment, re-dispatch and loop flows. Additional interconnection capacities with some neighbouring countries are planned. • The energy law requires transmission and distribution system operators to expand their system capacity to accommodate renewable energy generation, except for possible curtailment of a maximum 3% of total energy generation. • Fossil plants, in particular CHP, have to be included in congestion management procedures to a higher degree than today. • Co-operation between the four German transmission system operators reduces the redispatch needs and increase flexibility. • Improved forecast models that explicitly incorporate the effect of renewables and the use of improved day-ahead weather forecasts was already adopted in Germany. • Changes in market design to facilitate flexibility: <ul style="list-style-type: none"> • Free price formation in wholesale markets (no price caps) • Strengthened obligations to uphold demand and supply schedules • Shortened trade and balancing periods (to 15 minutes) • Introduction of negative electricity prices • Balancing markets opened to new providers • Rules for aggregators • Gradual introduction of smart meters • Investment in combined heat and power (CHP) production, due to its flexibility (EPE and BMWi, 2017). 	

INDIA - TAMIL NADU

VRE penetration:	Challenges:
<p>14% of wind and solar generation in 2016/17, from 32% of total installed capacity.</p> <p>Target: 17.5% wind and solar share to be reached between 2021 and 2022; 21% by 2027 (CEA, 2018).</p>	<ul style="list-style-type: none"> • Insufficient grid capacity in South India to export wind power has resulted in curtailment. • Further increase in frequency fluctuations.
Innovations implemented and planned:	
<ul style="list-style-type: none"> • Market design: Over the last decade, India has progressively moved towards a single national electricity grid, with increased interstate connectivity. • Interconnections with Bangladesh, Bhutan and Nepal have been strengthened. A subsea cable connection to Sri Lanka is also under consideration. • Tamil Nadu is looking at the viability of the Kundah 500 MW pumped hydro storage proposal • Existing flexible generation in the system was an important enabler 	

AUSTRALIA - KING ISLAND, TASMANIA

VRE penetration:	Challenges:
<p>65% wind penetration; 100% instantaneous share of VRE was reached in 2013. High imported diesel fuel costs led to the installation of three 250 kilowatt (kW) wind turbines in 1998, followed by two 850 kW wind turbines in 2013 and 3 MW/1.6 MWh of battery storage (Zaman, 2018).</p> <p>Target: A 100% renewable energy grid.</p>	<p>Maintain the reliability of intermittent renewable sources in a small system with no interconnections.</p>
Innovations implemented and planned:	
<ul style="list-style-type: none"> • Battery storage: 3 MW of power contribution has been installed, storing 1.6 MWh of usable energy. The battery allows the system to operate at 100% wind power for longer periods of time. • Integration of smart grid technology is needed to enhance the ability to control customer demand to match the available renewable energy supplies (Hydro Tasmania, 2014). 	

1.4 INNOVATION TRENDS AND CHANGING ROLES IN FUTURE POWER SYSTEMS

Policy frameworks for VRE need to combine present needs (for deployment) with future needs (for integrating VRE into the energy system at scale). Real trade-offs exist between quick wins and long-term strategies. In targeting high levels of renewable energy deployment and integration, policy makers should not focus too much on quick wins; instead they need to look forward to a time when renewable energy deployment has been successful and should design the markets/systems around this future and around these paradigms.

This includes taking holistic views on system planning, the electricity demand growth profile, permitting, network charging and network access rights, as well as the treatment of balancing and system services for harnessing flexibility (whether within a liberalised market framework or a more centrally co-ordinated system). In this future the value would not be in kWh of electricity generated and consumed, but rather in the combined flexibility – provided by all actors – to enable a secure and affordable operation of a low-carbon system based on VRE generation.

A number of changes are already happening:

- **Generation:** Large, inflexible thermal generation is progressively being replaced by smaller-scale renewable generation, much of which is not commercially flexible (zero marginal cost) and which is weather dependent (non-energy-price-responsive resources). In the short term, existing conventional generators need to become more flexible, with improved ability to provide a faster ramping capacity to react to increasing volatility of net load. In the long term, flexibility also will come from demand management and increased grid interconnectivity.

- **Sector coupling/demand:** A trend of electrification of end-use sectors, such as electrification of transport (electric vehicles) and potentially of the heating sector, will eventually develop, greatly increasing the load on distribution networks. These new loads could be relatively high capacity/low energy if not managed, but they are inherently flexible: electrification technologies include battery or thermal storage that could help smooth out the demand pattern to match the availability of generation and the capacity of the distribution grid. This optimal contribution to system flexibility will happen only if the integration of these new loads is properly managed and if customers accept that their use patterns are not solely their personal choice.
- **Energy storage:** Battery technology is becoming increasingly affordable. Even domestic users, especially households with solar PV systems that want to maximise self-consumption, are installing batteries at scale due to personal preference over economics. Distribution grid operators are turning to mid-scale batteries to avoid network upgrades. Also, power-to-X applications are emerging that support sector coupling (power-to-heat and power-to-hydrogen), with great potential to store energy in different forms.
- **Distribution grid:** The growing awareness of “predict and provide” for network capacity (predict the load and provide the available capacity to balance supply and demand) will become unsustainable, especially with electrification. Flows on distribution networks will become less predictable. Also, distribution system operators will need better visibility on lower-voltage parts of their networks, and better tools for control.



1

Aggregation/demand response: A variety of factors provide a growing space for increasing demand response, including improved technology readiness, the availability of ancillary service products and marketplaces, and new business models and platforms. Active energy consumers, often called “prosumers” because they both consume and produce electricity, are changing the dynamics of the sector, with great potential to unlock demand-side flexibility.

The power system already looks very different than it did just a few years ago (see Figure 3).

The ongoing power sector transformation is accelerated by three main innovation trends that have now reached the energy sector, as Figure 4 illustrates: 1) digitalisation, 2) decentralisation and 3) electrification. These trends are changing paradigms, unlocking system flexibility for a high share of VRE penetration. They are changing the roles and responsibilities of actors and opening doors to new entrants in the sector.

Figure 3 Innovations taking place in the electricity supply chain

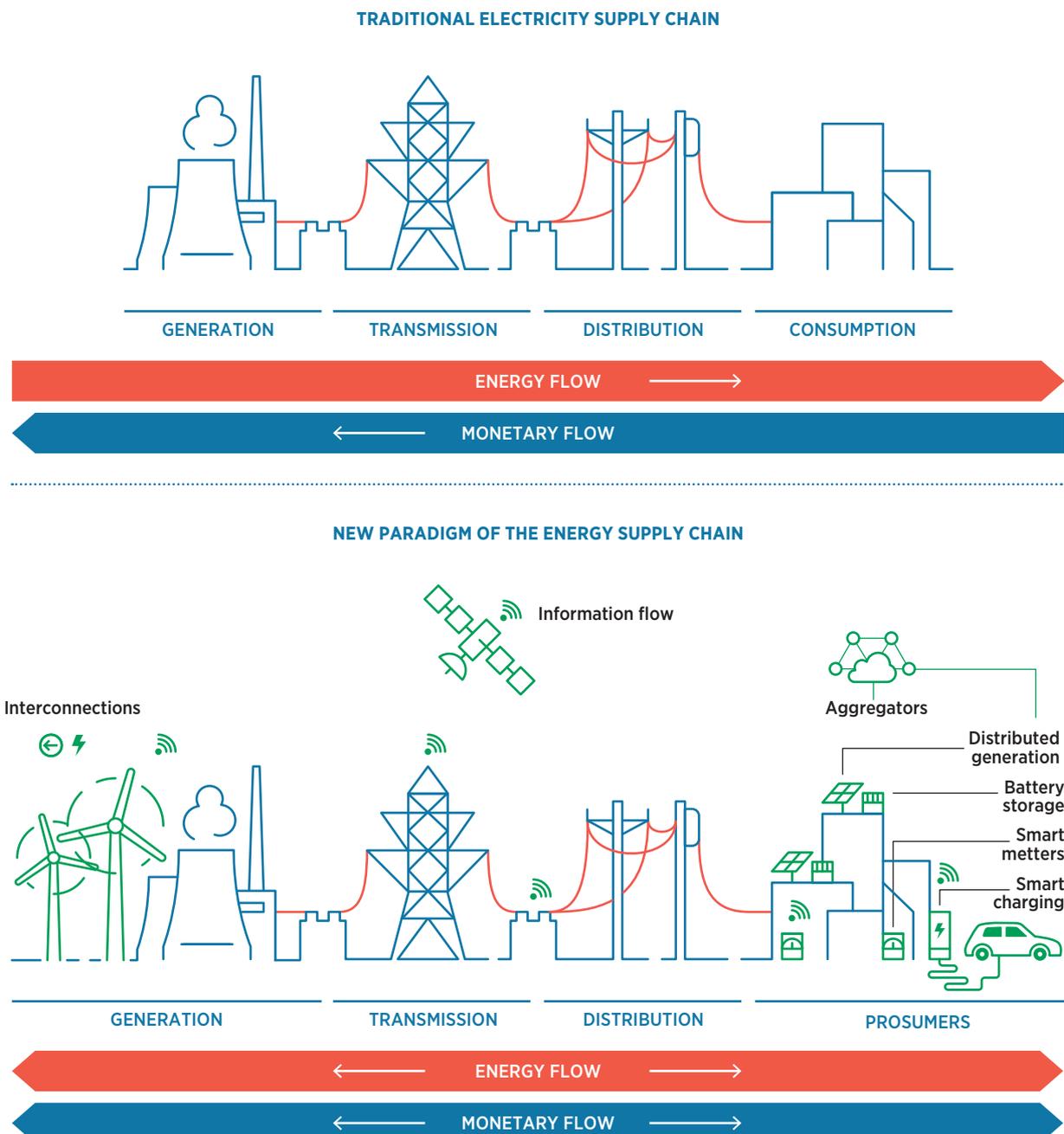
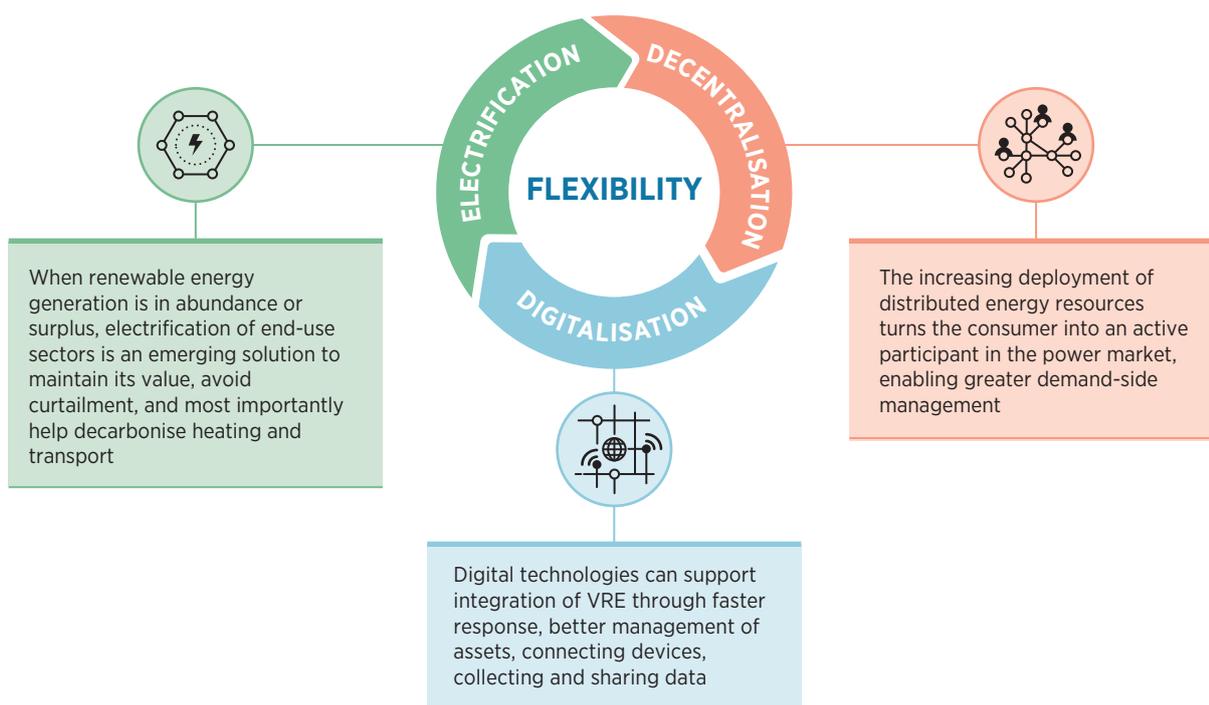


Figure 4 Innovation trends

Digitalisation of the power sector



Digitalisation can be defined as converting data into value for 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 (see Figure 5). Wider usage of smart meters and sensors, the application of the Internet of Things 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.

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 electric vehicles, heat pumps and electric boilers. All those new assets on the supply side (due to decentralisation)

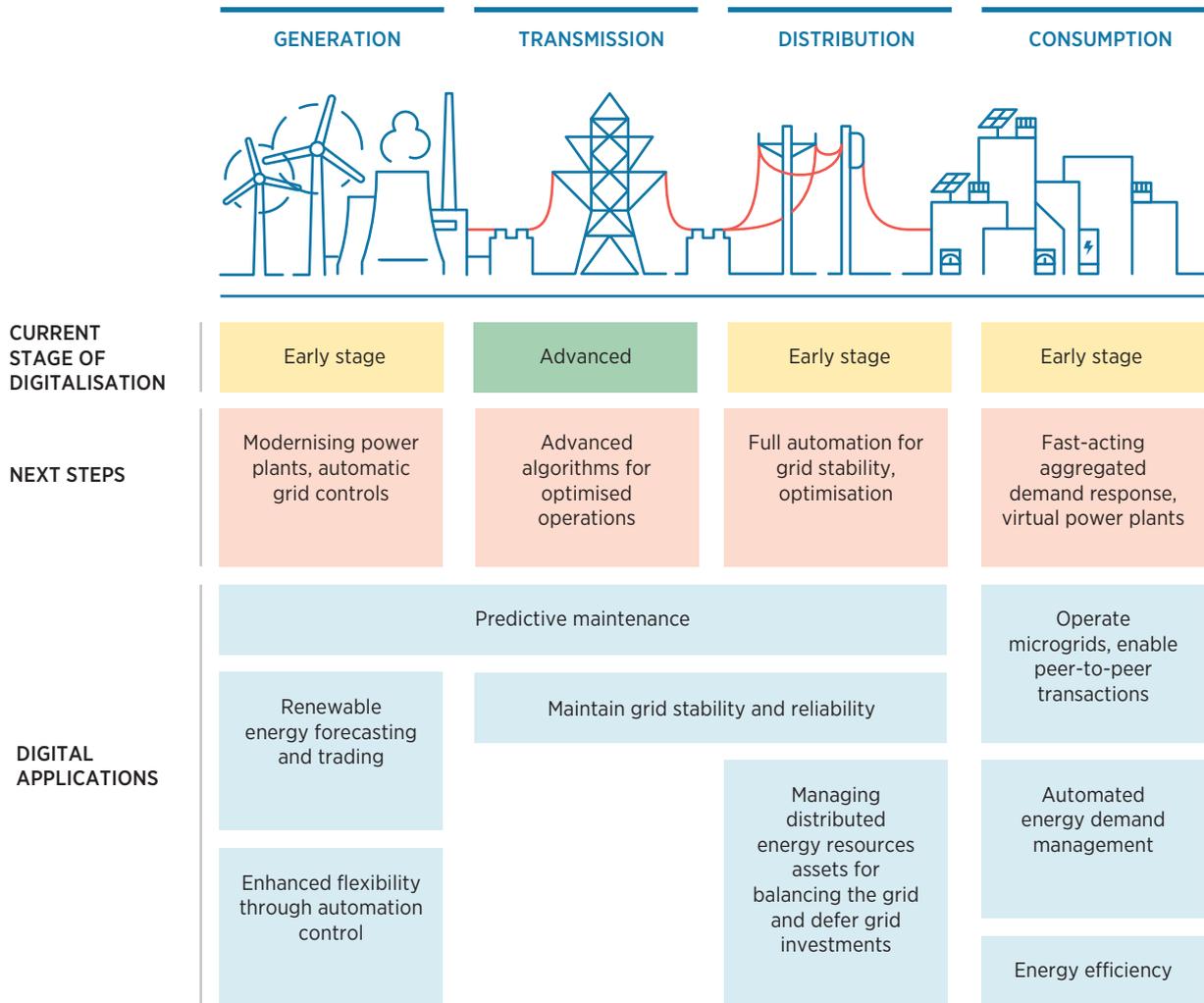
and demand side (due to electrification) have an impact on power systems, making monitoring, management and control crucial for the success of the energy transformation.

Digitalisation is therefore 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 the future, automated smart contracts based on blockchain technology, allow distributed energy resources to be bundled by “aggregators”.

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 features allow the system to be operated with a higher share of VRE, as the supply and demand uncertainty and related risk are reduced, without increasing the operation costs.

1

Figure 5 Emerging digital applications in the power system



Complex systems gain the most from digitalisation, where many actors and devices are participating in the power system by injecting or withdrawing power from the grid. Digitalisation enables the management of data, thereby optimising systems. Digitalisation becomes important for large systems and for wholesale market optimisation (e.g., Europe's Common Grid Model, ENTSO-E Awareness System, Transparency Platform), but it plays a particularly key role for distributed energy resources and decentralised systems. It facilitates the physical integration of distributed energy resources and enables new forms of operation that previously were not possible. Digitalisation strengthens links, co-ordination and interaction among all actors in the system, with consumers' investments and behaviour in the centre (e.g., during energy scarcities).

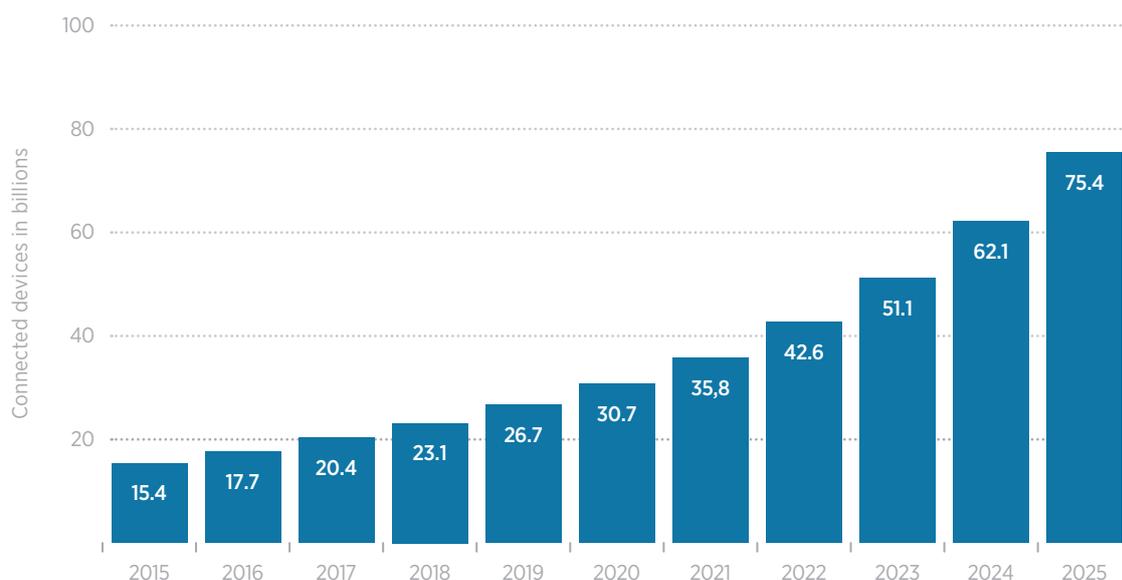
Digitalisation can be defined as converting data into value for the power sector

■ Information technology companies entering the power sector

By 2025, 75 billion electrical devices are expected to be connected and sharing data worldwide, providing a wealth of information to consumers, manufacturers and utility providers (Statista, 2018). The rise of the Internet of Things goes hand in hand with the rise of artificial intelligence, powered by big data, as it provides the granular information needed to feed machine-learning algorithms.

A high number of companies, consortiums, foundations and groups in the information and communications technology (ICT) domain are entering the energy sector at different levels (app layer, data layer, connectivity layer and device layer). They are developing various new applications in the sector, including providing new services to consumers, demand management, energy efficiency, renewable energy forecasting, asset management, energy trading and mini-grid operation Internet of Things technologies (see Figure 6).

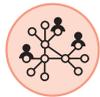
Figure 6 Internet of Things-connected devices worldwide (billions), 2015-2020



Source: Statista, 2018.

1

Decentralisation of power systems



Individuals and communities have greater control over the generation and consumption of energy. Emerging distributed energy resources that are connected at the consumer end – such as rooftop solar PV, micro wind turbines, battery energy storage systems, plug-in electric vehicles and demand response – are decentralising the system. Optimising the consumption of electricity that is now locally produced provides a great advantage for the system, decreasing the need for other costly flexibility measures.

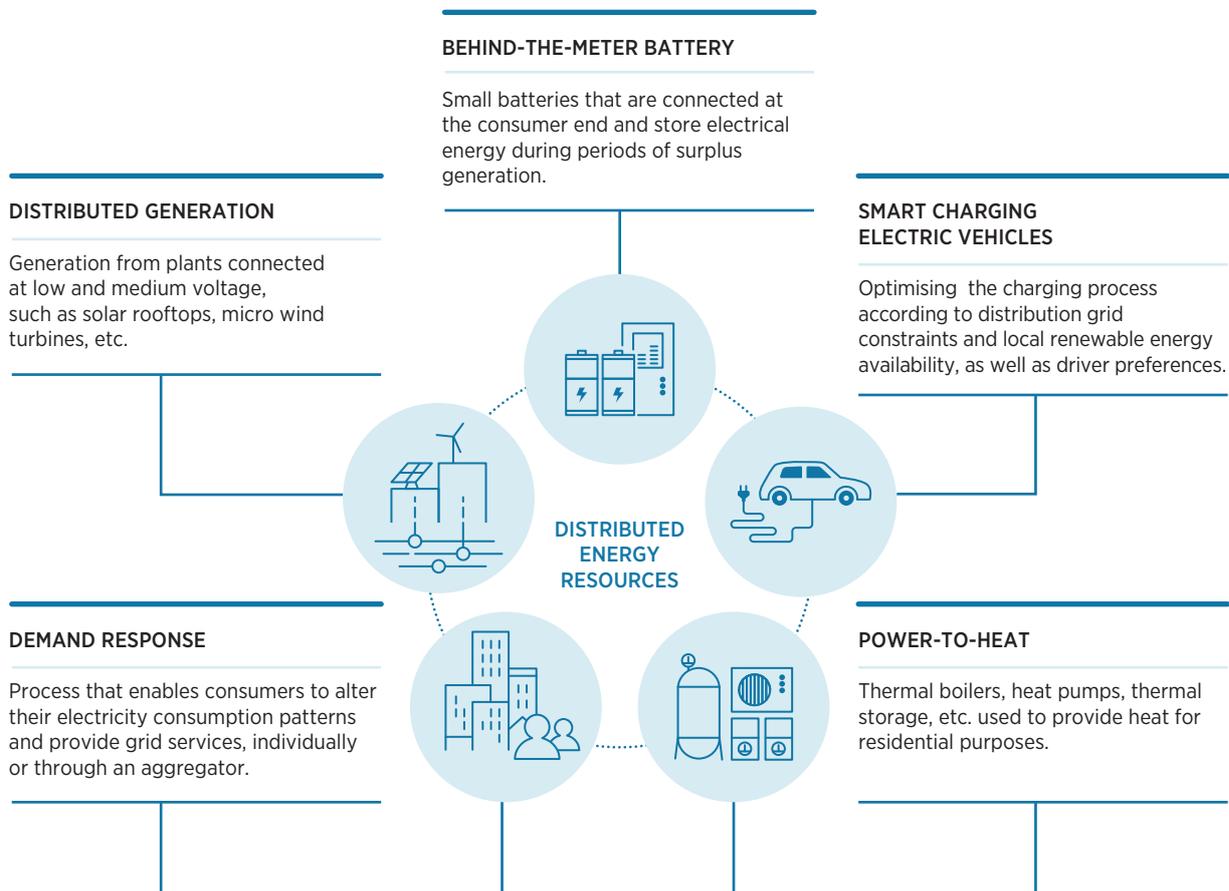
Deployment of solar PV panels has increased dramatically in recent years. Distributed storage has gained momentum as well. A behind-the-meter storage business model allows customers to store the electricity generated by their rooftop solar panels and use it later when needed or sell it to the grid. Figure 7 illustrates the distributed energy sources that decentralise the power system.

The new consumer and new business models

Increased deployment of distributed generation has given individuals and communities greater control over electricity generation and consumption. Consumers are exploring avenues to optimise their consumption and better manage their electricity bills. The energy-related needs of consumers in the residential, commercial and industrial segments are changing. For residential consumers, the availability of smart home devices has spurred a market for continuous monitoring and control of electricity consumption. Commercial and industrial consumers are evaluating options to reduce the cost of electricity procurement by switching to renewable energy-based sources of generation, such as rooftop solar PV, and by adopting smart devices that can operate, monitor, control and optimise energy consumption.

Smart devices such as thermostats for heating/cooling and home security are gaining popularity, although this is not a new area. More

Figure 7 Distributed energy resources



sophisticated devices are emerging that go beyond merely monitoring residential energy use and are optimising residential consumption and generation including rooftop solar, but they are still relatively expensive. Such advanced devices might boost the economics of residential solar by eliminating exports to the grid, for example by storing the generated electricity in batteries and/or as hot water.

Consumers are transitioning from being passive, captive actors into active players in the energy transition. They can now generate, trade and store electricity and provide services to the grid, thereby converting to prosumers. Digitalisation not only enables all these new applications, it also allows for communication among them and optimises their interactions with the grid. Digitalisation is strongly interlinked with decentralisation.

However, consumers would not take an active role in decision making if this would require drastic behavioural change or a large investment in time. Consumers would be willing to engage actively in decision making only if they can see the benefits and if automation makes reacting to price signals easy. New business models providing “ready-made” services for customers are therefore emerging, enabling consumers to play an active role in the power sector and unlock demand response. The role of an electricity provider also has evolved into that of an energy service provider, answering to the changes that customers need.

Smart devices have created room for new business models and platforms to be implemented/tested in the energy sector. The increase in digitalisation and smart metering has allowed large amounts of data to be collected and collated. This provides the basis for developing electricity trading and electricity exchange systems. Digitalisation enables the communication of data to different stakeholders. It provides transparency in services, meter reading, billing automation and accuracy, minimising/eliminating the need for estimation, reducing human intervention, energy efficiency, instant data for better dispatch by the system operator, etc. The main risk faced by consumers in this new paradigm of information being shared among all actors is related to cyber security and privacy.

■ Adapting the role of distribution system operators

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. To take advantage of these new opportunities, and to keep pace with both the transformation of the power sector and changing customer needs, distribution system operators will have to adjust their current role and transform their business model. Changing the regulatory framework for these operators and introducing new incentives to adapt the operation of distribution networks to the new paradigm of distributed energy resources is key for their successful transition.

With the emergence of distributed generation and other distributed energy resources, the role of distribution system operators will expand. They will have to manage the assets connected to their grid for the benefit of both the grid and consumers. In their new role they will need to operate the distributed energy resources (or at least provide high-resolution price signals to them) to optimise the use of networks and to avoid new investments in assets, while supplying new loads, given the electrification of end-use sectors (as is the case of charging stations for electric vehicle charging stations). In a relevant initiative, a European Commission proposal from November 2016 mandates Member States to ensure that regulation enables and promotes distribution companies to procure flexible services from network users (EC, 2016a).

■ System operators' new challenges and responsibilities

A key element of innovation for system operators is to ensure that they can use new providers of system services and flexibility (demand-side management, other distributed resources, etc.) rather than relying on thermal generation (which will reduce in importance in the system as renewables increase).

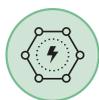
With the decentralisation of the system, micro-level monitoring and control is needed to ensure optimal system operation and the integration of these sources into the system.

At the same time, the sources of flexibility are being decentralised. Bringing this flexibility into system operation or into the market depends on harvesting the potential for new small-scale demand response and batteries. Besides flexibility, distributed energy resources can provide a readily available benefit for system operators to avoid additional investments in transmission grids. Also, they can avoid making interventions to ensure system security and reliability through re-dispatch orders.

All this comes as additional costs to the power system, costs that can be reduced by taking advantage of all devices already connected to the grid. Digitalisation and the Internet of Things are necessary to monitor, harness and control the micro-sources of flexibility. Increased co-operation with distribution system operators is key for the system operator to get more visibility on the energy resources connected on the distribution grid.

However, another precondition is consumer acceptance that their assets may be used flexibly. Development mechanisms and market designs that reward flexibility are vital in an energy system with high levels of renewables. And making these incentives available for all players connected to the grid is key. Until the regulatory model is set, consumer acceptance and engagement cannot be assumed, and therefore, the precise form of the digital algorithms for automation control cannot be built.

Electrification of end-use sectors



The electrification of end-use sectors is a trend driven by national energy security concerns relating to over-reliance on imported oil and diesel, in addition to the increasing availability of cheap electricity from renewable energy sources and its potential to decarbonise end-use sectors. If done smartly, electrification can convert these new loads into flexibility sources.

Electrification, without a smart grid strategy, will increase power supply costs and may even undermine security of supply. Fortunately, electrification comes with features that complement well the variable nature of renewable energy. If planned smartly, electrification will lead to a new design of the overall energy system centred on renewable energy, making the entire

system more sustainable. A strategy is required to create the synergies between electrification and renewable energy.

Current trends in the electrification of end-use demand go hand in hand with digitalisation trends, making appliances smarter and increasingly connected. This increases the complexity of the power demand characteristics, and may drive the fundamental transition of a power system from one that is designed to cope with clearly defined peak loads, to one that takes full advantage of demand as a source of flexibility.

Electric vehicles (EVs), for example, are not only transforming the transport industry but are on the verge of reshaping the power market. Increasing numbers of EVs present both a challenge and an opportunity for further VRE integration and sector decarbonisation. Over 4 million electric passenger cars were on the road worldwide in 2018, 40% of them in China (BNEF, 2018). However, 4 million EVs consume around 1.2 TWh of electricity per year. This is a dent compared to global electricity demand, but if not managed smartly, it can have an impact on the distribution load. On the other hand, the distribution network and the system as a whole could obtain great advantage from the small EV batteries connected to the grid, if the vehicles are charged smartly.

New EV registrations hit a world record in 2017, with over 1 million sales worldwide, or around 1.3% of all car sales. China's EV sales grew 56% year-on-year and reached a total of 1.05 million EVs on the road in 2018 (NBS, 2018; CAM, 2019). Moreover, industrial applications have started using converted forms of power such as hydrogen or heat, thus allowing VRE generation to be absorbed during off-peak times.

Oil and gas companies entering the power sector

With different types of industries leading electrification efforts in the end-use sectors, the demand for oil and gas decreases. This powerful impact is leading oil and gas companies to transition into the power sector. Interesting business opportunities are emerging for these companies in the power sector, in terms of new services provided to consumers, or through electrification of the transport sector. For example, EV chargers have been installed in petrol stations.

Also, the uptake of the production of hydrogen with electricity through electrolysis – which can indirectly electrify the heat, transport and industry sectors – gives gas companies a great advantage, especially because hydrogen can be stored and transported through existing natural gas grids. Little investment is needed to adapt natural gas infrastructure to transport hydrogen: existing gas pipelines can support 10% to 20% hydrogen without any adjustments (ARENA, 2018). When produced with renewable electricity, hydrogen plays an important role in the decarbonisation of these sectors. Hydrogen also can be used for power generation. The know-how built in this sector, as well as access to the pipelines, gives gas companies a thrust advantage in this new business.

Royal Dutch Shell is a classic example of an oil and gas company entering the power sector. In February 2018 Shell entered the energy service provider business with the acquisition of the independent UK household energy and broadband supplier, First Utility (Shell, 2018), which became a wholly owned subsidiary within Shell's New Energies division. Additionally, in 2017, Shell acquired Netherlands-based NewMotion (Shell, 2017), the owner of one of Europe's largest EV-charging networks, which manages over 30 000 charging points in Western Europe. An estimated 1 million to 3 million public charging points could be needed in Western Europe by 2030 (De Clercq and Steitz, 2017), and Shell aims to be a part of this segment.

In August 2016 France's Total acquired the French battery manufacturer Saft Groupe for USD 1.1

billion as a way to access leverage to battery storage opportunities (Total, 2016). Previously, in 2011, Total acquired one of the world's biggest solar PV manufacturers, SunPower. Total also recently entered the retail electricity market, with a new unit called Total Spring offering tariffs that are 10% less than regulated prices (Felix, 2017).

The Spanish company Repsol is another major player in the oil and gas market that recently updated its corporate strategy and is developing new businesses linked to the energy transition, following its disinvestment in Naturgy (formerly Gas Natural Fenosa). As a new entrant in the power sector, Repsol has acquired a 264 MW solar PV project, created an electricity retail company, and invested in both a Spanish home automation company and a US start-up dedicated to the development of EVs. It also has allied with Enagás (a Spanish gas transmission system operator) to promote the production of renewable hydrogen and participated in the launch of a hybrid car-sharing business (El Periódico de la Energía, 2018).

However, the oil and gas industry is very different from the electricity sector. While oil and gas are both commodities traded in the global market, and are driven heavily by geopolitics, electricity production and consumption is limited to a regional or at most a continental market. The businesses have different scales in both geographical coverage and revenues. Moreover, electricity is a heavily regulated sector compared to the oil and gas industry, where opportunities for businesses are much bigger.



2

THE LANDSCAPE OF INNOVATIONS FOR VARIABLE RENEWABLE POWER INTEGRATION

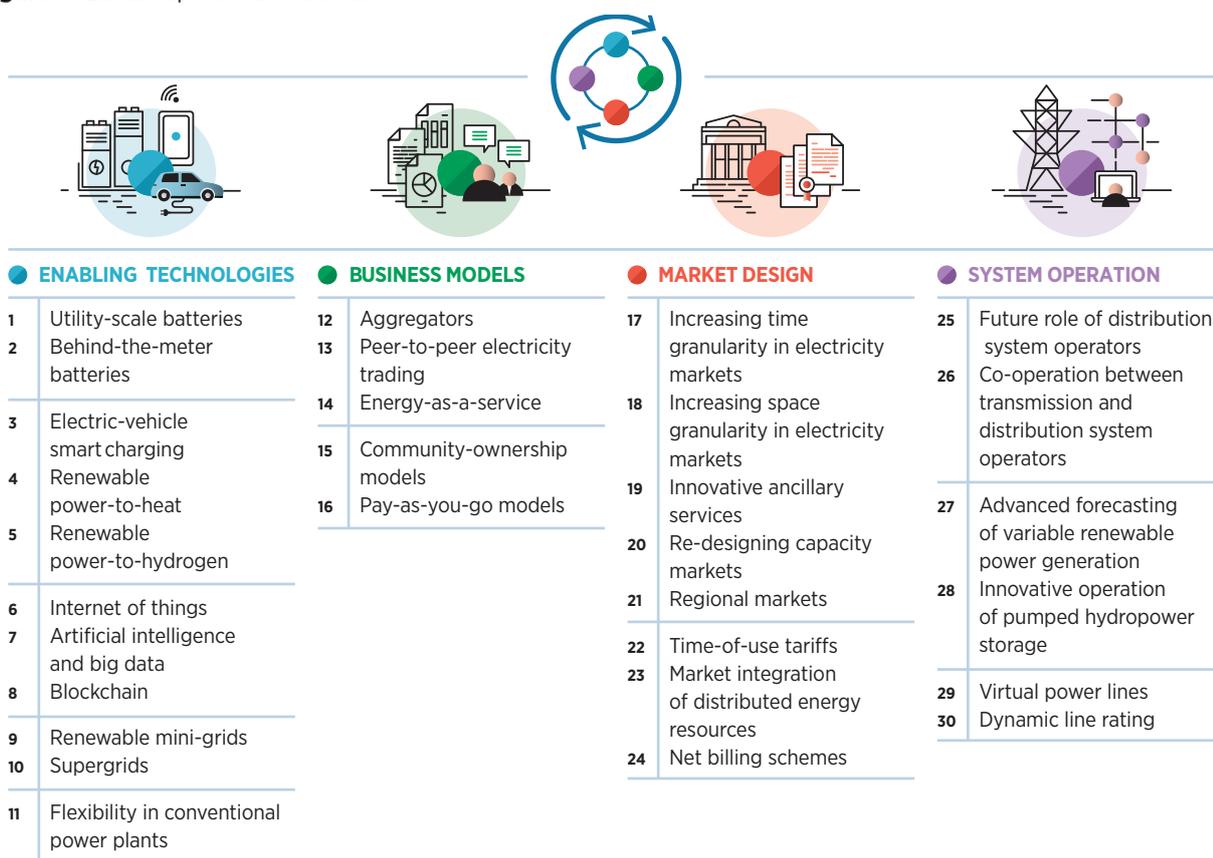


The rapid reduction in the costs of solar PV and wind power generation has placed these technologies at the core of the ongoing power sector transformation. According to an IRENA analysis (2018b), the share of VRE in global electricity generation needs to grow from 4.5% in 2015 to more than 60% by 2050 to enable decarbonisation of the energy sector. Numerous innovative solutions that integrate more VRE are being tested and implemented in different countries and regions. However, just a small handful of countries are close to achieving high shares of

VRE in the generation mix, and only particular ways of operating the power system allow this. The challenge for such a transition is huge.

IRENA has investigated the landscape of innovations to facilitate the integration of high shares of VRE. The innovations have been categorised into 30 innovation types across four dimensions: enabling technology, business model, market design and system operation (see Figure 8). For each of the innovations, a short brief with more detailed information is available on IRENA's website.

Figure 8 Landscape of innovations



2

● **Enabling technologies** for infrastructure development play an important role in facilitating the integration of renewable energy. Battery storage, together with digital technologies, is changing power sector paradigms and opening doors to various new applications that unlock system flexibility. The electrification of end-use sectors, done smartly, can emerge not only as a new market for renewables, but also as future flexible demand. The system needs to be flexible to be able to absorb electrification, and electrification can bring flexibility if managed in a smart way.

● **Business models** are essential to monetise the new value created by these technologies and hence enable their deployment. Several innovative business models emerge at the consumer end, given the deployment of distributed energy resources, along with innovative schemes that enable renewable energy supply in areas with limited possibilities, such as off-grid or densely populated areas.

● Innovation in regulation and **market design** is needed, but there should be a balance between stable and predictable regulation that can ensure private sector investments, and flexible regulation that enables innovation. At the same time, the speed of regulatory innovation needs to be aligned with the speed of business model and technology innovation. Adapting the market design to the new premises becomes crucial for accelerating the energy transition, enabling value creation and adequate revenue streams. Both wholesale market and retail market innovations are needed, to unlock all of the flexibility potential in the power system.

● With new technologies and a sound market design in place, innovations in **system operations** are needed as well and are emerging in response to the integration of higher shares of VRE into the grid. These innovations have been grouped into two categories: innovations accommodating uncertainty, and innovative operation of the system integrating distributed energy resources.

The required innovations have the immediate objective of increasing the flexibility of power systems to integrate higher shares of VRE. The ultimate objective is to decarbonise the energy sector.

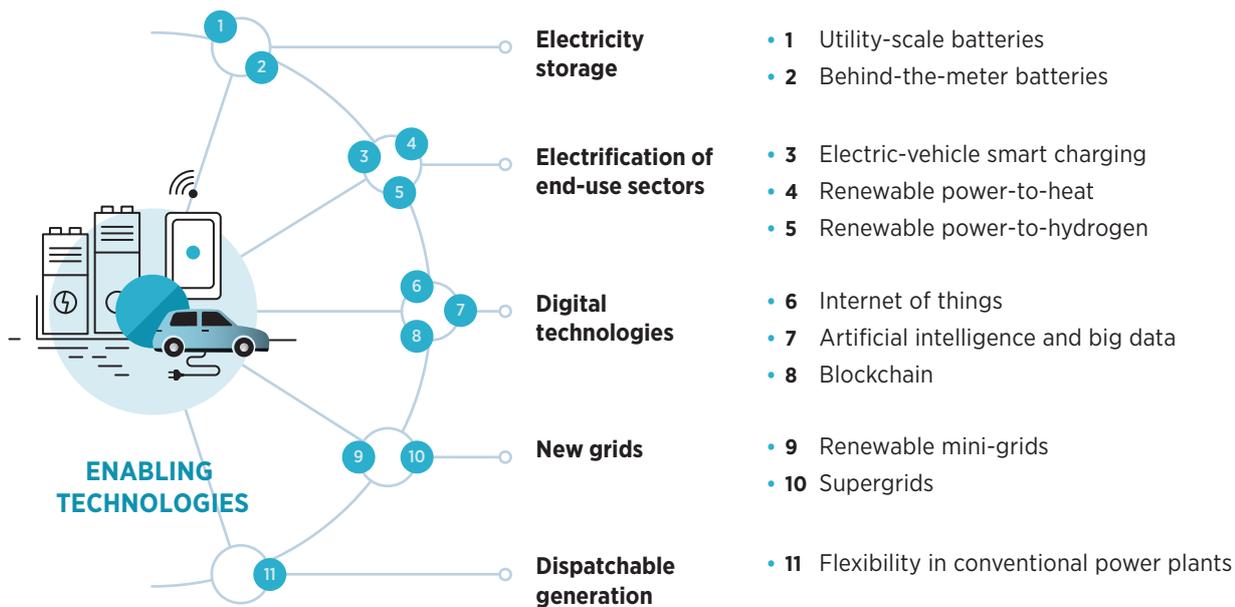


2.1 ENABLING TECHNOLOGIES

Enabling technologies facilitate the integration of VRE generation technologies. Such technologies include, among others, storage batteries, technologies that enable the electrification of other sectors with renewable electricity, digital

and ICT developments, and smart grid solutions (see Figure 9). All of these developments bring new opportunities for integrating higher shares of renewables, as they enable new ways of operating and optimising power systems.

Figure 9 Enabling technologies innovations



2

Electricity storage

The cost of storage continues to fall (IRENA, 2017a), opening the door to accelerated deployment for current applications (kWh of storage) and becoming a provider of new services to power systems (kW-type services for frequency control). Particularly in systems with significant transmission constraints, storage offers innovative approaches for economic solutions to increase the flexibility

of the system. Storage may provide significant benefits in power systems, especially for ancillary services and to support meeting residual demand peaks (*i.e.*, avoiding investments in peaking plants). Beyond these initial applications, country pathways for innovative deployment of storage services may emerge based on the specificities of each system.

INNOVATION 1: UTILITY-SCALE BATTERIES

Description	Ongoing developments
<p>Utility-scale batteries are used mainly to provide grid support functions, but also can be associated directly with a renewable generation source to provide more controllable/firm generation.</p> <p>Contribution to VRE integration:</p> <ul style="list-style-type: none"> • Load shifting – charging batteries to avoid curtailment of excess generation • Provision of ancillary services • Provision of capacity reserve • Reliable power supply to isolated grids • Offsetting transmission and distribution upgrades 	<ul style="list-style-type: none"> • Global installed capacity of large-scale battery storage systems: 10 gigawatt-hours (GWh) in mid-2017 (IRENA, 2017a). • Key countries where large-scale batteries are used (2017): Australia, China, Germany, Italy, Japan, Republic of Korea, UK, US. • Most established large-scale battery storage technology: Lithium-ion batteries constitute more than 90% of the current total installed capacity for large-scale battery storage (IEA, 2018b). • Costs have fallen 80% between 2010 to 2017 (IRENA, 2018b). • In November 2018 PG&E in California awarded the world’s two largest battery contracts to-date, at 300 MW / 2 270 MWh and 182 MW / 730 MWh (Bade, 2018). • Transmission system operators in UK (National Grid) and Netherlands (TenneT) also have contracted large-scale batteries for balancing services.

INNOVATION 2: BEHIND-THE-METER BATTERIES

Description	Ongoing developments
<p>Behind-the-meter storage is located at or close to the site of energy usage, and downstream from the connection point between the utility and the customer. It is usually applied in homes and workplaces.</p> <p>Contribution to VRE integration:</p> <ul style="list-style-type: none"> • Enables the effective integration of local renewable energy generation, to unlock the benefits of distributed generation. • Smooths the peak load profile. • Facilitates demand-response services and participates in ancillary service market, providing flexibility to the system. • Cuts the cost of distributed renewables by maximising self-consumption. 	<ul style="list-style-type: none"> • Key regions where small batteries are used (2017): Germany, Italy, UK, Australia, Japan, Netherlands, China. • Germany: 100 000 batteries installed (August 2018), 60% of the new rooftop PV systems equipped with batteries (IRENA, 2018b). • South Australia’s government launched a programme in October 2018 to install 40 000 household batteries (Skyes, 2018).

Electrification of end-use sectors

IRENA's analysis of the global energy transformation to 2050 (IRENA, 2018b) indicates that to achieve an energy scenario that is compliant with the Paris Agreement, the electricity consumed as a share of total final energy consumption needs to rise, from 20% in 2015 to 40% in 2050. Other recent studies indicate that a rise to 50% to 60% may even be feasible. Replacement of the direct or indirect use of fossil fuels in the end-use sectors of transport, buildings and industry by electricity from renewables is gaining momentum due to the falling costs of renewable electricity.

Electrification occurs in two ways: by decarbonising end-use sectors through renewable electricity and, if done in a smart way, by becoming a flexibility source for integrating more renewables in power systems. In the transport sector, the share of electricity rises in IRENA's REmap scenario* from just above 1% in 2015 to 33% in 2050. More than 1 billion EVs would be on the road by 2050, and their consumption would be equivalent to more than 10% of today's global electricity demand. In the buildings sector the share of electricity in final

energy use would rise from 31% in 2015 to 56%, and in industry it would rise from 27% in 2015 to 43%. Heat pumps in buildings are a key solution, and their number would need to increase from 20 million in 2015 to over 250 million in 2050 (IRENA, 2018b). Mechanical vapour recompression and dielectric heating are several industrial electrification solutions. Hydrogen produced from renewable electricity also may play an important role in the future (IRENA, 2018d).

The key challenge is to ensure that electrification happens in a systems-friendly way. This means that, where possible, electricity consumption should occur at times of high VRE availability. For example air conditioners should ideally operate when the sun shines. EVs should be connected for charging/discharging whenever they are parked, and their batteries should be used for grid services and charged when most optimum (e.g., from rooftop solar during the day, either at home or in the office carpark). This has profound implications for charging infrastructure, as well as on the electricity pricing regime for charging, in order to create an appropriate incentive.

INNOVATION 3: ELECTRIC-VEHICLE SMART CHARGING

Description	Ongoing developments
<p>Smart charging of EVs adapts the charging cycle to events in the power system, enabling the vehicles to be integrated into the power system in a grid- and user-friendly way.</p> <ul style="list-style-type: none"> Smart charging of EVs (charging following renewable energy generation profiles) can help mitigate curtailment of renewables, while avoiding the addition of extra load to peak demand and additional infrastructure costs. Vehicle-to-grid (V2G) technologies could bring even greater flexibility in the system by supplying power back to the grid when needed. The potential for smart charging to adapt the charging time depends strongly on the kinds of vehicles, the charging location, and the power and speed of the charging equipment. In an extreme case, autonomous electric collective taxis might fast-charge at 150 kW to 500 kW for 10 minutes several times a day, with practically no flexibility during daytime but only during the night. 	<ul style="list-style-type: none"> 4 million EVs on the street in 2017, with 40% of them in China (BNEF, 2018). 57% compound annual growth rate of sales over the last six years (IRENA, forthcoming a). Largest markets for EVs: China, Germany, Norway, UK, US. Share of total electricity demand if all light-duty vehicles were electric, in 2016: 24% in US; 10-15% in Europe, with impact on peak demand, if not smartly charged (IRENA, forthcoming a).

* IRENA's global REmap roadmap in its "REmap Scenario" analyses the deployment of low-carbon technologies, largely based on renewable energy and energy efficiency, to generate a transformation of the global energy system with the goal of limiting the rise in global temperature to below 2°C above pre-industrial levels by the end of the century

2

INNOVATION 4: RENEWABLE POWER-TO-HEAT

Description	Ongoing developments
<p>Renewable power-to-heat is the use of renewable power to generate useful heat energy for buildings or industrial processes, for example via heat pumps or electric boilers.</p> <p>Power-to-heat could:</p> <ul style="list-style-type: none"> • Store energy on a large scale through thermal storage. • Reduce the curtailment of renewable energy by transforming it into heat: a fuel to help decarbonise other energy sectors. • Enable demand-side management with heat pumps, which are more energy efficient than other forms of heating. 	<ul style="list-style-type: none"> • Cost of heat production with heat pumps: EUR 0.06-0.12 per kWh, which is less than half the cost of heat production with natural gas condensing boilers. • Heat pumps installed in EU-21 (2017): 10.5 million units; with a storage capacity of 368 GW and contributing to 116 TWh of renewable energy (EHPA, 2018). • Key regions where power-to-heat systems have been implemented (2017): Europe (primarily Denmark, Sweden, Germany, UK, Switzerland), US, China, Canada.

INNOVATION 5: RENEWABLE POWER-TO-HYDROGEN

Description	Ongoing developments
<p>Hydrogen produced from renewable electricity through electrolysis can be used as a medium for energy storage. It can be distributed to users in re-purposed natural gas grids. It can be reacted in fuel cells to generate electricity, burned to drive a generator, used as a transport or heating fuel, and added to gas distribution networks or as a feedstock in other industries.</p> <p>Hydrogen from renewable power could:</p> <ul style="list-style-type: none"> • Store energy on a large scale and for the long term, in salt caverns or storage tanks. • Reduce the curtailment of VRE. • Decarbonise the industry and transport sectors through sector coupling strategies. • Replace “grey” hydrogen made from natural gas in certain industrial processes. 	<ul style="list-style-type: none"> • Cost of hydrogen production from electrolysis, through the proton exchange membrane (PEM), in 2017: EUR 6.7 per kilogram (kg) with the potential to drop to EUR 4.1 per kg in 2025 (Tractebel, 2017)*. (PEM technology is better suited to provide flexibility.) • By 2030 between 70% and 88% of the cost of producing hydrogen will be explained by the cost of energy; higher shares of cheap renewable energy can accelerate technology adoption (CORFO, 2018). • 4% of the global hydrogen supply is produced via electrolysis (the rest is fossil fuel-based) (IRENA, 2018d) • A Hydrogen Council study envisages that hydrogen could meet 18% of global final energy demand by 2050, equal to about 78 exajoules (IRENA, 2018d)

* Note that prices are for the European market only



Digital technologies

Digitalisation can be defined as converting data into value for the power sector. Increased digitalisation offers an opportunity to gather more system information. Gathering information and recognising patterns can enable the proactive operation of the grid to avoid faults or reduce outage times. At the same time, due to more certainty and better predictability of the system response, the system can be operated with a higher share of VRE without increasing the operation costs.

VRE-based distributed power systems essentially require the combination of energy and information for optimum operation and increased flexibility. The operation and control of a large number of distributed generation and consumption components is only possible through intensive use of the latest information and communication technologies in the energy sector. The digitalisation of power systems results in the collection and management of a huge amount of operational data. This creates control possibilities and new opportunities to optimise and reduce the VRE integration cost.

Digital technologies are reshaping the energy system by:

- **The massive collection and analysis of data:** applications that generate a great deal of data, such as the grid or the home, could see significant performance benefits by employing big data techniques – for example, big data,

cloud storage, home energy management and smart grids. Today only 10% of the data generated by distribution companies is used for analytical purposes.

- **Enhancing controllability:** if assets can be controlled remotely, they can be used for applications beyond their initial purpose, such as for aggregating behind-the-meter generation to provide community energy – for example, demand response, behind-the-meter generation, home energy management and EVs.
- **Increasing flexibility:** most forms of renewable power need flexible loads and generation assets to accommodate their intermittency. Digital technologies unlock this flexibility from different sources – for example, battery management systems, EVs, demand response, etc. Put simply, devices that intelligently direct solar generation to daytime loads or storage for night-time use will cut the cost of grid integration. Such devices are already available for residential uses, for example eliminating grid exports of solar power by using rooftop generation to charge batteries, run electric heat pumps and operate appliances. But their cost must fall further to see adoption at scale.
- Smart meters are improving the electrification of emerging markets such as India through the use of prepayments to reduce debtor losses as well as to achieve less curtailment (theft).

INNOVATION 6: INTERNET OF THINGS

Description	Ongoing developments
<p>The IoT enables real-time communication through the Internet, among devices in electricity demand centres (homes, commercial and industry facilities) and across the grid, facilitating information gathering and exchange.</p> <p>The IoT, together with optimisation algorithms, could:</p> <ul style="list-style-type: none"> • Increase system flexibility by enabling remotely managed and/or rapid automatic changes in distributed resources and demand. • Improved renewable energy forecasting and trading, decreasing uncertainty. 	<ul style="list-style-type: none"> • By 2025, 75 billion devices are expected to be connected worldwide, compared to 15 billion in 2015 (Statista, 2018). • A large number of companies, consortiums, foundations and groups are working on IoT technologies at different levels: app layer, data layer, connectivity layer and device layer. • All Nordic countries are moving towards the implementation of data hubs for electricity meter data and market processes. Transmission system operators in Denmark, Finland, Norway and Sweden are responsible for introducing a data hub for each of the electricity retail markets (NordREG, 2018).

2

INNOVATION 7: ARTIFICIAL INTELLIGENCE AND BIG DATA

Description	Ongoing developments
<p>The combination of big data with with artificial intelligence (AI) has emerged as one of the most important developments in several fields. Although many AI technologies existed for several decades, only now are they able to take advantage of sufficiently sized datasets, providing meaningful learning and results for energy market applications.</p> <p>This combination could help integrate VRE in the power system by:</p> <ul style="list-style-type: none"> • Increasing the accuracy of renewable energy generation forecasting. • Improving the operation of the system and better management of the distributed sources. • Improving asset management through remote monitoring, analysis and maintenance optimisation. 	<ul style="list-style-type: none"> • Key regions where AI is implemented in energy applications: US, Europe (France, Germany, Spain, UK, etc.).

INNOVATION 8: BLOCKCHAIN

Description	Ongoing developments
<p>Blockchain is a distributed ledger technology that can be used to securely record all transactions taking place on a given network.</p> <p>Blockchain potentially allows:</p> <ul style="list-style-type: none"> • Increased direct trading and sharing of verifiable information, removing the need for the middleman, and enabling newer / lower-cost operating models on a smaller scale. • Flexibility in the system, enabling decentralised flexible energy sources to provide services to the electricity grid. • New markets and transaction with products with a certified and trustable energy footprint. • Potential cyber security benefits. 	<ul style="list-style-type: none"> • Top three countries in the number of pilot blockchain initiatives in the energy sector: Germany, Netherlands, US (with most blockchain energy start-ups concentrated in Europe). • Currently the most conspicuous application for energy is peer-to-peer energy trading. However, business models that enable distributed energy resources to provide services to the grid are much stronger so far. • USD 466 million had been invested in blockchain technology as of October 2018.

New grids

High VRE penetration in the system would require a new approach to grid operation, one that uses data and communication tools to manage the variability and uncertainty associated with VRE. Smart grid technologies can help to effectively integrate high VRE shares by incorporating information and communications technology into every aspect of electricity generation, transmission and consumption. This enhances the flexible operation of the grid, reduces operational costs and

improves efficiency (Kempener *et al.*, 2013). Two directions of grid types are emerging: 1) mini-grid solutions offering reliable and clean energy to both grid-connected and off-grid communities, and 2) supergrids emerging as a solution for transporting renewable energy over long distances. A so-called grid of grids would develop in the future, with different levels of operations and trading to optimise renewable energy generation and demand.

INNOVATION 9: RENEWABLE MINI-GRIDS

Description	Ongoing developments
<p>Renewable mini-grids are integrated energy infrastructures that combine loads and renewable energy resources and that are designed to be able to operate on a self-sustainable basis. Renewable generation, intelligent switching and protection, a controller and energy storage typically form the backbone of a renewable mini-grid.</p> <p>When connected to the main grid, mini-grids can be a source of flexibility, providing frequency response, reduced grid congestion and load management.</p> <p>Direct current (DC) mini-grids are emerging as a solution to increase efficiency in the grid; however, the integrated control of alternating current (AC) and DC hybrid grids is a challenge that has not been tested much yet.</p>	<ul style="list-style-type: none"> • 12 000 MW of mini-grids worldwide. • Key regions where grid-connected mini-grids are being developed: Australia, Netherlands, US.

INNOVATION 10: SUPERGRIDS

Description	Ongoing developments
<p>DC supergrids have the potential to transmit electricity over long distances in a more efficient manner than AC systems. Coupling renewable energy generation and power load centres across long distances with fewer line losses reduces the cost of electricity transport from remotely located renewable sources to distant consumers.</p>	<ul style="list-style-type: none"> • Key regions where supergrids are being developed: Europe, India-Bangladesh-Nepal-Bhutan, North Asia (China-Japan-Russian Federation-Republic of Korea-Mongolia). • Average costs for developing DC 500 kilovolt (kV) transmission lines: approximately USD 570 000 per kilometre (EIA, 2018b).

Dispatchable generation

Improving thermal flexibility as a short- to medium-term solution is becoming popular in many countries (IRENA, 2018c). Certain generation technologies are inherently more flexible than others. However, older, less flexible technologies can be improved through retrofits, at a cost.

INNOVATION 11: FLEXIBILITY IN CONVENTIONAL POWER PLANTS

Description	Ongoing developments
<p>Conventional thermal generators can be made flexible by retrofitting certain physical components and making operational modifications, in order to achieve lower minimum load, shorter start-up times and higher ramp rates.</p> <p>This technological upgrade could:</p> <ul style="list-style-type: none"> • Increase flexibility in the system and enable higher VRE integration. • Increase profitability of conventional generators. 	<ul style="list-style-type: none"> • 12 000 MW of mini-grids worldwide. • Key regions where grid-connected mini-grids are being developed: Australia, Netherlands, US.

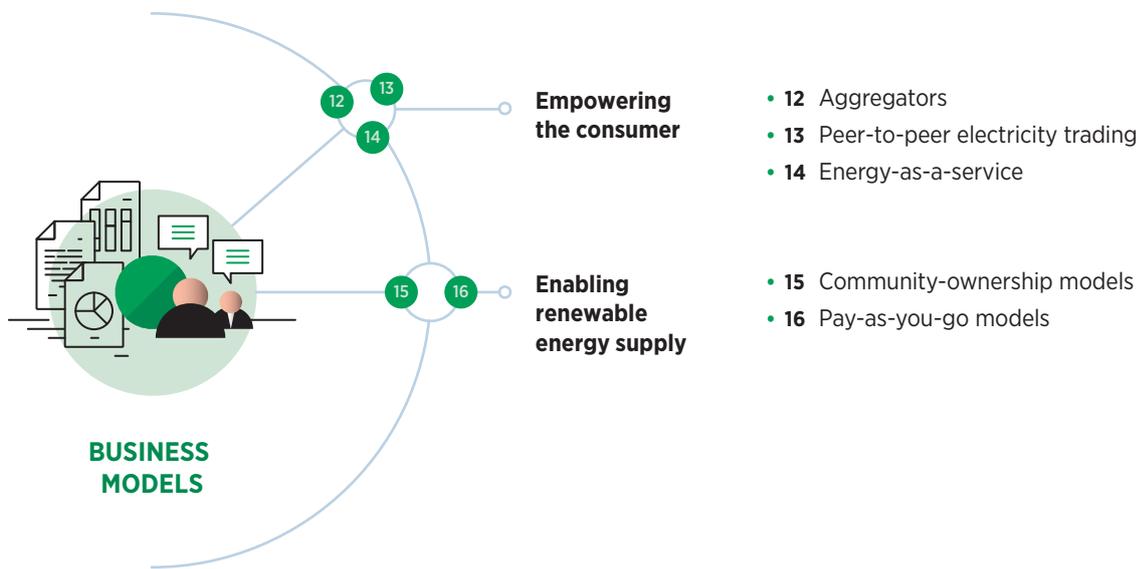
2

2.2 BUSINESS MODELS

Business models play a vital role in monetising the new value created by these technologies and in accelerating their deployment. With the deployment of distributed energy resources, innovative business models emerge to empower consumers, turning them into active players. Aggregators allow small consumers to participate in electricity markets, in peer-to-peer trading

platforms or in the energy-as-a-service model, enabled by smart meters and digitalisation. Also, business models enable renewable energy supply in off-grid areas (such as the Pay-as-you-go models) or in places where collective ownership and management of energy assets is preferred over individual ownership (the Community-ownership models).

Figure 10 Business model innovations



Empowering the consumer

With the rising share of distributed generation, consumers are increasingly becoming prosumers. They not only withdraw energy from the network, but also produce, store and supply energy to it. Distributed energy resources, together with emerging information and communications

technology applications in the energy sector, place consumers at the centre, informing and enabling them to take active decisions regarding their energy supply and consumption. Several innovative business models are emerging that might define the prosumer’s future role in the power sector.

INNOVATION 12: AGGREGATORS

Description	Ongoing developments
<p>An aggregator can operate many distributed renewable energy sources together, creating a sizeable capacity similar to that of a conventional generator (also called a “virtual power plant”). As such, aggregators can then sell electricity or ancillary services via an electricity exchange or in the wholesale market, or in the system operator’s ancillary services procurement.</p> <p>An aggregator enables smoother integration of distributed energy resources into the power system, by allowing them to provide energy to the wholesale market and ancillary services to the grid operator. Thus, it contributes to the system’s flexibility.</p>	<ul style="list-style-type: none"> • Countries with an established regulatory framework for aggregators: Australia, Belgium, France, Germany, Netherlands, UK, US. • Number of aggregators in the UK: 19 (National Grid ESO, 2018). • Installed capacity of aggregators in the UK: approximately 10 GW.

INNOVATION 13: PEER-TO-PEER ELECTRICITY TRADING

Description	Ongoing developments
<p>Platform business models are sometimes referred to as the “Uber or Airbnb of energy”. They create an online marketplace for energy where consumers and distributed energy suppliers make peer-to-peer transactions. The primary objective of a P2P market is to provide a transparent and trusted mechanism for prosumers to fairly balance their preferences and requirements.</p> <p>P2P trading encourages more renewable energy distributed generation installations and increased local use of energy resources. But the regulatory treatment, for example for grid usage charges, still requires strong evolution before large-scale implementation of P2P trading would be likely to provide strong benefits to consumers.</p>	<p>Countries where projects are in place:</p> <ul style="list-style-type: none"> • Bangladesh (SOLShare) • Germany (Lumenaza, sonnenCommunity) • Netherlands (Vandebrom, Powerpeers) • UK (Piclo – Open Utility) • US (TransActive Grid).



INNOVATION 13: ENERGY-AS-A-SERVICE

Description	Ongoing developments
<p>EaaS refers to the shift from selling kWh to selling services to customers, given the increased potential of “behind-the-meter” services, such as demand management, support for customers with decentralised generation and energy storage, and the exchange of electricity via local networks, advice on energy savings, comfort and security-enhancing measures, and other different services (e.g., E.ON Cloud, smart home solutions from EDP, ENECO, ENECO, etc.)</p> <p>EaaS enables the deployment of distributed generation and supports demand-side management, unlocking demand-side flexibility. For example, it provides automatic control in the exchange of financial compensation to consumers. Smart meters and ICT technologies are becoming key enablers for this.</p>	<ul style="list-style-type: none"> • Countries where EaaS models have been implemented: Australia, China, Finland, Ireland, Italy, Japan, Sweden, UK, US. • Investment in EaaS models: approximately USD 14.3 billion (SEI, 2016). <ul style="list-style-type: none"> • Smart meters and advanced meters installed: <ul style="list-style-type: none"> • Global: ~700 million (2016) (SEI, 2016), and 88.2 million units installed in 2017 alone (GlobalData, 2018) • China: 408 million (2017) (SEI, 2017). • US: 78.9 million (2017) (EIA, 2017). • UK: 8.61 million (2017) (BEIS, 2017). • Finland: 3.4 million (2016) (Finnish Energy, 2017).

Enabling renewable energy supply

Innovative business models also are emerging in response to increased environmental concerns and

sustainability goals, when there is no financial or physical possibility to install a private renewable energy power plant.

INNOVATION 15: COMMUNITY-OWNERSHIP MODEL

Description	Ongoing developments
<p>CO schemes refer to the collective ownership and management of energy-related assets, allowing members of a community to share the benefits of a renewable power plant.</p> <p>CO enables renewable energy supply for consumers who cannot, or prefer not to, install the power plant on their own property. These schemes encourage distributed generation deployment and energy usage from sustainable, local renewable energy sources.</p>	<ul style="list-style-type: none"> • Number of CO projects: 4 000-plus globally (primarily in US, Europe, Australia) (REN21, 2016). • Size of CO model projects: approximately 50 kW to 10 MW; however, they can be much bigger (e.g., the 66 MW community-owned wind turbines in Dardesheim, Germany; a 102 MW community-owned wind project in Krammer, Netherlands). • First countries to implement CO model projects: Australia, Denmark, Germany, Netherlands, Norway, UK, US.

INNOVATION 16: PAY-AS-YOU-GO MODELS

Description	Ongoing developments
<ul style="list-style-type: none"> • PAYG models make small electricity generators (e.g., solar panel home systems) affordable for the end-user, facilitated by mobile payment technologies that are easily accessible in remote areas. Instead of regular, fixed payments, customers pay directly for the service they use, often in the form of a package of appliances and the associated power supply; they do not receive any service for which they have not first paid. As a result payments often can be made in smaller amounts than otherwise would be possible, and customers have greater control over their consumption and thus of their spending. PAYG makes renewable energy accessible in off-grid areas, but in online locations. 	<ul style="list-style-type: none"> • PAYG solar systems sales by geography, (2016): East Africa 7.3 million units; West Africa 30 000 units; Latin America 10 000 units; South Asia 20 000 units. • Market potential: 772 million or around 64% of off-grid consumers have access to mobile networks (as of 2016). • Total value of investments made in PAYG solar companies: more than USD 770 million (from 2012 to 2017).

2.3 MARKET DESIGN

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. The glue that holds all of this together is a market that prices energy and balancing services properly and that remunerates all actors that are able to provide these services. The further the market is away from this – for instance, by setting price caps too low or by socialising congestion costs – the more patches are required, such as cost-based re-dispatch or capacity markets, to pay for needed investment. None of these patches allocate value as effectively as a well-functioning energy and services market. Gradual improvement of energy market pricing is critical regardless of any short-term patches that might be adopted.

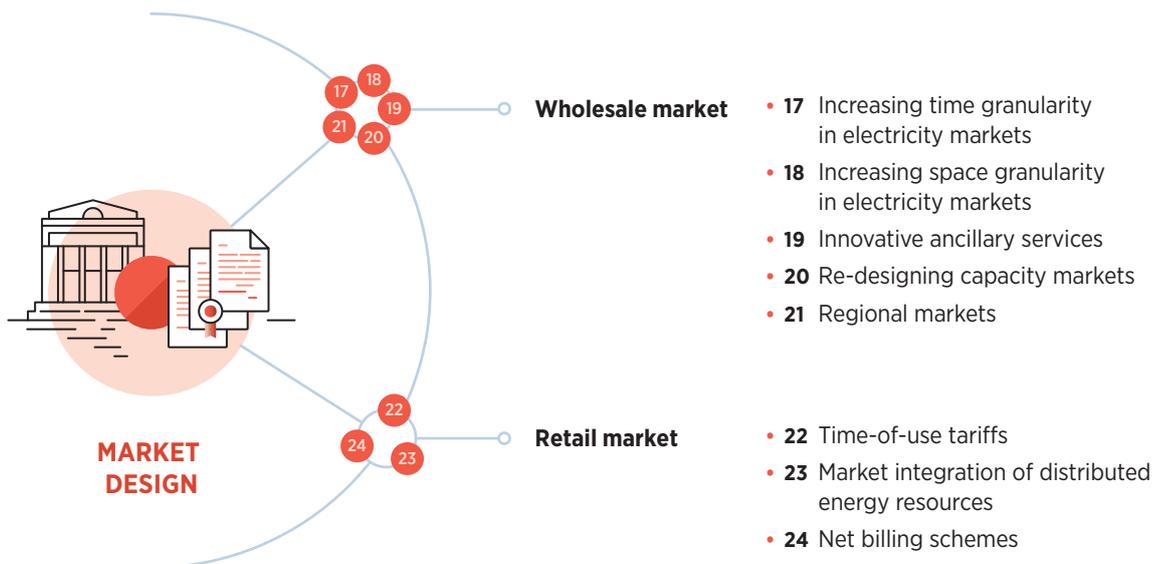
Looking forward, ambitious targets and a regulatory framework that enables innovation are needed. Innovations proposed by the European Commission in the Clean Energy for All Europeans

package include short-term market and wholesale prices that reflect the real value of electricity in time, new dispatch rules, better demand participation to ensure flexibility, a better economic case for distributed energy resources, self-consumption and market coupling¹.

Flexible behaviour needs to be incentivised in the wholesale markets, such as an increase in time and space granularity and the redesign of balancing services. Also, properly rewarding demand-side response in the retail market is key in the new power system context. Regulations such as time-of-use tariffs, net billing schemes for self-consumption, or allowing distributed energy resources to participate in wholesale markets (through aggregators) are all innovative practices emerging in different systems. This section is based on the IRENA report *Adapting market design to a high share of variable renewable energy* (IRENA, 2017b). For a more in-depth analysis, please refer to this report.

New market designs are required in both the wholesale and retail markets, such as:

Figure 11 Market design innovations



¹ Based on discussions during the Innovation Ministerial Roundtable at the IRENA 9th Assembly, January 2019.

2

Innovative wholesale market design

To further enable a large share of VRE penetration into power grids, trading rules in power markets must change. They must adapt to the new market conditions and value flexible behaviour needed to counteract the short-term variability and uncertainty of renewables. New products

should be designed, and new participants should be allowed to offer their flexibility services. For example, demand-side response should be able to participate in all wholesale markets (energy, ancillary service, and capacity market, if one is established), in the same way as the supply-side generators.

INNOVATION 17: INCREASING TIME GRANULARITY IN ELECTRICITY MARKETS

Description	Ongoing developments
<p>New regulations that make it possible to better capture the flexibility that the system needs, by providing better signals to flexibility sources to participate in the market. This is key to cope with the uncertainty and variability of VRE generation.</p> <p>Increasing time granularity by introducing new products (e.g., 15-minute contracts) and bringing trading intervals closer to real time is a way to value the flexibility of technologies that can respond quickly to fast-changing conditions (but may not be able to commit with longer lead-times), or of renewables that can contribute to a market with high certainty only if the lead time is very short.</p>	<ul style="list-style-type: none"> • Australia transitioned from a 30-minute to a 5-minute financial settlement, and from a 2-hour to a 30-minute gate closure time. • In 2016 Nord Pool, Fingrid and Elering launched a pilot with a 30-minute gate closure time in the intraday market on the Estonian-Finnish border, to replace the previous 60-minute one. • In Austria, Belgium, Germany and Luxembourg (in certain transmission system operator areas only) the local intraday gate closure time is five minutes before the beginning of physical delivery (ACER, 2018). • California is proposing to move from a 1-hour to a 15-minute scheduling interval. • France, Germany, Luxembourg, Switzerland and the UK introduced 30-minute products for continuous trading in intraday markets. • 15-minute products for continuous trading are available in Austria, Belgium, Germany, Hungary, Luxembourg, the Netherlands Slovenia and Switzerland. 15-minute products are auctioned (as opposed to continuous trading) in Germany and Luxembourg (ACER, 2018).

INNOVATION 18: INCREASING SPACE GRANULARITY IN ELECTRICITY MARKETS

Description	Ongoing developments
<p>Increasing the locational granularity by using zonal or nodal prices or price signals on both the transmission and distribution level (including re-dispatch costs or flexibility markets) captures the new network constraints and conveys efficient locational signals.</p> <p>Because a high share of VRE might lead to an increasingly constrained transmission system, determining prices at a granular spatial level would reflect this condition, avoiding costly re-dispatch, incentivising demand response and showing price signals that would incentivise generation capacity investment in the right location of the network.</p>	<ul style="list-style-type: none"> • Several US independent system operators have implemented locational pricing: ISO-NE (ISO New England); NYISO (New York ISO); ERCOT (Electric Reliability Council of Texas); MISO (Midcontinent ISO); PJM (Pennsylvania – New Jersey – Maryland Interconnection) and CAISO (California ISO) (NPTEL, 2012). • Italy uses a zonal pricing mechanism and has divided the national transmission system into 10 zones (IRENA, 2017b). • The pan-European market uses a zonal pricing mechanism, and some countries have divided the national transmission system into more bidding zones, including Denmark (two bidding zones), Italy (six geographical bidding zones), Norway (five bidding zones) and Sweden (four bidding zones) (IRENA, 2017b).

INNOVATION 19: INNOVATIVE ANCILLARY SERVICES

Description	Ongoing developments
<p>To address the variability and uncertainty of the increasing VRE in the grid, ancillary services products need to be adapted to increase the system flexibility, incentivise fast-response and ramping ability and remunerate each of the services, accordingly. The ancillary service market also should be open to new participants, such as battery storage, demand response and other distributed energy resources, and VRE generators.</p>	<ul style="list-style-type: none"> • In the UK, US and Germany, new products for flexibility have been designed, and batteries are allowed to participate. • PJM, a system operator in the US, has developed different frequency regulation products for the slower conventional resources and for the faster battery storage ones. • In the UK, a new product was introduced for battery storage: enhanced frequency response. • In Chile the first pilot was implemented to enable a PV power plant to provide ancillary service to the utility grid and ensure grid stability. • In the UK in 2018, the grid operator increased charges for suppliers and generators that inaccurately forecast electricity demand and supply, incentivising them to invest in flexibility. • EirGrid, the Irish transmission system operator, has defined several additional system service products to cope with wind energy fluctuations.

INNOVATION 20: RE-DESIGNING CAPACITY MARKETS

Description	Ongoing developments
<p>Capacity mechanisms are designed to ensure that sufficient reliable firm capacity is available, so that adequacy in the system is ensured in the long term.</p> <p>Innovations in capacity markets include:</p> <ul style="list-style-type: none"> • Allowing renewables to participate in the capacity markets – even though their generation is intermittent and VRE generation can be integrated into the system. At times, they provide reliability, especially if there is some complementarity with other sources in the system or via integrated hybrid wind-solar-battery projects. • Introducing a requirement for flexibility in the capacity market. This ensures that future generation is flexible and the integration of VRE. • Allowing demand response, energy storage and cross-border interconnections to participate in capacity markets. 	<ul style="list-style-type: none"> • The main developments are taking place in the US and Europe, with the newest capacity mechanisms being approved in Belgium, France, Germany, Greece, Italy and Poland in 2018. • California is implementing flexible requirements in its capacity market structure. • PJM in the US, and France, allow participation of demand-responsive loads and VRE resources in capacity markets.

INNOVATION 21: REGIONAL MARKETS

Description	Ongoing developments
<p>Regional markets imply harmonised rules in the wholesale market, ancillary service market and capacity markets across the region. Creating a regional market by taking advantage of the interconnections consolidates balancing areas and increases flexibility. By sharing resources over large regions, the need for operating reserves, as well as curtailment requirements and costs, are reduced.</p>	<ul style="list-style-type: none"> • Regional markets: European day-ahead and intraday market, West African Power Pool, South African Power Pool, Central America Power Market, western Energy Imbalance Market (US), etc. • Denmark managed to reach a 50% VRE share in 2017 due to strong interconnections with Germany, Sweden and Norway.

2

Innovative retail market design

Electricity markets traditionally have been tailored to grid-connected, large-scale power plants that supplied electricity to a relatively easy-to-forecast, passive and inelastic demand. The increasing

deployment of distributed generation, together with storage technology placed on the consumer-end and improved demand response, turns consumers into active market participants. Market regulation is key to unlock demand-side flexibility:

INNOVATION 22: TIME-OF-USE TARIFFS

Description	Ongoing developments
<p>Demand response can be achieved by exposing consumers to time-varying power prices so that they can voluntarily react to these prices, particularly for infrequent ultra-peak price periods (known as the implicit demand response), with or without automation.</p> <p>Based on tariff signals, consumers may opt to shift their consumption from peak time intervals to off-peak time intervals. This can result in reduced VRE curtailment or distribution congestion, and thus in savings in peak capacity investment.</p>	<ul style="list-style-type: none"> • The US utility Con Ed offers an hourly pricing programme, enabling consumers to shift their load and save approximately 15% on the electricity bill. • In Finland consumers have an option for dynamic pricing tariffs, based on the wholesale market spot price; 10% of consumers choose this tariff. • Hourly real-time pricing for the supply of electricity is used in five European countries: Estonia, Romania, Spain, Sweden and the UK. In Spain and Estonia household customers can choose a tariff varying by the hour with the spot price. Between 25% and 50% of consumers have chosen it (ACER, 2016). • Other dynamic pricing methods apply to electricity households in Denmark, Norway and Sweden, where consumers incur spot market-based pricing through the monthly average wholesale price (ACER, 2016).

INNOVATION 23: MARKET INTEGRATION OF DISTRIBUTED ENERGY RESOURCES

Description	Ongoing developments
<p>Demand response can be achieved through allowing distributed energy resources to participate in the wholesale market, being exposed to market prices (referred to as the explicit demand response).</p> <p>Besides load shifting, distributed energy resources also can provide ancillary services or electricity to the grid, increasing flexibility in the system while being remunerated for it.</p>	<ul style="list-style-type: none"> • The system operator in New York released a market proposal that will enable participation of distributed energy resources and their complete integration into the energy and ancillary service markets. • The EU's Network Code on Balancing is proposing smaller quantities (MW) and shorter time frames for the balancing market, so that it becomes accessible for smaller sources, such as PV and wind, but also for demand response. • Markets in which distributed energy resources are allowed to participate via aggregators: Belgium, France, Germany, etc.

INNOVATION 24: NET BILLING SCHEMES

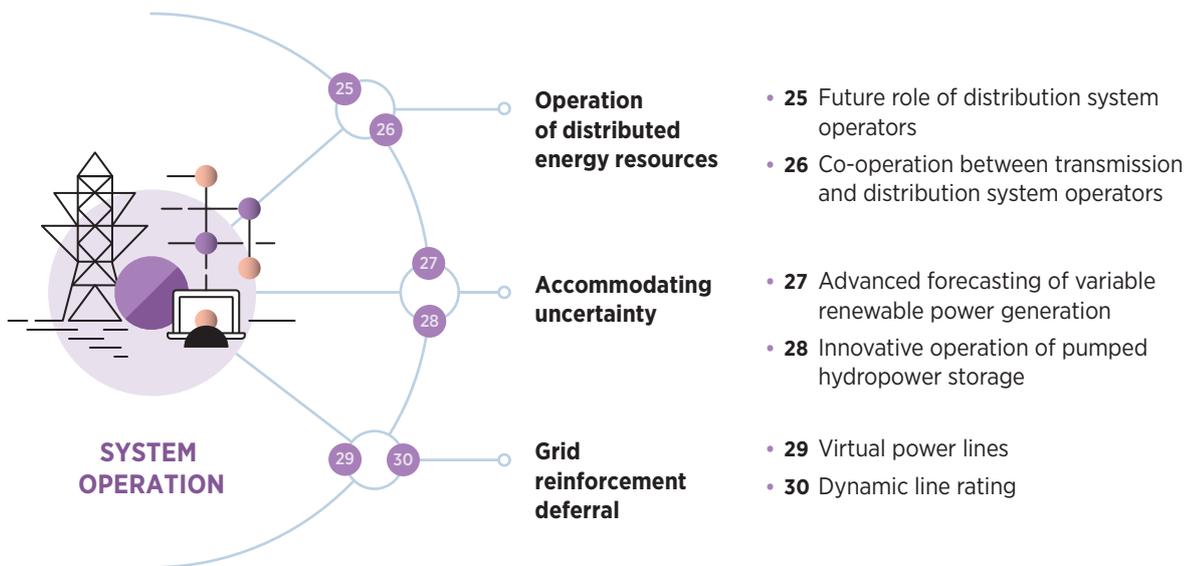
Description	Ongoing developments
<p>Under net billing mechanisms, the electricity injected in the grid from a rooftop PV owner is compensated based on the value of the kWh injected at that moment. The invoice issued is based on the value of the withdrawn energy, after subtracting the value of the injected energy as opposed to net metering schemes, where the invoice is based on the difference between the amount of electricity injected and withdrawn. The prosumer is, therefore, an active participant and can provide grid flexibility based on price signals.</p>	<ul style="list-style-type: none"> • Regions that implement net billing: Mexico (time-varying tariffs determined in advance), California (dynamic tariffs), Mexico and New York (location-varying tariffs), Arizona (tariffs based on avoided cost of electricity).

2.4 SYSTEM OPERATION

The operation of power systems is changing due to new technologies and market regulations and driven by new challenges. Firstly, increasing the share of distributed generation and the decentralisation of the system turns the distribution grid into a bi-directional power flow network, which requires new operational practices. To facilitate the integration of such technologies, distribution companies should assume new roles. Also, co-operation between distribution and transmission system operators is required to better integrate distributed energy resources into the whole system.

Secondly, new operations practices to manage the uncertainty of VRE generation are required. Advanced VRE generation forecasting methods and tools have been developed to reduce the uncertainty. Other operational practices to increase flexibility are emerging, such as new operations of pumped hydro storage. With rich VRE sources areas located far from demand centres (especially wind), grid congestion occurs for limited periods of time. Innovative operation practices emerge to replace the high investment required to reinforce the lines: either using or dynamic line rating.

Figure 12 System operation innovations



2

Operation of distributed energy resources

Electric power systems are experiencing a deep transformation worldwide. Grids are becoming a more prominent part of the whole energy spectrum. Traditionally considered the “sleeping” part of the industry, grids are taking an important and active role in integrating VRE.

The emergence of distributed energy resources such as rooftop solar PV, micro wind turbines, battery energy storage systems, plug-in electric vehicles, smart home appliances, etc. have

turned consumers into active participants in the electricity system. This will have a significant impact on the roles and responsibilities of system operators. In particular, the responsibility of distribution system operators would expand from being simple electricity carriers to having an active role in operating the network and facilitating the participation of distributed energy resources in the system. Also, co-ordination with transmission system operators would need to tighten, with information flowing in both directions.

INNOVATION 25: FUTURE ROLE OF DISTRIBUTION SYSTEM OPERATORS

Description	Ongoing developments
<p>The responsibility of distribution system operators should expand to effectively manage the distributed energy resources connected to their grid, enabling their integration into the grid and maximising the benefits they can provide.</p> <p>This new role would include:</p> <ul style="list-style-type: none"> • Procurement of grid services from distributed energy resources. • Operation of distributed energy resources to optimise the use of existing grids and defer new unnecessary investments, either through direct control or through price signals. 	<ul style="list-style-type: none"> • The main developments are taking place in the US and Europe, with the newest capacity mechanisms being approved in Belgium, France, Germany, Greece, Italy and Poland in 2018. • California is implementing flexible requirements in its capacity market structure. • PJM in the US, and France, allow participation of demand-responsive loads and VRE resources in capacity markets.

INNOVATION 26: CO-OPERATION BETWEEN TRANSMISSION AND DISTRIBUTION SYSTEM OPERATORS

Description	Ongoing developments
<p>The distribution system operator should act as a neutral market facilitator for participation of distributed energy resources in upstream services and markets. For these resources to participate in wholesale markets, efficient co-ordination between the distribution and transmission system operators becomes essential.</p> <p>The distribution system operators also should contribute to or act as a data exchange platform between the transmission system operators and the owners of distributed energy resources, providing visibility to the transmission system operators on the type and availability of these resources.</p> <p>This would enable a smooth integration of distributed energy resources into the system, increasing its flexibility and maximising the benefits of the already connected assets.</p>	<ul style="list-style-type: none"> • Key regions where programmes have been implemented for co-ordination among transmission and distribution system operators: Belgium, Austria, Italy, all Nordic countries, Estonia, Spain, Netherlands. • In Belgium the transmission and distribution system operators collaborated to develop a centrally shared IT platform. Through this data hub, the data related to procuring distributed energy resources for flexibility can be shared, and all users and generators connected to the distribution / transmission grid can provide flexibility services to the transmission system operators on a daily basis (Elia, 2018). The other countries named above have also developed data hubs. • The SmartNet project, funded by the European Commission, has the objective to identify models for transmission and distribution system operator interactions.

Accommodating uncertainty

The variability and uncertainty of wind and solar generation pose a major challenge to power system operation. Balancing generation with load in real time requires greater power system flexibility. It requires the procurement of more back-up capacity, also called reserve capacity,

to cope with this variability. Existing pumped hydropower plants are flexible plants that can be operated to increase the system’s capability to react to generation variability. Tools and models to better forecast renewable energy generation also are being developed.

INNOVATION 27: ADVANCED FORECASTING OF VARIABLE RENEWABLE POWER GENERATION

Description	Ongoing developments
<p>New models could improve the accuracy and detail of renewable energy generation forecasting, by using cloud-based computing, improved mathematical models (that produce forecast results in 15 minutes instead of an hour), very high-resolution weather forecasts and machine learning / AI. Better forecasting the renewable energy generation decreases uncertainty for system operators, resulting in better integration of renewable energy.</p> <p>Long term (<i>i.e.</i>, daily and seasonal) forecasting is also important for transmission system operators to plan for adverse forecast weather conditions (<i>e.g.</i>, the negative North Atlantic Oscillation in Europe, which led to low wind speeds). Improved seasonal forecasting can allow the system operator to plan for alternative capacity during the period when such extreme events occur.</p>	<ul style="list-style-type: none"> Improvement in weather forecasting accuracy: 10-30%. Countries where advanced weather forecasting projects are piloted: US, Germany, Netherlands, Spain, China.

INNOVATION 28: INNOVATIVE OPERATION OF PUMPED HYDROPOWER STORAGE

Description	Ongoing developments
<p>Pumped hydro storage plants are flexible plants that can be operated in a way that complements wind / solar power generation in the short term, reacting to variability with fast ramps, as well as in the long term, given the complementarity in daily, weekly or seasonal generation patterns.</p>	<ul style="list-style-type: none"> Key regions with innovative operation of pumped hydro storage: Japan, Portugal, Costa Rica, Iceland, Denmark, Norway, Switzerland, Republic of Korea, China, UK, France, Brazil, Singapore, Malaysia, Italy, Australia, US.



2

Grid reinforcement deferral

The electrical transmission system is becoming more complex with higher shares of renewable generation. Changing demand patterns and new utility-scale VRE generation assets require efficient management of transmission assets to prevent congestion and curtailment of renewable generation. When VRE penetration is high,

congestion in grids might occur for limited periods of time. Non-wire alternatives are entering the system as a substitute for expensive upgrades to the transmission infrastructure, using either batteries, building-integrated wind-solar-battery hybrids or dynamic line rating.

INNOVATION 29: VIRTUAL POWER LINES

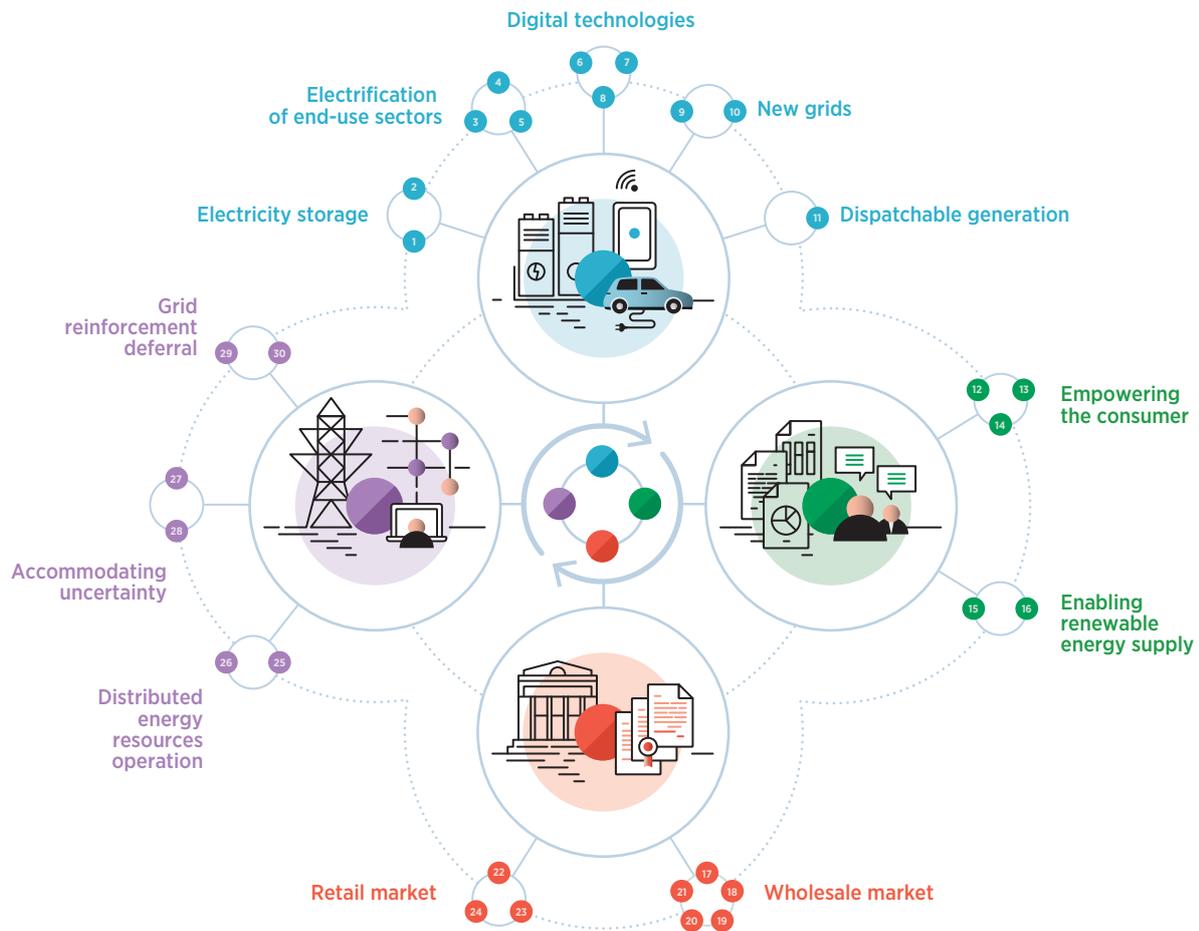
Description	Ongoing developments
<p>Batteries located at both sides of a congested part of the grid point can provide back-up energy storage during a contingency event to relieve thermal overload. These virtual transmission lines defer or avoid the need to upgrade physical transmission lines. A relatively modest amount of storage can be used to serve the small portion of peak demand that would will exceed transmission line capacity. This would reduce the curtailment of VRE generation due to grid congestion.</p>	<ul style="list-style-type: none"> • The French transmission system operator RTE is piloting a project (Ringo project) that aims to install 100MW of energy storage to alleviate grid congestion and increase the VRE share in the grid. • Terna, the Italian transmission system operator, plans to utilise batteries to relieve the congestion between the north and south and reduce wind and solar curtailment. • Following the success of the 100 MW / 129 MWh Tesla battery in South Australia, Australia is installing utility-scale batteries at points of network congestion (80 MW across two sites were commissioned in regional Victoria in 2018). • The Republic of Korea is installing a number of distributed utility-scale lithium-ion battery systems (245 MWh in total) (Kenning, 2018).

INNOVATION 30: DYNAMIC LINE RATING

Description	Ongoing developments
<p>DLR implies that the capacity of the transmission lines varies dynamically according to weather conditions (e.g., the thermal capacity of the line is higher when the wind blows or when the temperature drops, because of the better cooling). DLR mitigates grid congestion, facilitates wind energy integration, enables economic benefits and improves the reliability performance of power systems.</p>	<ul style="list-style-type: none"> • In Germany DLR systems have been examined and installed to improve the integration of wind generation into the transmission system and for better congestion management. • In Europe 11 transmission system operators have DLRs in operation. • DLR also is used in distribution networks, e.g., UK Power Networks and Northern Power Grid in the UK.



Figure 13 The innovation landscape for variable renewable power integration



● ENABLING TECHNOLOGIES	● BUSINESS MODELS	● MARKET DESIGN	● SYSTEM OPERATION
1 Utility-scale batteries	12 Aggregators	17 Increasing time granularity in electricity markets	25 Future role of distribution system operators
2 Behind-the-meter batteries	13 Peer-to-peer electricity trading	18 Increasing space granularity in electricity markets	26 Co-operation between transmission and distribution system operators
3 Electric-vehicle smart charging	14 Energy-as-a-service	19 Innovative ancillary services	27 Advanced forecasting of variable renewable power generation
4 Renewable power-to-heat	15 Community-ownership models	20 Re-designing capacity markets	28 Innovative operation of pumped hydropower storage
5 Renewable power-to-hydrogen	16 Pay-as-you-go models	21 Regional markets	29 Virtual power lines
6 Internet of things		22 Time-of-use tariffs	30 Dynamic line rating
7 Artificial intelligence and big data		23 Market integration of distributed energy resources	
8 Blockchain		24 Net billing schemes	
9 Renewable mini-grids			
10 Supergrids			
11 Flexibility in conventional power plants			

3

INNOVATIONS CREATING SOLUTIONS FOR A RENEWABLE-POWERED FUTURE

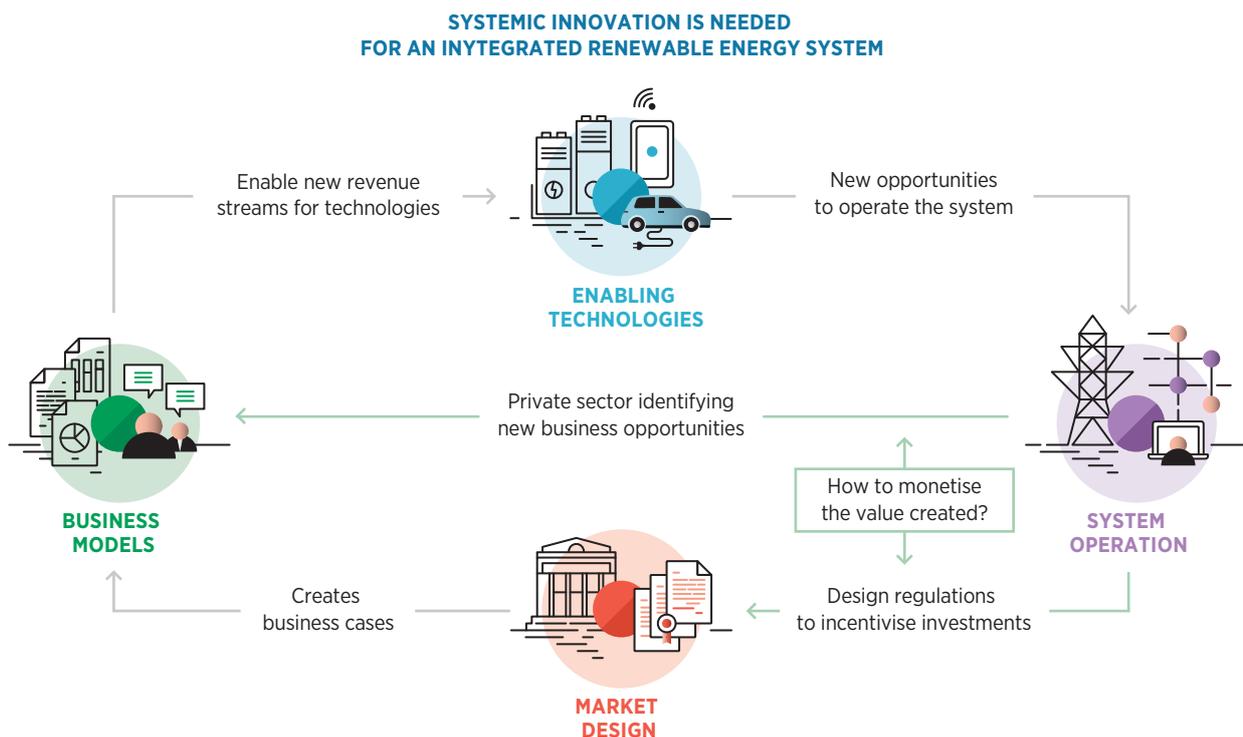


Starting with the innovations mapped in Chapter 2, this chapter highlights 11 emerging solutions that illustrate the bringing together of several innovations in a complementary way, thus facilitating the integration of higher shares of VRE into the system.

Innovations are not implemented in isolation. Innovative solutions for VRE integration come from the synergies of different innovations across all four dimensions: technology, markets, business models and system operation.

Without a proper business model, innovations in technologies do not have a real impact. Also, regulations require adaptation to create a framework that enables new values to be remunerated, or for system operation to integrate new technologies into actual system practices. Matching and leveraging from synergies among innovations in multiple components of the power system, to formulate solutions for a renewable-powered system, is called “systemic innovation”, as illustrated by Figure 14.

Figure 14 Systemic innovation for power sector transformation



Emerging technologies that enable the integration of renewable energy into a power system allow **new ways to operate the system**. They provide new services that enhance the system's flexibility, helping to address challenges posed by the variability and uncertainty of renewable generation. For example, large-scale batteries can be used for short-term flexibility needs, permitting systems to operate with back-up power for at most a few hours, and usually shorter. Digitalisation and automation could enable demand response in the system's current conditions, unlocking the huge flexibility potential on the demand side.

Operational flexibility ensures that grid operators can meet daily, hourly or sub-hourly fluctuations in supply and demand. This kind of short-term operational flexibility has not traditionally been explicitly valued. A range of technologies is now available that could provide the services needed for a large share of VRE integration. The key question is how to monetise the new value streams, created so that appropriate business models can support the further development and deployment of these technologies.

One way to enable value creation and adequate revenue streams is to implement supportive regulation. Appropriate **market designs** are important to achieve policy objectives through a well-functioning electricity market, as discussed in the IRENA report *Adapting market design to a high share of variable renewable energy* (IRENA, 2017b). Incentives that stimulate flexibility by encouraging flexible behaviour on the supply side, as well as properly rewarding demand through demand-side response, are all innovative regulations. These, in turn, enable innovative **business models**. Adapting the design of the market to the changing paradigms in power systems is important in accelerating the energy transition.

However, even when regulation is missing, the private sector might still identify some new business model opportunities enabled by technological advancements. For example, in the absence of demand-response programmes implemented by the regulatory body, private companies start offering customers energy services, such as load shifting and energy savings, using batteries

and artificial intelligence in exchange for a lower electricity bill. The rise of the corporate power purchase agreement market was a major new feature during 2017/18 as corporations seek to lower their total electricity costs by procuring low-cost, fixed-price VRE in the US, Europe and Australia.

Solutions to unlock flexibility across the whole power system

As explained in Chapter 1, system flexibility traditionally was provided by generation, which followed demand. However, greater flexibility is required in the system with the growing share of VRE generation, connected across all levels of the supply chain. An emerging, powerful approach for further unlocking flexibility is coming from the demand side. With the increased decentralisation and digitalisation of the system, many generation technologies are connected to the consumer end, while digital technologies can support in providing demand response and other services to the grid. Also, flexibility in the grid is becoming increasingly important, through increased transmission capacity and the establishment of regional markets. Figure 15 illustrates the transition from a system in which generation is the only source of flexibility to one that has flexibility sources across the entire supply chain.

The optimal strategy for integrating even higher shares of VRE is country- and context-specific. Solutions emerging from the synergies among innovations across all dimensions of the system will make it possible to create reliable and affordable power systems that are based predominantly on renewable energy. This chapter identifies 11 solutions that are being implemented across the globe and that unlock flexibility in the power system, as shown in Figure 16.

The following sub-sections elaborate on each of these 11 solutions. They explain the types of innovations required for a sound solution and the potential impact of the solution on the power system. A few case studies in which the solutions have been implemented are also cited.

Figure 15 Traditional flexibility providers (left) versus emerging flexibility providers (right)

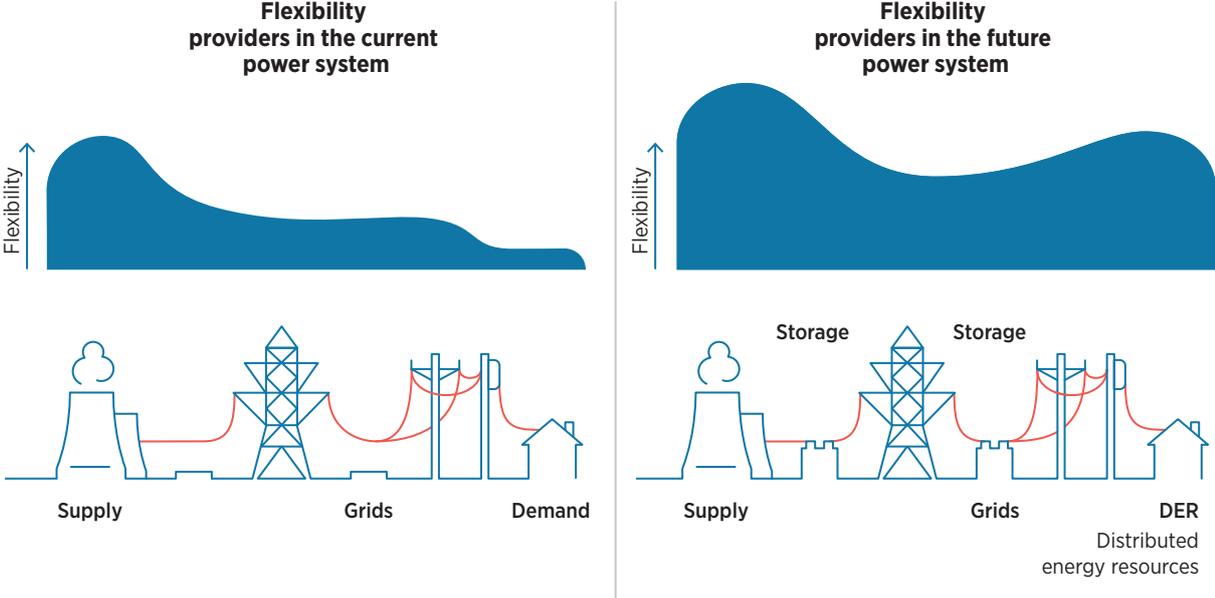
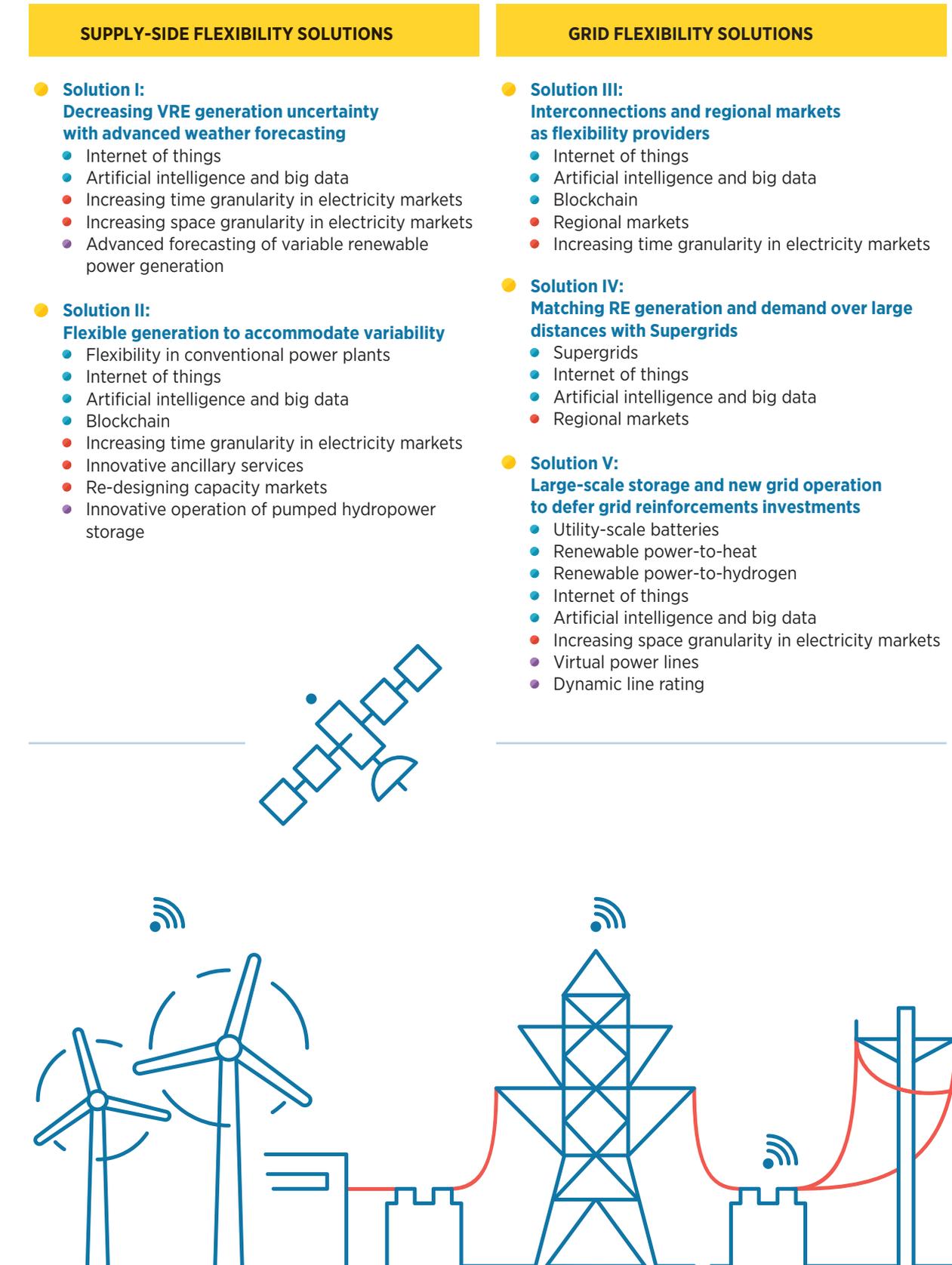


Figure 16 Solutions created by combining innovations in enabling technologies, business models, market design and system operation



DEMAND-SIDE FLEXIBILITY SOLUTIONS

- **Solution VI:**
Aggregating distributed energy resources for grid services
 - Behind-the-meter batteries
 - Electric-vehicle smart charging
 - Renewable power-to-heat
 - Internet of things
 - Artificial intelligence and big data
 - Blockchain
 - Aggregators
 - Market integration of distributed energy resources
 - Innovative ancillary services
 - Co-operation between transmission and distribution system operators

- **Solution VII:**
Demand-side management
 - Behind-the-meter batteries
 - Electric-vehicle smart charging
 - Renewable power-to-heat
 - Internet of things
 - Artificial intelligence and big data
 - Energy-as-a-service
 - Time-of-use tariffs
 - Net billing schemes
 - Advanced forecasting of variable renewable power generation

- **Solution VIII:**
RE mini-grids providing services to the main grid
 - Renewable mini-grids
 - Behind-the-meter batteries
 - Electric-vehicle smart charging
 - Renewable power-to-heat
 - Internet of things
 - Artificial intelligence and big data
 - Blockchain
 - Peer-to-peer electricity trading
 - Community-ownership models
 - Market integration of distributed energy resources

- **Solution IX:**
Optimising distribution system operation with distributed energy resources
 - Internet of things
 - Behind-the-meter batteries
 - Electric-vehicle smart charging
 - Artificial intelligence and big data
 - Aggregators
 - Net billing schemes
 - Future role of distribution system operators
 - Virtual power lines

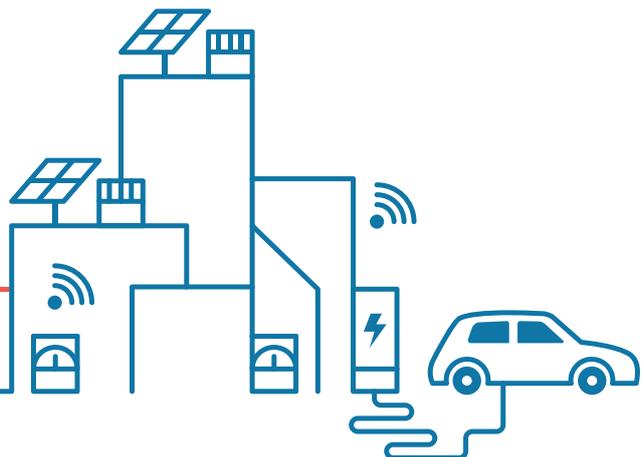
SYSTEM-WIDE STORAGE FLEXIBILITY SOLUTIONS

- **Solution X:**
Utility-scale battery solutions
 - Utility-scale batteries
 - Internet of things
 - Artificial intelligence and big data
 - Aggregators
 - Innovative ancillary services
 - Increasing time granularity in electricity markets
 - Increasing space granularity in electricity markets
 - Re-designing capacity markets
 - Virtual power line

- **Solution XI:**
Power-to-X solutions
 - Renewable power-to-hydrogen
 - Renewable power-to-heat
 - Artificial intelligence and big data
 - Innovative ancillary services
 - Virtual power lines



- Enabling technologies
- Business models
- Market design
- System operation



3

3.1 SUPPLY-SIDE FLEXIBILITY SOLUTIONS

Dealing with variability and uncertainty in balancing the power system is not a new issue for power system operation. Demand has always been variable and uncertain to some extent, but relatively easy to forecast. However, as the share of VRE supply increases in a system, the variability and uncertainty of VRE generation becomes more frequent and significant, posing additional challenges to system operation. Solutions to address this on the supply side include:

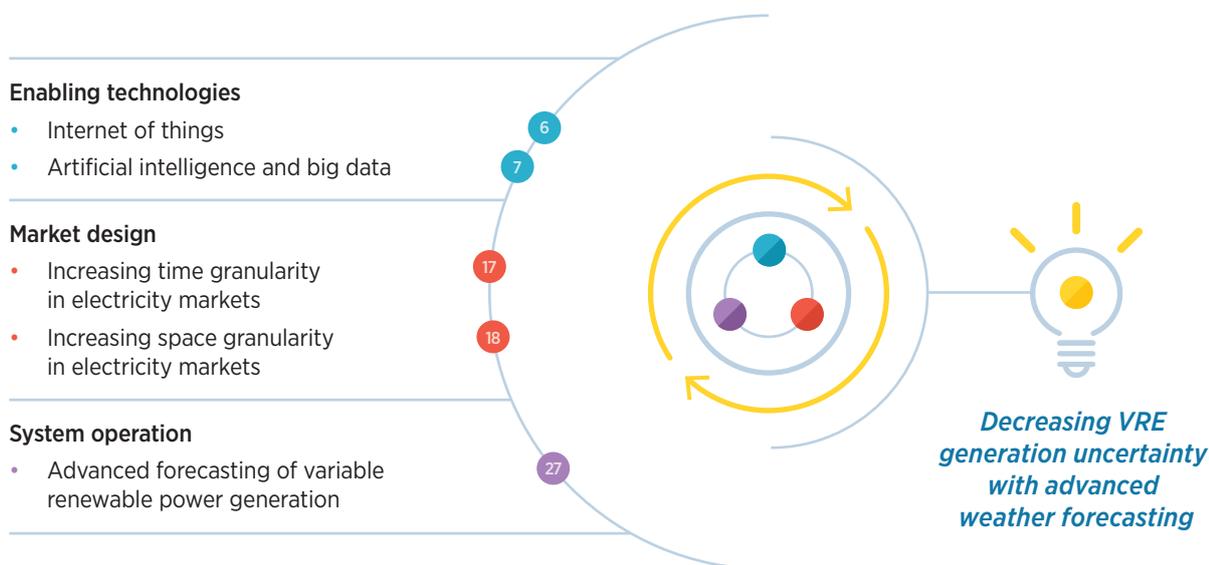
- **Minimising the uncertainty of wind and solar generation through advanced weather forecasting.** This solution depends on the methodology and technique used. Enhancements from the use and management of big data and artificial intelligence can increase the accuracy of the forecast and hence the overall reliability of the system.
- **Incentivising existing generation towards more flexible behaviour,** for example from fast-responding pumped hydro storage or fast-ramping gas generation. This also involves remunerating non-flexible power plants to become flexible through technical upgrades. This solution is focused on technological and market design innovation, which could have a significant impact on system flexibility.



SOLUTION I

Decreasing VRE generation uncertainty with advanced weather forecasting

Figure 17 Synergies between innovations for decreasing uncertainty of VRE generation with advanced forecasting



● **At the system operation level**, effective VRE forecasting is crucial to integrate wind and solar resources into the grid, especially at high penetration levels. As one of the most cost-effective tools available to system operators, advanced forecasting helps reduce the uncertainty associated with VRE generation, providing support in operation planning to counteract its variability. Better forecasting does not remove the need for action, it just gives longer to plan. Accurate forecasting can help improve unit commitment and dispatch efficiently and reduce reliability issues, hence reducing the amount of operating reserves needed in the system. Also, it permits VRE to be used to provide system services such as operating reserves. For example, through blade pitching, wind turbines can provide upward and downward reserve. When system services can be obtained also from VRE, the power system can integrate more VRE (IRENA, IEA and REN21, 2018).

High-quality weather forecasting can accurately predict output on a two- to six-hour interval, greatly improving system reliability. Today, forecast

errors typically range from 3% to 6% of the rated capacity an hour ahead and from 6% to 8% a day ahead on a regional basis (as opposed to for a single plant). In comparison, errors for forecasting load typically range from 1% to 3% a day ahead (Lew *et al.*, 2011). Even slight improvements in generation forecasting have the potential to result in large operational and economic benefits. *(Key innovation: Advanced forecasting of variable renewable power generation)*

● **Thanks to enabling technologies**, advanced weather forecasting models now take into consideration site-specific parameters and real-time data gathered from advanced meteorological devices. By using the significant processing power afforded by modern ICT, such as cloud-based computing, improved mathematical models (which produce forecast results for 5 or 15 minutes instead of an hour) and artificial intelligence, together with the big data collected on past weather patterns and generation outputs, accuracy and locational resolution of VRE generation forecast could be improved. Some other weather forecast models

3

also use advanced cloud-imaging technology, sky-facing cameras to track cloud movements, and sensors (installed on the turbines) to monitor wind speed, temperature and direction. *(Key innovations: Artificial intelligence and big data; Internet of Things)*

A successful example is the EWeLiNE, a machine-learning-based software used in Germany. It uses artificial intelligence and the data from solar sensors, wind turbine sensors and weather forecasts to predict power generation. It therefore helps minimise losses due to surplus power generation and intermittency in the renewable energy integrated system. Another example is Utopus Insights, a company based in New York and India that is focused on improved forecasting for the electrical grid using machine learning as a way to respond to renewable energy growth, which poses a significant challenge to balancing supply and demand. Along with predicting and managing peak loads, the Utopus Insights software will anticipate icing events that can knock down power lines, block solar panels and cause wind turbines to emit unpleasant sounds (Polhamus, 2017).

● **Market design** would need to adapt in order to best capture the benefits of improved forecasting. Improved weather forecasting can be used to update commitment and dispatch and transmission schedules more frequently. This enables better scheduling of the system and reduces the need for expensive operating reserves. Accurate solar and wind generation forecasts could give conventional generators sufficient time to ramp up or down, thereby reducing emissions and balancing the system cost-effectively.

Increasing time and space granularity in the wholesale market helps to capture the value of advanced weather forecasts for VRE generation in the market and dispatch schedule. ERCOT, in Texas, has reduced the dispatch time intervals from 15 minutes to 5 minutes, allowing updates in generation schedules until 10 minutes before the actual power dispatch. This change in the rule helps to minimise forecast error and to reduce wind curtailment due to better accuracy in forecasts (Bridge to India, 2017). *(Key innovations: Increasing time granularity in electricity markets; Increasing space granularity in electricity markets)*



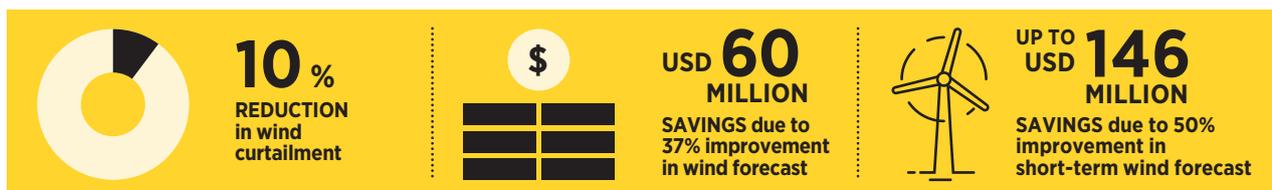
Impact of better forecasting through digital technologies:

- **Artificial intelligence can improve the renewable energy generation forecast from 88% to 94%.**

Digital technologies, such as machine-learning algorithms, when applied to weather and power plant output data, can increase the accuracy of renewable forecasts to up to 94%, from around 88% across the industry. Most of these systems are in the pilot phase. In addition, retrofitting digital systems can improve VRE integration by allowing operational data to be provided directly to operators (BNEF, 2017).

- **30% improvement in accuracy for solar irradiation forecasting when using artificial intelligence.**

In 2015 a project by IBM and a team of partners, developed through the US Department of Energy’s SunShot Initiative, was able to show an accuracy improvement of 30% for solar forecasting due to the building of a better solar forecasting model using deep-machine-learning technology. The self-learning weather model and renewable forecasting technology, named Watt-Sun, integrated large sets of historical data and real-time measurement from local weather stations, sensor networks, satellites and sky-imaging cameras (NREL, 2015a).



Impact on VRE curtailment:

- **10% reduction in wind curtailment from a 670 MW solar-wind facility enables powering of 14 000 homes.**

IBM created the Hybrid Renewable Energy Forecasting (HyRef) solution for the Chinese State Grid's Jibei Electricity Power Company Limited to perform advanced data analysis and improve wind power predictions for a 670 MW solar-wind energy facility. HyRef uses weather modelling capabilities, advanced cloud-imaging technology and sky-facing cameras to track cloud movements, along with wind turbine sensors, weather forecasts and images of clouds to forecast power outputs for periods ranging from 15 minutes to a month in advance. The technology has helped integrate more renewable energy into the grid through a reduction in wind power curtailment of 10%. This additional energy can power approximately 14 000 homes (NREL, 2013).

Impact on cost savings:

- **USD 60 million in savings between 2009 and 2016 for an investment of USD 3.8 million that improved forecasted wind generation by 37.1% in Colorado, US.**

Colorado utility Xcel Energy calculated that a 37.1% improvement in wind generation forecasting saved the utility's customers USD 60 million between 2009 and 2016. The forecast was made based on surface-level measurements when the average wind turbine hub could be 80-100 metres above the ground. Also, some measuring stations were around 50 km away from the turbines. The improvement in forecasting was achieved by deploying a state-of-the-art wind forecasting system that was specific to each farm and that provided hub-height speeds and was updated every 15 minutes. Its wind production displaces approximately 11.7 million tonnes of carbon dioxide emissions annually (Baskin, 2016; RAL, 2014).

- **Between around USD 5 million and USD 146 million in annual cost savings (capacity reserve, frequency regulation reserve and production cost savings) for improved short-term wind forecasting in California.**

A study done for the California Independent System Operator (CAISO) shows that improved short-term wind forecasting in the CAISO market can result in annual total cost savings (capacity reserve, frequency regulation reserve and production cost savings) of approximately USD 5 million to USD 146 million considering various scenarios (NREL, 2015b). In a low-wind scenario, a total of 7 299 MW of available wind capacity is expected, and in a high-wind scenario a total of 11 109 MW of available wind capacity is expected. The time-based variability in the wind speed determines the instantaneous penetration level and the degree to which the forecasting accuracy influences the actual dispatch of generation.

Wind scenario	Forecast improvement	Annual savings (USD millions)
Low	10%	5 050
High		25 100
Low	25%	14 800
High		62 900
Low	50%	34 700
High		146 000

Source: NREL, 2015

3

IMPLEMENTED SOLUTION

Germany is using advanced weather forecasting to reach its renewable energy target

● Since 2012 the Deutscher Wetterdienst (German Meteorological Service) has been working on optimising its weather forecasts for renewable energy applications within the two research projects EWeLiNE and ORKA, funded by the Federal Ministry for Economic Affairs and Energy (BMWi). Based on the findings of the ORKA project in December 2015, this successful co-operation was continued in a new project, ORKA2, implemented in January 2016. The working field has been expanded through prediction of the current-carrying capacity of power lines.

In the EWeLiNE project, the German Meteorological Service and the Fraunhofer Institute for Wind Energy and Energy System Technology are working with the three German transmission system operators: Amprion GmbH, TenneT TSO GmbH and 50 Hertz Transmission GmbH. Their goal is

to improve the weather and power forecasts for wind turbines and solar PV plants and to develop new forecast products focusing specifically on grid stability. EWeLiNE takes real-time data from solar panels and wind turbines around Germany and feeds it into an algorithm that uses machine learning to calculate the renewable energy output for the next 48 hours. Researchers then compare the real data with EWeLiNE predictions to refine the algorithm and improve its accuracy.

PerduS, another research project funded by the BMWI, was launched in March 2016. It focuses on Saharan dust outbreaks and on improving weather and PV power forecasts during such weather situations, thereby supporting the incorporation of an increasing share of renewable energy into the German power mix (DWD, 2018). For example, on 5 April 2014, a large day-ahead Germany-wide PV power forecast error, on the order of 10 GW, occurred. During this and preceding days, Saharan dust was transported to Germany.

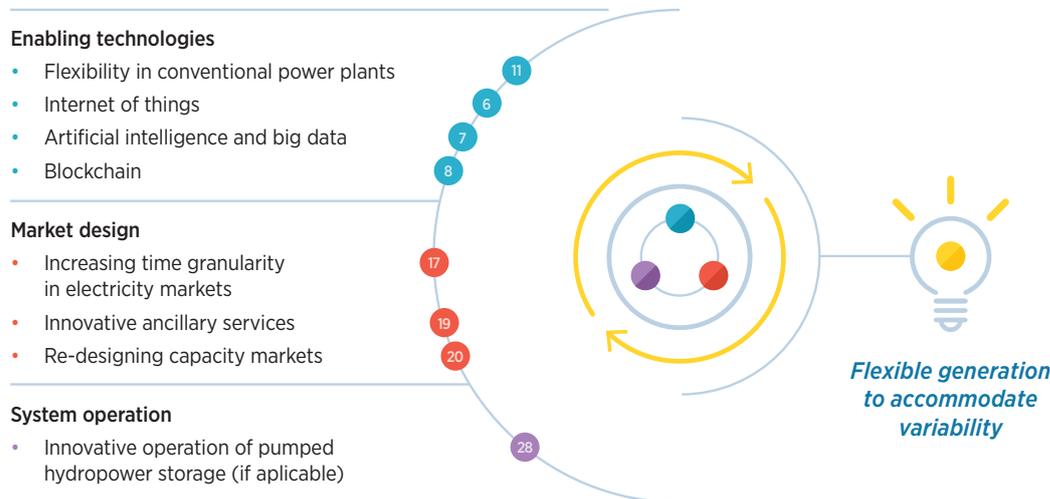
SUMMARY TABLE: BENEFITS AND COSTS OF DECREASING VRE UNCERTAINTY THROUGH ADVANCED WEATHER FORECASTING

Decreasing VRE generation uncertainty with advanced weather forecasting	Low	Moderate	High	Very high
BENEFIT				
Potential increase in system flexibility				
Flexibility needs addressed	from minutes to weeks			
COST and COMPLEXITY				
Technology and infrastructure costs				
Required changes in the regulation framework				
	regulation can incentivise this solution, e.g., providing VRE balance responsibility would improve their forecast			
Required changes in the role of actors				
Other challenges	• availability of historical weather data for small players			

SOLUTION II

Flexible generation to accommodate variability

Figure 18 Synergies between innovations for increased flexible generation



● **At the operation level**, supply-side resources that are quick ramping and that have short time activation and short reaction time can add great flexibility to the grid. Typically, hydropower and gas-fired plants offer such fast ramping and fast reaction times. Hydro plants have the capability to react instantaneously, at zero costs. However, for gas-fired plants, the flexibility cost increases with the steepness and the length of the ramp, and they are greatly exposed to gas fuel costs, particularly for markets reliant on imported liquefied natural gas (LNG). Pumped hydro storage plants can provide a great degree of flexibility in terms of both supply (firm electricity as needed) and demand (pumping to refill reservoirs in times of excess supply). *(Key innovation: Innovative operation of pumped hydropower storage)*

● **On the technology side**, with technical enhancements, the normally inflexible generating technologies also can contribute to system flexibility (Jacobs *et al.*, 2016). At the power plant level, operational flexibility is characterised by three main features: the overall bandwidth of the operation (turndown ratio, ranging between minimum and maximum load); the speed at which

the net power feed-in can be adjusted (ramp rate); and the time required to attain a stable operation when starting from a standstill (start-up time) (Agora Energiewende, 2017). Research has shown that coal power plants, although traditionally believed to be relatively inflexible, can in fact provide flexible output, supported by the necessary technical and operational upgrades (Cochran *et al.*, 2013) and if the owner is incentivised or forced to run at a capacity utilisation rate average that is well below the optimal design rate of 70-85%. Both India and Australia are examining retrofits to existing fleets to accommodate lower utilisation rates and more flexible ramping management. *(Key innovation: Flexibility in conventional power plants)*

● **Regarding market design**, encouraging power plants to operate as balancing loads, rather than as base loads, will require new revenue streams that compensate operators for making these changes and incurring extra costs in plant operation. For example, the transition of a coal power plant from base load to balancing load implies that operators will likely have to invest in new equipment, while facing lower annual capacity factors and more

frequent forced outages. Innovative market regulations need to be designed in order to adequately remunerate and incentivise operators to run such plants for balancing, while also maintaining profits.

A way to achieve this is through increasing the time granularity in wholesale energy markets. This better reflects the conditions at a particular time and remunerates efficient response from the existing generators. Trading products or contracts with shorter intervals, as well as trading as close as possible to real time, helps to internalise in the price the value of flexibility, thus creating value for the flexible sources that are capable of responding in near-real time by ramping up or down easily. The more reflective the prices are of the short-term demand-and-supply conditions, the better are the price signals sent to the generators that can quickly alter their output when needed by the system. Increases in the shares of wind and solar generation will increase the volumes of intraday trading necessities and the need to adjust production schedules to the most recently updated forecast. This requires the market time frame (both the settlement period and gate closures) to adapt to fully exploit the potential of renewable energy sources and the flexible behaviour of other existing generators in the system, to counteract the VRE generation.

On the day of delivery, where intraday markets are in place, participants must submit their bids for supply and demand for any given trading interval, also called the settlement period. Market participants can trade up to a certain point before the settlement period, called the gate closure. One of the examples with a low time granularity is Germany where the gate closure is between 5 and 30 minutes before the start of the physical delivery for a 15-minute settlement period (EPEX SPOT, 2019), while in England the gate closure is 16 to 19 minutes before the 30-minute settlement period (IEEFA, 2018). A narrower gate closure would reduce forecasting errors for renewable generation and minimise the amount of costly reserve generation that must be contracted to respond to unpredicted variability. *(Key innovation: Increasing time granularity in electricity markets)*

In real time, system operators use primary, secondary or tertiary reserves to handle the real-time deviation in forecasted demand and supply. Such ancillary service products need to be adapted to increase the system's flexibility, incentivise fast response and ramping ability, and remunerate each of the services accordingly. For instance, PJM Interconnection, a transmission system operator in the US, has developed different frequency regulation products for the slower conventional resources and the faster battery storage resources. Also, opening the market to all new actors, including small players and distributed energy resources, and making all actors responsible for balancing the system could improve the system flexibility. Marginal pricing of balancing energy and the removal of price caps will allow prices to reflect the real value of electricity. This also will provide the correct incentives to invest in flexibility and to offer balancing energy and reserve services. *(Key innovation: Innovative ancillary services)*

Through capacity market mechanisms, sufficient reliable firm capacity can be assured if 1) such capacity mechanisms are designed in a way to allow the equal participation of all flexibility service providers, such as demand-side response, interconnectors and storage operators, and 2) such mechanisms are designed as a response to real identified adequacy concerns. However, for a future system with a high share of VRE, flexibility in the system is required due to the variability introduced by these renewable sources. By introducing flexibility requirements in capacity market products, investments in power plants can be incentivised. *(Key innovation: Redesigning capacity markets)*

- A system where energy is traded more quickly, closer to real time and in shorter increments, is more difficult to manage and requires a greater degree of automation. **Enabling technologies**, such as digital systems, can monitor remote generators and automatically send simple instructions and corrections to the operators. Data reporting from generators and power exchanges can inform grid operators' expectations and allow them to make better decisions on energy and service procurement. ICT developments and advanced control centres will unlock opportunities

and have the potential to change the way that energy systems are operated, providing greater flexibility to the system.

Until recently it was costly to put in enough sensors, transmit high-frequency data, store the large volume of data, perform smart analytics of the data and tune the process for optimal performance. These constraints are being

overcome as digital technologies unleash a “full digitalisation” of the process. It makes the grid intelligent and flexible, giving it the capability to manage variability and uncertainty. On the operations end, the Internet of Things can increase the generation flexibility by lowering the minimum capacity factor and increasing the ramp rate. *(Key innovations: Artificial intelligence and big data; Internet of Things)*



Impact of increased time granularity in the wholesale markets:

- **Integration costs in the US are lower with faster dispatch: USD 0/MWh to USD 4.40/MWh in areas with five-minute dispatch, compared to USD 7/MWh to USD 8/MWh in areas with hourly dispatch.**

Five-minute dispatch is currently the norm for independent system operators throughout the US, serving more than two-thirds of the national load. With faster dispatch, load and generation levels can be more closely matched, reducing the need for more expensive regulating reserves. Five-minute scheduling was adopted not to enable renewable generation integration, but because it reduces power system operating costs. Five-minute scheduling has helped reduce regulation requirements to below 1% of peak daily load. Integration costs prove to be lower in areas with faster dispatch. For example, integration costs have ranged from USD 0/MWh to USD 4.40/MWh in areas with five-minute dispatch, compared to USD 7/MWh to USD 8/MWh in areas with hourly dispatch (WGA, 2012).

- **An additional 15-minute intraday call auction increased the efficiency of the German electricity intraday market and helps set a clear price signal; refurbishments of coal power plants helped to increase flexibility and increase renewable generation share.**

In December 2014 EPEX launched an additional 15-minute intraday call auction at 3 p.m. on the day before (D-1). This helped optimise the constraints due to the hourly product in the day-ahead and intraday markets. This is a uniform price auction for the 96 quarters for the following day. It has increased the efficiency of the German electricity intraday market and helps set a clear price signal. The variation of the price also has decreased since the implementation of the 15-minute intraday call auction (EPEX SPOT, n.d.). Hard coal power plants are adjusting their output on a 15-minute basis to participate in the intraday market. Upgrades at Weisweiler power plant reduced minimum load by 170 MW and 110 MW at two generation units and increased the ramp rate by 10 MW/minute. Retrofits of the Bexbach power plant reduced the minimum load from 170 MW to 90 MW. These retrofits, and operating the plants flexibly, increases operation and maintenance costs. However, these increases are small compared to the fuel savings associated with higher shares of renewable generation in the system (Agora Energiewende, 2017).

- **The need for balancing power is reduced by several hundred GWh a year when the gate closure is reduced from 75 minutes to 15 minutes before delivery.**

For instance, RWE’s transmission system operator Amprion in Germany revealed in documentation provided to the energy regulator that if the 75-minute period could be reduced to just 15 minutes before delivery, the need for balancing power in its zone alone could be reduced by several hundred GWh a year.



USD 262 MILLION SAVINGS by introducing a new ancillary service product



70% Procurement COSTS SAVINGS for TSOs



200% INCREASE in VRE due to new players providing ancillary services

Impact of innovations in the ancillary service market:

- **National Grid, the transmission system operator in the UK, could save USD 262 million by introducing a new ancillary service product.**

Grid operators have to deal with increasing volatility due to a growing share of wind and solar power. The deployment of the sub-second Enhanced Frequency Response by National Grid in the UK is expected to provide National Grid with greater control over frequency deviations, resulting in potential cost savings of GBP 200 million (USD 262 million) (KPMG, 2016).

- **Allowing renewable energy generators, battery storage systems and industrial loads to provide ancillary services could lead to 70% procurement costs savings for transmission system operators and to a 200% increase in VRE installed capacity.**

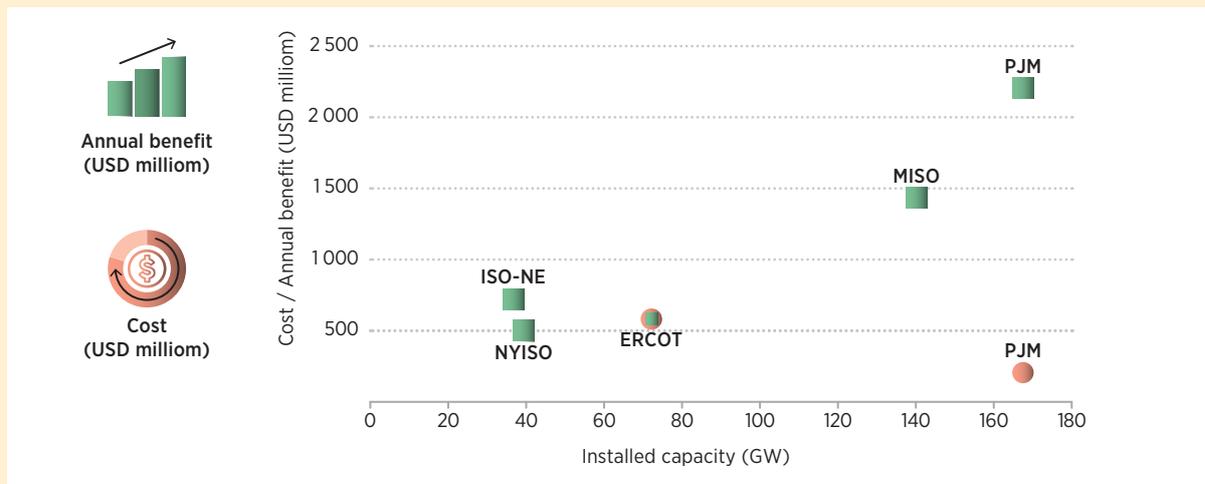
In Germany, alongside conventional generators, renewable energy generators, battery storage systems and industrial loads also were allowed to participate in the balancing markets in 2009. In the period from 2009 to 2015 the balancing market size (in GW) decreased by 20%, the ancillary service procurement costs for transmission system operators decreased by 70%, while in the same period the 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).

Impact of zonal or nodal prices:

- **Investment in transitioning to a nodal pricing system has been recovered within one year of operation by different independent system operators in the US.**

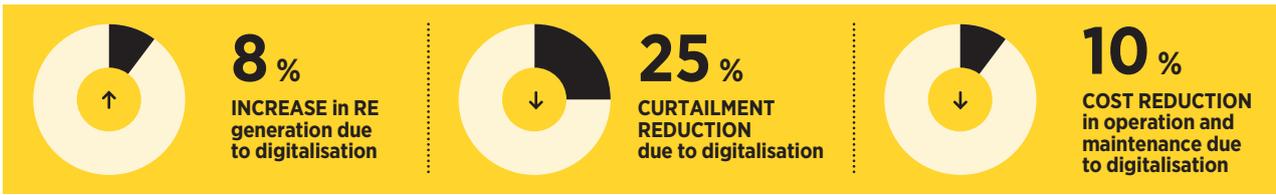
Nodal pricing system implemented in US resulted in better congestion management, improved grid reliability, increased retail access and competition, reduced transition costs, improved planning and better co-ordination with regulatory agencies (Eto *et al.*, 2005). Investment in transitioning to a nodal pricing system has been recovered within one year of operation by different independent system operators, as Figure 19 illustrates.

Figure 19. Costs and benefits of nodal pricing



ISO-NE = Independent System Operator – New England; NYISO = New York Independent System Operator; ERCOT = Electric Reliability Council of Texas; MISO = Midcontinent Independent System Operator; PJM = Pennsylvania – New Jersey – Maryland Interconnection.

Source: Neuhoff and Boyd, 2011.



Impact of digitalisation on the wholesale market:

- Digital system implementation and data analytics led to an 8% increase in renewable energy generation, a 25% reduction in curtailment and a 10% reduction in operation and maintenance costs.

General Electric estimates that by implementing digital systems and data analytics, renewable energy operation and maintenance costs can be reduced by 10%, production increased by 8% and curtailment cut by 25% (Neuhoff and Boyd, 2011).

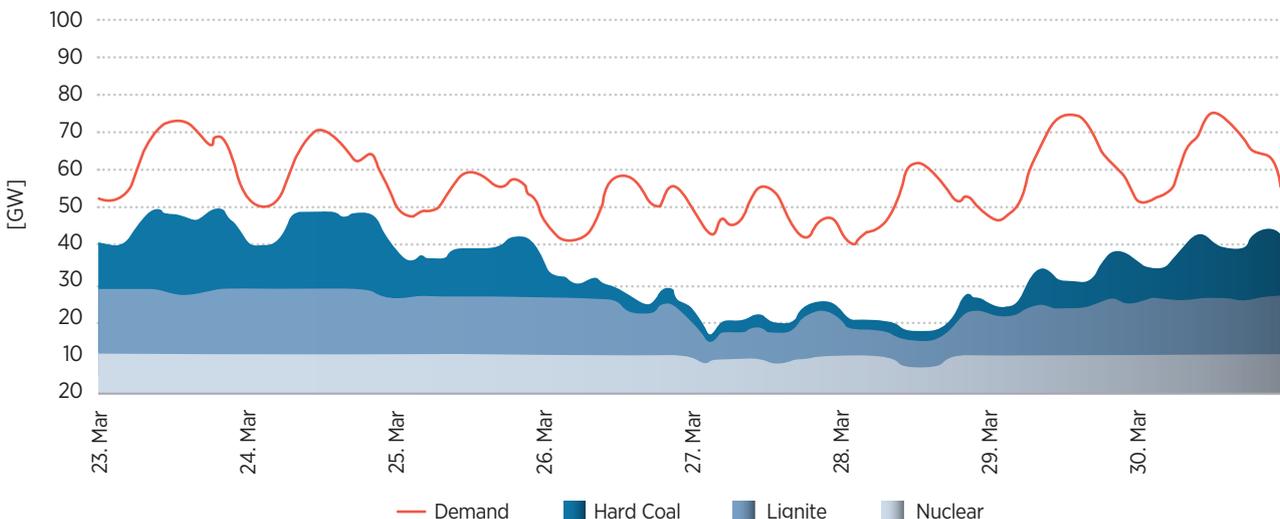
IMPLEMENTED SOLUTION

Increased flexibility of coal power plants and market design in Germany

• Operators of existing coal power plants can technically provide much more flexibility than is often believed. In countries such as Germany and Denmark, targeted retrofit measures have been implemented on existing power plants, greatly enhancing their technical flexibility. Furthermore, effective market incentives – including intraday electricity markets – have been introduced in order to remunerate the provisioning of flexibility. Such measures have enabled renewable generation to be integrated more easily and in an economically efficient way, thus limiting wasteful curtailment.

State-of-the-art hard coal power plants can operate at minimum load levels of 25% to 40% of the nominal load. State-of-the-art lignite power plants can achieve minimum loads of 35% to 50% of the nominal load. By contrast, power plants built 10 to 20 years ago in industrialised countries had minimum load levels of 40% (hard coal) to 60% (lignite). Retrofitting can reduce minimum loads even further. In Germany, for example, minimum load levels of 12% have been achieved (Agora Energiewende, 2017). Figure 20 illustrates how hard-coal-fired power plants, and to some extent lignite-fired power plants, are already providing significant operational flexibility in Germany, adjusting their output to the variation in renewable energy feed-in and demand.

Figure 20 Power generation from nuclear, hard coal and lignite power plants and demand in Germany, 23 to 30 March 2016



Source: Agora Energiewende, 2017.

3

Whether, and to what extent, flexibility retrofitting measures are profitable varies on a case-by-case basis in relation to the plant characteristics and the market environment (e.g., age of the plant, market share of renewables, general market design, remuneration options for flexibility). However, it has been seen that flexibility retrofitting is likely to be profitable in Germany when the market is properly designed to remunerate the flexibility. The introduction of short-term electricity markets and the adjustment of balancing power arrangements are important measures for remunerating flexibility. The introduction of a 15-minute-based intraday market incentivised the retrofits of coal plants.

In Germany, some power plant operators deliberately push flexibility, even though this reduces the plant's life. This relates in part to the shift in energy policy away from coal over the coming decades. It also explains the relatively higher flexibility of German power plants compared to other countries.

In systems with high shares of wind and solar PV, conventional plants must serve the load that is not covered by variable renewables – that is, the residual load curve. Therefore, the operation of these plants has to be significantly more flexible, and a proper market design should be adapted. The need for flexibility and the challenges faced by conventional power plants in Germany are illustrated in Figure 21.

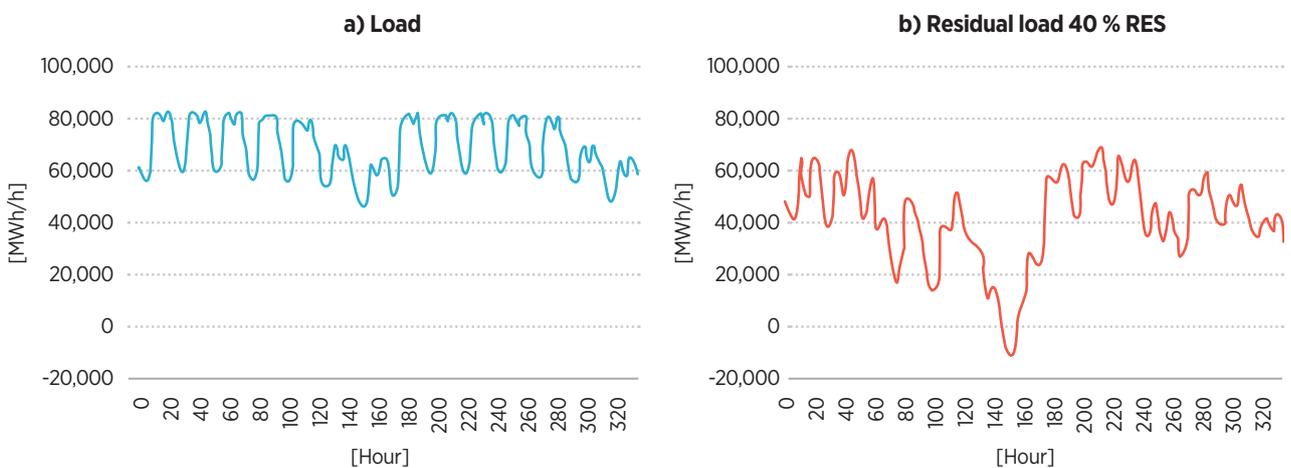
Market design and flexibility providers in Denmark

- In Denmark, the development of the electricity market is the foundation for the integration of VRE. It allows for better balancing of VRE over a large market area by incentivising the increase in thermal power plant flexibility, and through the establishment of dynamic and close-market coupling.

Denmark has been part of the Nordic power market since 2000. The Danish generation mix consists of wind and thermal sources, with the thermal power plant fleet almost exclusively comprising combined heat and power production. As the share of VRE increased, the role of CHP plants changed from being the main base load of the power system to becoming a key source of system flexibility.

The default ramping ability in a thermal power plant built to deliver a continuous amount of power is typically 1% of maximum power output per minute. Danish thermal power plants are built or retrofitted to ramp on average 4% per minute, in response to the demand for flexibility in the production fleet, expressed through power price fluctuations throughout the day. Improved ramping properties allow the plant to increase or decrease participation in the market more quickly and to follow the volatility in power prices. Similarly, the minimum load is as low as 15% in some Danish thermal power plants, whereas the

Figure 21 Flexibility requirements in Germany. Example load curves for two weeks during winter in Germany



Source: Agora Energiewende, 2017.

standard load, if the plant is not optimised, is 30% to 40% (Energinet, 2018).

A number of issues in the market design influence flexibility. Some of the most important characteristics of the Nordic market design are listed in Figure 22.

An advantage of a very low minimum load on thermal power plants is that they can participate in the day-ahead market with minimum load, say 20%, and then participate in the intraday and balancing markets with the remainder of the plant capacity. If there is a great demand for flexibility, the prices are likely to be higher in the intraday and the balancing markets. Therefore, plants with higher levels of flexibility will be able to minimise the production sold at low prices and maximise the production at high prices, yielding higher profits (Energinet, 2018).

Flexibility incentivised in California's power market

- California's independent system operator, CAISO, has proposed several changes in the power market to incentivise system flexibility due to large solar PV generation. One of the changes being proposed is in the day-ahead market, to change the granularity

from 1 hour to 15 minutes² (CAISO, 2018a). The reduction in scheduling intervals would allow power-generating resources to follow the load curve as forecasted by CAISO more closely. CAISO also may be able to reduce procurement from the real-time market, especially during morning and evening ramping times.

In November 2016 CAISO implemented a separate flexibility ramping product on the ancillary service market: Flexible Ramp Up and Flexible Ramp Down Uncertainty Awards, which are products to procure ramp-up and ramp-down capability for 15-minute and 5-minute time intervals through the ancillary service market. The product is procured in terms of megawatts of ramping required in a five-minute duration, and any resource capable of fulfilling the ramping requirement can participate. The price for providing ramp-up service is capped at USD 247/MWh, and the price for providing ramp-down service is capped at USD 152/MWh (CAISO, 2018b).

Following CAISO's successful implementation, the New York Independent System Operator (NYISO) also proposed a similar flexible ramping product as part of its 2018 Master Plan (Avallone, 2018).

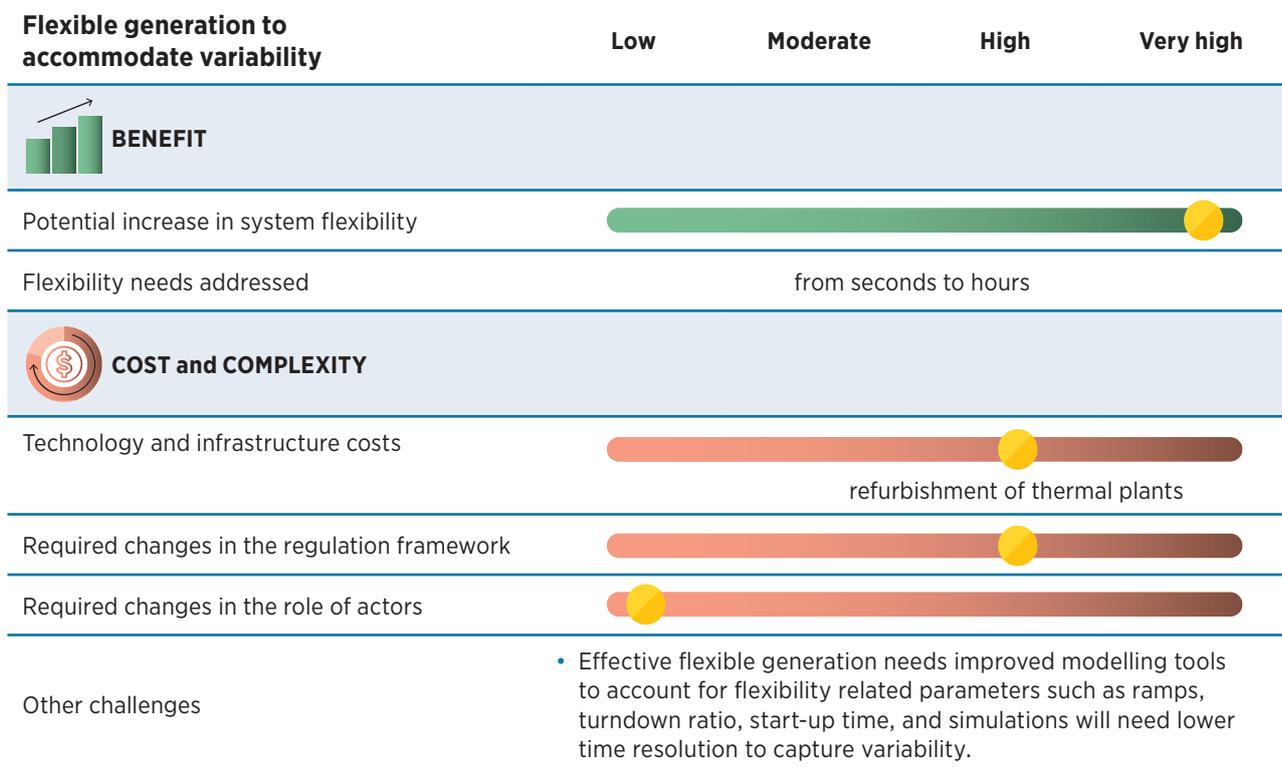
Figure 22. Key characteristics of the design of the Nordic market

	DAY-AHEAD	INTRADAY	BALANCING
Market type	Auction/Marginal pricing	Continuous bid matching	Prioritised bid activation/mix of marginal price and pay ad bid
Minimum product size	1 MW	1 MW	5 MW
Gate closure time	12-35 hours	60 minutes	45 minutes
Bid linking	Yes	No	No
Validity periods	60 minutes	60 minutes	60 minutes
Settlement of imbalances	1 hour (2-price model)		

Source: Energinet, 2018.

² Other changes proposed include combining Integrated Forward Market (IFM) and Residual Unit Commitment (RUC), and procurement of imbalance reserves that will have a must-offer obligation to submit economic bids for the real-time market.

SUMMARY TABLE: BENEFITS AND COSTS OF FLEXIBLE GENERATION TO ACCOMMODATE VARIABILITY



3.2 GRID FLEXIBILITY SOLUTIONS

The grid itself is a powerful flexibility provider when it is strong and well interconnected. Emerging innovative solutions that could further increase grid flexibility include:

- **Creating regional power markets that can help exploit the synergies** from renewable energy development across the region. Regional markets can help manage fluctuations in their electricity production by increasing the geographical scope and thus reducing the probability of a concurrent lack of renewable energy.
- **Building a high-voltage grid, or supergrid, to transport electricity to another region and to avoid renewable energy curtailment** in places that have the potential for large amounts of

surplus renewable generation in the system. The cost of building such a grid is high and must be measured against the economic benefits of both of the systems that the grid is linking.

- **Enabling the integration of a higher share of renewable energy generation while avoiding grid reinforcements**, through innovative solutions such as:
 - The use of battery storage.
 - The use of power-to-X solutions (e.g., power-to-hydrogen or power-to-heat) – that is, converting electricity to another energy carrier that can then be stored or transported. These are known as virtual power lines.
 - Using dynamic line rating to allow more VRE through the grid, when meteorological conditions allow.

SOLUTION III

Interconnections and regional markets as flexibility providers
Figure 23 Synergies between innovations for unlocking flexibility through interconnections and regional markets


Creating a regional market by taking advantage of the interconnections between power systems is a very effective way of increasing flexibility in power systems. Increased transmission capacity and interconnections allows electricity to be transported more readily within a balancing area, meaning that more of an area's resources can be used to help balance supply and demand. Consequently, operators in different systems can buy and sell electricity and other grid services from one other, creating regional markets (Aggarwal and Orvis, 2016).

● In terms of **market design**, creation of the regional electricity market will require harmonisation of the rules of all participating markets to allow electricity to flow freely in response to price signals. Truly integrated regional markets imply harmonised rules in the wholesale market, the ancillary service market and the capacity market across the region. In general, when a diverse portfolio of energy resources is balanced over a wide geographical area, fluctuations in the output tend to be localised, greatly minimising variability in the electric grid. Also, regional markets take advantage of the spatial complementarities among renewable energy sources. *(Key innovation: Regional markets)*

There are multiple ways to improve co-ordination among different systems, such as:

- **Reserve sharing**, whereby multiple balancing-area authorities maintain, allocate and supply the same set of operating reserves for each balancing area.
- **Co-ordinated scheduling**, in which balancing-area authorities exchange energy over shorter time scales (short-term dispatch on a 5-minute to 1-hour time scale). This increases dispatch efficiency by making available a larger array of resources for commitment. Co-ordinated scheduling requires increased communication and planning and the design of market mechanisms to compensate participants for energy production.
- **Consolidated operation**, or the merging of two or more balancing areas into one system operator. This combines all of the time scales of system operation including unit commitment (24 hour), short term dispatch (5 minutes to 1 hour) and reserves provision (Zaman, 2018). *(Key innovation: Increasing time granularity in electricity markets)*

Enabling technologies can help a regional market operator to handle orders from all participating countries in a transparent manner. With increasing penetration of VRE, increasing granularity of the power market in terms of time and space can help in integrating more VRE in the grid. As the granularity increases, the modelling of power markets becomes increasingly complex. Interlinking power markets in a particular region can lead to further complexity, as the market/system operator needs to ensure the participating country's energy security before power can flow through the interconnections. The number of bidders and contracts also will increase greatly once the power markets merge.

Robust IT systems are essential for the market operator to process the orders efficiently and seamlessly. Digital innovations such as the Internet of Things, artificial intelligence and big data can play an important role in managing that complexity. Blockchain technology, as an interoperable layer of technology that allow different parts of the system to communicate at a lower cost, might facilitate transactions and payments in a large regional market, with many actors involved. *(Key innovations: Internet of Things; Artificial intelligence and big data; Blockchain)*



**MORE THAN
700 000 GWh**
 Avoided
 curtailment
 (2014-2018)



49 %
 WIND GENERATION
 in Denmark due to
 interconnections



50 %
 CURTAILMENT
 REDUCTION due
 to interconnection

Impact on VRE integration:

- 715 405 GWh of avoided curtailed renewable energy in four years due to the regional market, meaning 0.5% of total VRE generation in California, US.**

The Western Energy Imbalance Market helped avoid curtailment of 715 405 GWh of renewable energy from 2014 to mid-2018, avoiding emissions of 306 112 tonnes of carbon dioxide-equivalent (CAISO, 2018).

- 49% wind power integrated into Denmark's power system due to interconnections.**

Significant interconnection with neighbouring countries (Germany, Sweden and Norway) allows Denmark to integrate around 49% wind power without major curtailment. Between 2008 and 2015 wind power generation was curtailed only twice (by 200 MW to 300 MW for 6 to 8 hours, in 2008 and in 2010) due to outage in one of the interconnectors (DEA, 2015). The excess wind power is used or stored as pumped hydropower storage by neighbouring countries (IEEFA, 2018).

- 50% reduction in power curtailment in Ireland due to interconnection with the UK.**

Export of power from Ireland to the UK (via two sub-sea interconnections) helped reduce power curtailment by an estimated 50% in 2013. Ireland has limited cross-border interconnection equivalent to just 7% of its total installed generation, which is below the target for all EU Member States of 10% by 2020 (IEEFA, 2018).

- Regional markets unlock synergies among renewable energy generation in Europe.**

Better use of current interconnections and the deployment of new ones provides various advantages such as increased flexibility of the European system by exploiting access to hydro reserves in Norway, and by predictable solar power generation in countries like Italy, Spain and Greece (Neuhoff and Boyd, 2011).



Impact of interconnections and regional markets on operation costs:

- **Annual savings of EUR 260 million due to increased co-operation among transmission system operators in Germany.**

The German regulatory agency’s instruction to increase co-operation among transmission system operators and to collectively procure various types of balancing power from generation companies is expected to save around EUR 260 million per year (Knight, 2010). Annual re-dispatch, due to congestion, costs of EUR 138.2 million in Germany. Co-ordinating the use of transmission capacities renders annual costs of EUR 56.4 million, resulting in considerable savings on re-dispatch (DIW, 2013).

- **Annual savings of USD 5 billion to USD 8 billion due to regional trade in the Western African Power Pool.**

The World Bank estimated that the economic benefit of regional trade in the Western African Power Pool would be around USD 5 billion to USD 8 billion per year due to the reduced cost of operations while making power generation more sustainable, displacing baseload oil-fired power generation with cleaner sources of electricity such as natural gas, solar and hydropower (World Bank, 2018).

- **Economic benefit of EUR 40 billion per year by 2030 from integrating the European market** in a high renewable energy scenario (Neuhoff and Boyd, 2011).
- **Savings of USD 72 million to USD 208 million per year for trading balancing services between regions in the US.**

Special markets are developing in the US to trade grid balancing services between regions that to date have been operated independently from one another. Without needing to build new transmission capacity, but just simply by allowing trade between regions, is expected to save customers USD 72 million to USD 208 million per year (Aggarwal and Orvis, 2016).



IMPLEMENTED SOLUTION

Southern African Power Pool (SAPP)

● The Southern African Power Pool (SAPP) was created in August 1995 to promote regional co-operation and co-ordination in the planning and operation of the electricity business (Beta, 2016). Currently the SAPP includes 12 Southern African Development Community (SADC) countries³. The pool has a total installed generation capacity of 62 GW, planned generation capacity (2015-19) of 23.6 GW and a peak demand of 55 GW. Primarily, the SAPP uses the cheapest source of power generation in the region to meet demand.

An assessment done by IRENA on the SAPP concluded that by 2030 the share of renewable energy can increase from 10% to 46%. This would mean that around 80% of the new capacity addition from 2010 to 2030 would be related to renewable energy technologies. The financial investment required in enhancing the interconnections would be minimal (only 0.2% of total investment required) compared to the resulting benefits of international power trade. One of the largest clean energy power generation projects in the region is the Grand Inga project in the Democratic Republic of the Congo. This 40 000 MW hydropower project can be economically viable only if the inter-country transmission capacity is enhanced.

Western Energy Imbalance⁴ Market (EIM), US

● In November 2014 CAISO and PacifiCorp launched the western Energy Imbalance Market (EIM) (PacifiCorp, 2018). Currently the EIM has eight active members⁵, and four new members⁶ are to join by 2020. The western EIM was aimed at balancing the power demand for every five minutes with the lowest-cost energy available across the

combined grid. It leverages the flexible back-up resources and the demand across the combined grid. Apart from reducing the cost of power⁷, the western EIM also improves the grid integration of renewable energy (EIM, 2018). The EIM has helped to avoid the curtailment of 715 405 GWh since its inception (up to the first two quarters of 2018), avoiding 306 112 tonnes of carbon dioxide-equivalent emissions (CAISO, 2018c).

XBID Project in Europe

● The transmission system operators of 11 countries, along with the power exchanges EPEX SPOT, GME, Nord Pool and OMIE, started a joint initiative – single intraday coupling (known under its commercial name as the XBID project) – within the framework of European Commission Regulation 2015/1222 of 24 July 2015 establishing a guideline on capacity allocation and congestion management (CACM Guideline). The XBID project is aimed at creating a joint, integrated intraday cross-border market. The project went live in June 2018 with 14 countries⁸. It is expected to increase liquidity in the intraday markets, especially for newly joined markets, as bids/orders that were not met in local markets can now be matched with the larger integrated market.

This project also is expected to increase market efficiency since the capacity allocation and energy matching process are being done at the same time implicitly. The increased market liquidity and efficiency are expected to better facilitate the market integration of renewable energy with the grid. Also, since more resources are available in the integrated market, the need for power reserves is expected to decrease, leading to a decreased cost of power (Nord Pool, 2018). The remaining countries in the EU and in Southeast Europe are expected to join in the coming years.

3 Angola, Botswana, the Democratic Republic of the Congo, Eswatini, Lesotho, Malawi, Mozambique, Namibia, South Africa, United Republic of Tanzania, Zambia and Zimbabwe.

4 The “imbalance market” in the US is called the “balanced market” elsewhere.

5 Idaho Power Company, Powerex, Portland General Electric, Puget Sound, Arizona Public Service, NV Energy, PacifiCorp and CAISO.

6 Balancing Authority of Northern California/SMUD, Los Angeles Department of Power & Water, Salt River Project, Seattle City Light.

7 The western EIM has helped save USD 401 million in power costs from its inception to the second quarter of 2018 (CAISO, 2018c).

8 Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Latvia, Lithuania, Norway, the Netherlands, Portugal, Spain and Sweden.

SUMMARY TABLE: BENEFITS AND COSTS OF INTERCONNECTIONS AND REGIONAL MARKETS AS FLEXIBILITY PROVIDERS

Interconnections and regional markets as flexibility providers	Low	Moderate	High	Very high
BENEFIT				
Potential increase in system flexibility				
Flexibility needs addressed	from seconds to days (with a big enough region, regional markets can deliver flexibility over longer time frames)			
COST and COMPLEXITY				
Technology and infrastructure costs				
Required changes in the regulation framework	if interconnections are not in place			
Required changes in the role of actors	to partially integrate markets		to fully integrate markets	
Other challenges	<ul style="list-style-type: none"> Political and regulatory challenges Regional mindset and trust, strong institutional arrangements and governance model 			



3

SOLUTION IV

Matching renewable power generation and demand over large distances with supergrids

Figure 24 Synergies between innovations for matching renewable energy generation and demand using supergrids



● As an **enabling infrastructure**, a supergrid is a large transmission network that makes it possible to trade high volumes of electricity across great distances. Supergrids are high-voltage direct current (HVDC) power lines (greater than or equal to 500 kV) or ultra-high-voltage direct current (UHV DC) power lines (greater than or equal to 800 kV). DC technology is preferred for developing supergrids because the transmission of power over large distances using AC technology is challenging, as AC systems require reactive power support and also have 30% to 40% higher line losses than DC technology (Siemens, 2018). Supergrid networks are typically built independent of the conventional AC grid and can interact with the existing AC grid at a few or multiple nodes.

Resource-rich areas, such as geographies with high irradiation and/or wind speed, may not necessarily be in close proximity to major demand centres such as cities or industrial hubs. Supergrids are one of the solutions being explored for transporting large volumes of electricity over long distances, from resource-rich locations to demand centres. For instance, wind energy potential is much higher

at offshore sites than at onshore sites (Cuffari, 2018). Geographies with high solar irradiation such as those in the African desert may be optimal for deploying solar PV generation, but may not have a high local energy demand.

AC grids prevail because DC lines so far can be used only for point-to-point transmission and do not easily form the integrated grid networks that exist today. Research and development by equipment manufacturers has been intense over the past few years for DC breakers, and products have become available that would make a meshed DC grid feasible. The EU-Project PROMOTioN seeks to address challenges to the development of meshed HVDC offshore transmission grids (PROMOTioN, 2018).

The longer the distance and the higher the power to be transmitted, the more HVDC can be economically beneficial. DC grids are potentially more efficient at connecting sources of renewable energy with demand areas located at great distance, making it possible to average out local variations in wind and solar power while bringing power to areas without much sunshine or wind.

Solar power from the Sahara could power cloudy Germany, and wind power from all over Europe could keep the lights on at night. This would enable the integration of renewable power on a bulk scale. *(Key innovation: Supergrids)*

The Internet of Things, artificial intelligence and big data can support the operation of such grids. *(Key innovations: Internet of Things; Artificial intelligence and big data)*

● Regarding **market design**, because supergrids usually enable the trading of electricity between different power systems, the harmonisation of trading rules and the creation of some type of regional market is needed. *(Key innovation: Regional markets)*



Impact on renewable energy integration:

- **576 MW of offshore clean energy integrated in the German power system through an HVDC line.**

As a part of the German Energiewende, the HVDC HelWin1 was built to integrate offshore wind power with the German grid. It is a 130-kilometre-long, 250 kV HVDC transmission line owned and operated by TenneT to transmit power from Nordsee Ost and Meerwind Süd / Ost wind parks. It can transmit up to 576 MW of clean energy to more than 700 000 consumers (Offshorewind.biz, 2015).

- **Increased use of renewable energy and greater system reliability by connecting the UK and Denmark.**

Viking Link is a proposed offshore and onshore 1400 MW HVDC link between the UK and Denmark, including submarine and underground cables. The 770-kilometre-long transmission line is expected to enable effective use of renewable energy and increase security of energy supply for both countries. Denmark is aiming for half of the electricity it uses to come from wind power by 2020 (Viking Link, 2018).

Being able to balance wind production and demand across countries and closer integration between electricity systems are vital for the efficient transition towards a green energy future. The project is expected to be operational by 2022 (Viking Link, 2018).



3

IMPLEMENTED SOLUTION

North Sea Wind Power Hub consortium

● The North Sea Wind Power Hub is a proposed energy island complex to be built in the middle of the North Sea as part of a European system for sustainable electricity. The deployment estimates range from 70 GW to 150 GW of offshore wind in the North Sea in 2040 (NSWPH, 2018). A Power Link Island will be able to accommodate a large number of links to wind turbines and/or offshore wind farms and facilitate the distribution and transmission of wind-generated electricity via DC connections to the North Sea countries (the Netherlands, Belgium, the UK, Norway, Germany and Denmark). These connections – so-called Wind Connectors – will not only transmit wind power from the wind farms to the hub/island, but simultaneously serve as interconnectors between the energy markets of these countries, enabling them to trade electricity across their borders (TenneT, 2017a).

A consortium of transmission system operators is responsible for the initiative: TenneT Netherlands, TenneT Germany and Energinet from Denmark. In September 2017 the Dutch gas transmission system operator Gasunie joined the initiative with its interest in the power-to-hydrogen economy: wind power also can be converted to sustainable hydrogen for large-scale transport to shore or for storage or buffering purposes (TenneT, 2017a).

Raigarh-Pugalur 800 kV UHV DC project in India

● The Powergrid Corporation of India Limited (PGCIL), a transmission network operator in India, has teamed up with ABB to build an 800 kV UHV DC network from Raipur in central India to Pugalur in southern India. Once constructed, this transmission line will be among the world’s longest, at 1830 kilometres. Serving about 80 million people, the project will transmit wind power from southern India to the demand centres in the north during periods of excess wind generation, and will transmit thermal power from the north to the south when wind generation is low (ABB, 2017).

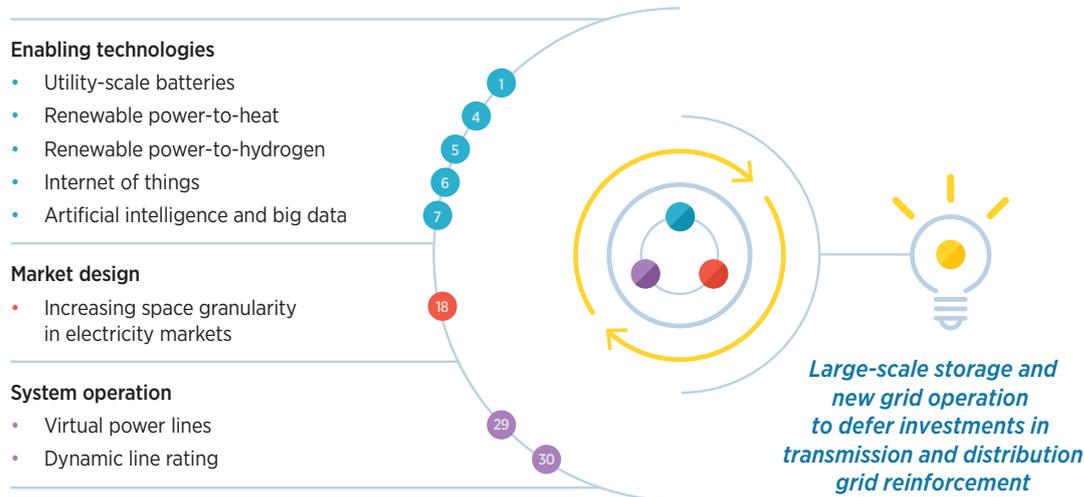
SUMMARY TABLE: BENEFITS AND COSTS OF MATCHING RENEWABLE ENERGY GENERATION AND DEMAND OVER LARGE DISTANCES WITH SUPERGRIDS

Matching renewable energy generation and demand over large distances with supergrids	Low	Moderate	High	Very high
BENEFIT				
Potential increase in system flexibility	[Progress bar from Low to High]			
Flexibility needs addressed	from seconds to weeks (not as exclusive solution but as a valuable contribution)			
COST and COMPLEXITY				
Technology and infrastructure costs	[Progress bar from Low to High]			
Required changes in the regulation framework	agreed regulatory frameworks between the connected regions			
Required changes in the role of actors	[Progress bar from Moderate to High]			
Other challenges	<ul style="list-style-type: none"> International, political needed, regarding ownership, rights, revenue allocation, etc. 			

SOLUTION V

Large-scale storage and new grid operation to defer grid reinforcements investments

Figure 25 Synergies between innovations for investments in transmission grid reinforcement



● Increased deployment of VRE may result in network congestions at both the distribution and the transmission level. **In terms of market design**, zonal or nodal prices would help reflect the network constraints and provide better operational and investment signals. *(Key innovation: Increasing space granularity in electricity markets)*

● Interconnections and grid reinforcements are key enablers for integrating a high share of VRE generation. However, these may require substantial investments, and most of the time the entire grid capacity might not be fully used. Therefore, innovative solutions emerge from **system operation** to increase VRE integration while deferring grid investments:

● One solution involves using **enabling technologies** such as 1) utility-scale battery storage or 2) power-to-hydrogen or power-to-heat solutions. Operating these technologies in a certain way can make them serve as virtual power lines.

Another solution involves 3) dynamic line rating, which implies allowing higher “dynamic” current, meaning allowing more VRE through the grid when actual atmospheric conditions offer better cooling (e.g., cables and lines can be utilised to

maximum capacity without risk of overheating). The meteorological variables that influence the thermal state of the conductor are: the speed and direction of wind, the ambient and the solar radiation.

Solution 1: Utility-scale battery storage systems

Utility-scale storage systems can be deployed at different points in the distribution and transmission network to store excess power during non-peak hours. These systems can then be discharged to meet load requirements in the local area during peak hours, without the need for transporting electricity through congested grid lines. This reduces network congestion and forms virtual power lines. In this case, instead of being merchant assets, batteries are network assets owned by the grid operator and used exclusively for managing the grid. For instance, Terna, a transmission system operator in Italy, has planned a pilot battery storage project of 35 MW on part of its 150 kV grid in southern Italy, for grid congestion management (Terna, n.d.). RTE, the French transmission system operator, is carrying out a similar project called Ringo. *(Key innovations: Virtual power lines; Utility-scale batteries)*

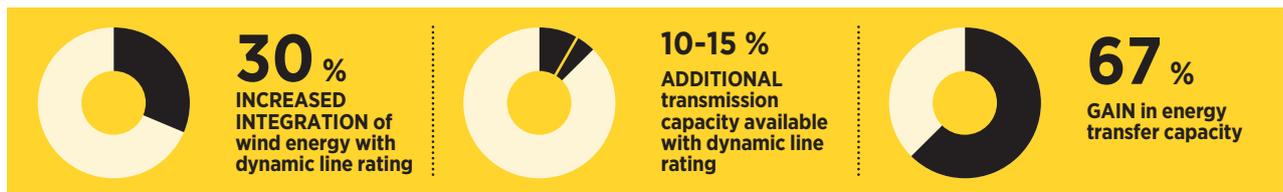
3

Solution 2: Power-to-hydrogen or power-to-heat

Some of the best wind resources are located in offshore or rural areas. Wind energy can be converted into hydrogen, which can be liquefied and transported to regions with energy deficits or demand centres. This facilitates wind power development without requiring large investments in new transmission capacity, although the costs and energy losses of electrolyzers are still very high. Similarly, the renewable power can be converted to heat in order de-congestion the grid and avoid investments in network infrastructure. *(Key innovations: Virtual power lines; Renewable power-to-hydrogen; Renewable Power-to-heat)*

Solution 3: Dynamic line rating

Power lines can carry only a specific amount of current at any given temperature. If more current is allowed through, this can lead to overheating of the cables. The amount of electric current that a transmission or distribution line can safely carry without overheating is often expressed in terms of static ratings, which system operators use to calculate the line capacity. However, these static ratings ignore the effect of cooling of power lines by weather conditions (the speed and direction of wind, the ambient and the solar radiation), especially in windy areas where wind energy plants are also installed. In such areas where lines are co-located with wind energy plants, weather monitoring equipment can be used to estimate the power line temperature and the resultant increase in current-carrying capacity. *(Key innovation: Dynamic line rating)*



Impact on renewable energy integration:

- In the UK, E.ON Central Networks has applied dynamic line rating systems, and estimates increased integration of wind energy into the grid by 30% (Fernandez *et al.*, 2016).
- The TWENTIES project – involving various stakeholders such as European transmission system operators, generation companies, power technology and wind equipment manufacturers, etc. – concluded that dynamic line rating forecasts lead to an average increase in transmission capacity of 10% to 15% (Alen Pavlinić, 2017).

Impact on operational costs:

- A study by Durham University, ScottishPower Energy Networks, Imass, PB Power and AREVA T&D concluded that the adoption of dynamic line rating can provide a 67% gain in energy transfer capacity at 62% of the re-tensioning cost (Roberts *et al.*, 2008).



IMPLEMENTED SOLUTION

Solution 1: RINGO Project – virtual power line in France

● The virtual power line designed by the French utility RTE, called the Ringo Project, will come into service in 2020 for a test period of three years. The project will use energy storage systems to relieve congestion instead of constructing extra power lines. The concept relies on artificial intelligence solutions to aid the dispatching process and to optimise the management of the electricity current in the grid.

Because the grid operator cannot disrupt the market by injecting electricity into the grid, a simultaneous battery storage and retrieval system has been designed to operate at three locations in the network. These battery storage systems will be placed where the lines are congested and will absorb large amounts of VRE resources. The battery capacity at each site will be 12 MW/24 MWh.

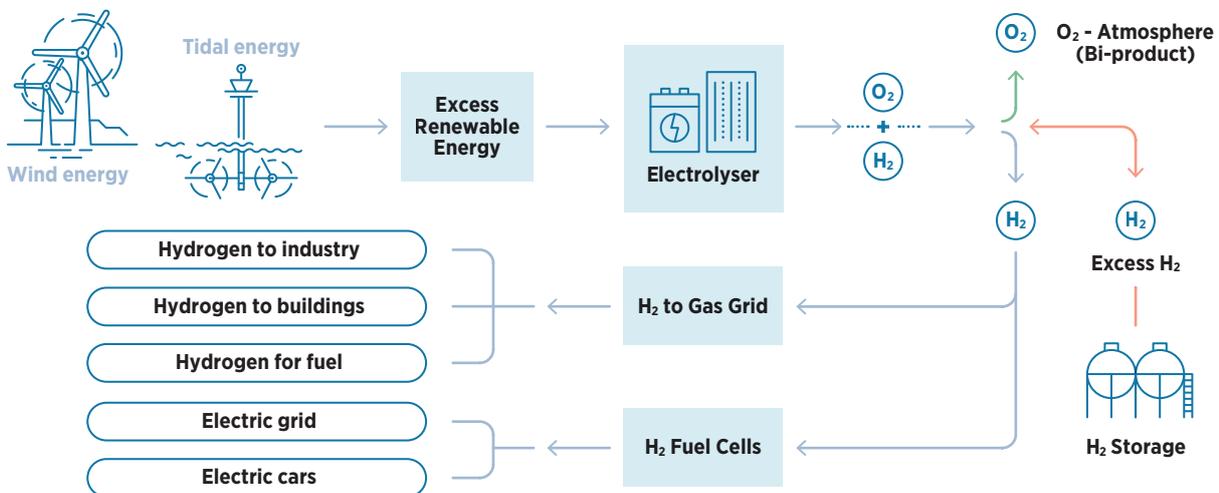
The project envisions that from 2020 to 2023 the batteries will be operated solely by RTE as virtual power lines. Starting in 2023 they will be open for use by third parties for potentially multiple uses such as frequency regulation, demand and supply adjustment, congestion resolution and energy arbitrage, among others.

Solution 2: Surf ‘n’ Turf Initiative – Orkney, UK

● The Surf ‘n’ Turf initiative uses the power generated from the tidal and wind energy produced at the island of Eday, Orkney. Eday is home to 150 people who collectively own a 900 kW wind turbine that was vulnerable to curtailment for various reasons, including lack of network infrastructure. Now the Surf ‘n’ Turf initiative converts excess wind and tidal energy to produce hydrogen via a 500 kW electrolyser in Eday. In Kirkwall (Orkney’s capital) systems are being developed to make use of the hydrogen produced, which is transported from Eday via ships (Surf ‘n’ Turf Initiative, 2018). The hydrogen can be used either during emergencies in industries and households, or during lean seasons when renewable energy generation is low. Figure 26 shows the schematic structure of the initiative.

Later, another 1 MW electrolyser was added in the island of Shapinsay, which also transported hydrogen to Kirkwall. Based on this, the BIG HIT project is being initiated which is expected to demonstrate that the Orkney Islands of Scotland have a replicable model and that hydrogen can be used as a flexible local medium for energy storage. Hydrogen is used for multiple purposes that include producing auxiliary power, heat for ferries in the Kirkwall harbour, fuelling a fleet of hydrogen range-extended light vehicles and heating of buildings in the Kirkwall area (BIG HIT, 2018).

Figure 26 Illustrative structure of the Surf ‘n’ Turf initiative



3

Solution 3: Terna’s pilot applications of dynamic line rating

● The Italian transmission system operator Terna is conducting pilot applications of dynamic line rating systems on four of its transmission lines: Spezia-Vignole (380 kV), Bargi-Calenzano (380 kV), Misterbianco-Melilli (220 kV) and Benevento2-Foiano (150 kV). The project involves deploying two sets of dynamic line rating equipment on the transmission line itself and deploying dynamic line rating equipment on the two end-point substations. It also utilises the weather forecast data taken from the Epson Meteo Centre to estimate the dynamic line rating value. This has allowed greater capacity of transmission lines during favourable weather conditions, enabling increased integration of wind generation from nearby wind farms (Carlini *et al.*, 2013).

Solution 3: Dynamic line rating system in US

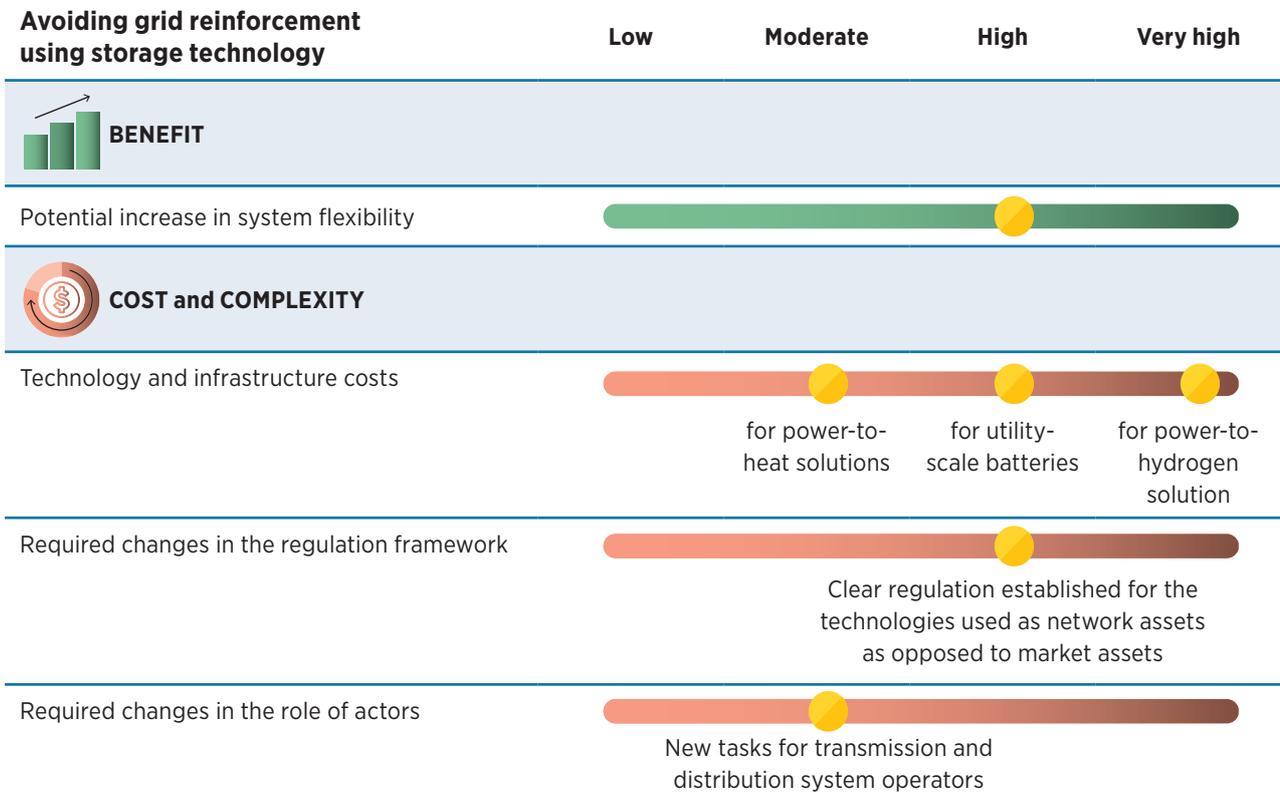
● Oncor Electric Delivery Company, a transmission and distribution utility operating in Texas, implemented a dynamic line rating system in a project funded under the US Department of Energy’s Smart Grid Demonstration Program. The dynamic line rating system monitored the real-time capacity of eight transmission lines that were being used for daily operations and wholesale market transactions. Oncor observed that the real-time transmission line capacities were above ambient-adjusted ratings by 8% to 12% for 132 kV transmission lines, and by 6% to 14% for 345 kV lines for about 84% to 91% of the time. Oncor now plans to deploy additional dynamic line rating systems in West Texas for congestion relief (US DOE, 2014).

E.ON Central Networks has proposed calculating the rating of the Skegness-Boston line dynamically in its control system (ENMAC) from local weather measurements to co-ordinate allowed generation automatically. This takes into account the cooling effect of the wind. This enhancement through dynamic line rating should facilitate the connection of around 30% more generation as compared to fixed winter/summer ratings (Yip *et al.*, 2009).

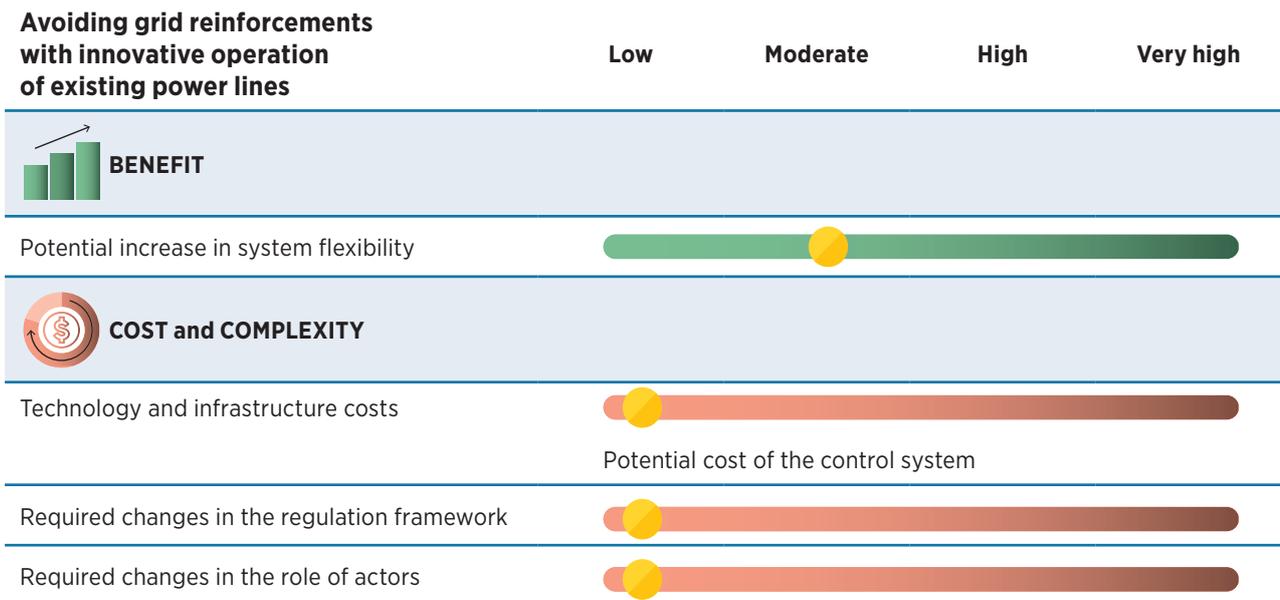


SUMMARY TABLE: BENEFITS AND COSTS OF AVOIDING INVESTMENTS IN TRANSMISSION AND DISTRIBUTION GRID REINFORCEMENT

AVOIDING GRID REINFORCEMENT USING STORAGE TECHNOLOGY



AVOIDING GRID REINFORCEMENT WITH INNOVATIVE OPERATION OF EXISTING POWER LINES



Note: This cost-benefit comparison is confined within system boundaries and focuses on the power sector alone. Wider benefits, which are excluded from this comparison, can be significantly higher than costs.

3.3 DEMAND-SIDE FLEXIBILITY SOLUTIONS

An emerging, powerful approach to increase system flexibility is to unlock demand-side flexibility through the better management of load and distributed energy resources:

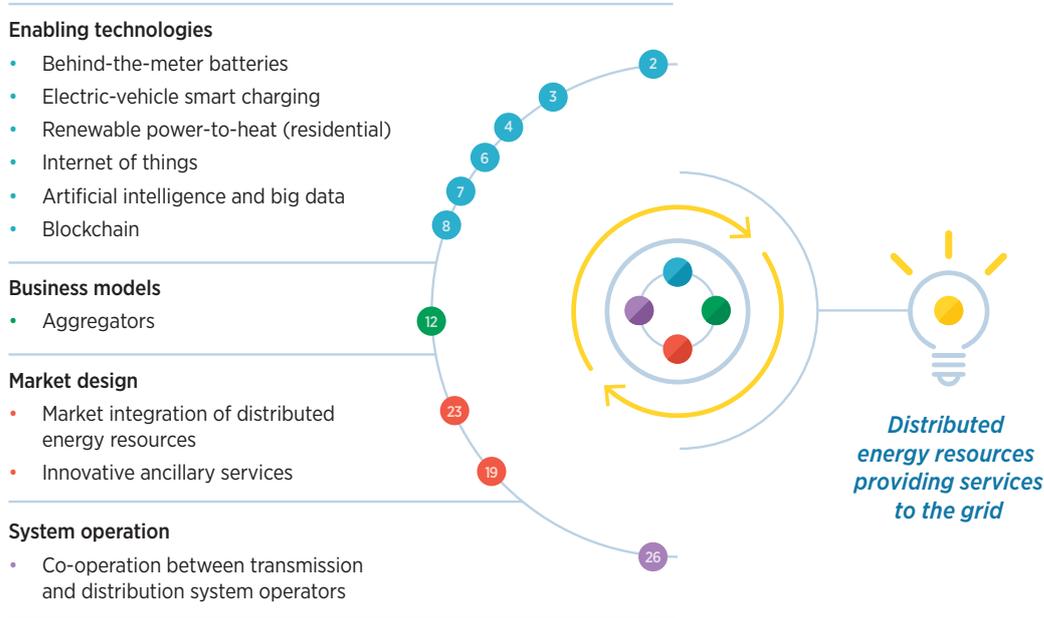
- **If distributed energy resources are provided with better visibility to network and system operators, they can help balance the grid and provide ancillary services** (spinning reserve, fast frequency response for stability and security, and reactive power for voltage support). Apart from the deployment of distributed energy resources, this solution requires a change in the regulatory framework, to allow these resources to provide such services. Given that the deployment of distributed energy resource technologies is already happening, using these technologies to maximise their benefits for the system is vital. This can have a great impact on the flexibility of the system at relatively limited cost (ICTs for aggregators, etc.).
- **The current advancements in metering, communication and control infrastructure make possible the development of demand-side management programmes**, targeting different types of customers through appropriate incentives. Automation processes, enabled by using smart appliances (converting houses into smart homes), can increase the consumer's responsiveness to price signals. Managing these large amounts of data with artificial intelligence can further improve the effectiveness of the demand response, increasing the predictability and reliability of the system.
- **Emerging mini-grid solutions (not only providing energy access in remote areas but also connected to the main grid) also operate independently and provide grid flexibility** when connected to the main grid. Peer-to-peer electricity solutions are emerging inside the mini-grids, providing consumers and prosumers with a marketplace to trade electricity without the need for a retailer. Blockchain technology has the potential to be a game changer in this peer-to-peer trading, replacing the middleman.
- **Using distributed energy resources for providing power to avoid distribution or transmission network congestion and to minimise network reinforcement needs** is another way of integrating distributed generation into the grid. Using these resources smartly in the local grid can increase flexibility and accommodate a higher VRE share.



SOLUTION VI

Aggregating distributed energy resources for grid services

Figure 27 Synergies between innovations that permit grid services based on distributed energy resources



● Distributed energy resources consist of various resource types and technologies that may be located at low- to medium-voltage networks, including distributed generation plants such as rooftop solar PV, and other **enabling technologies** such as behind-the-meter batteries, EVs, residential heat pumps and demand response, among others. (Key innovations: *Behind-the-meter batteries; Electric-vehicle smart charging; Renewable power-to-heat*) In most of the systems, these resources are operated based on a “plug-and-forget” approach. With further deployment, this approach can harm the system.

● Regarding **market design**, an emerging, powerful solution to increase grid flexibility is the better management of distributed energy resources to respond to the system’s overall condition. A key innovation to achieve this is to enable these resources to participate in the wholesale market, the ancillary service market and the capacity market (if established) and be exposed to market price signals. This can be done either via aggregators or by decreasing the capacity limit in

such markets. Distributed energy resources should be allowed to participate in the day-ahead and the intraday energy markets, in the same way that supply-side generators bid in these markets.

Some wholesale market operators in the US have experienced success with this approach. For example, PJM, the largest market operator in the country, has successfully enabled demand response in order to bid into its ancillary service markets to provide regulation services. ERCOT gets only half of its spinning reserves from demand response. In December 2017 the NYISO released a concept proposal for market design that would enable the participation of distributed energy resources in the wholesale as well as the ancillary service markets. As per this proposal, distributed energy resources will be treated in the same way as other market resources. They will be able to participate in capacity reserve markets, regulation service markets, etc., either directly or via the aggregators of the small-scale distributed energy resources (<100 kW) (NYISO, 2017). (Key innovations: *Market integration of distributed energy resources; Innovative ancillary services*)

- Allowing distributed energy resources to participate in wholesale markets would turn consumers into active participants, with incentives to act to the benefit of the entire system and facilitating the integration of these renewable energy generators into the system. To allow this interaction, innovations in **system operation** are needed: distribution companies may act as market facilitators by technically validating the offers submitted by the distributed energy resource to the upstream markets, and ensuring that no distribution constraints are violated.

This role would be similar to what a system operator does today with the wholesale market results. Close co-operation and co-ordination between transmission and distribution system operators in the electricity system becomes key for taking advantage of the increasing flexibility options available in a decentralised system. As electricity flows are changing significantly, and as more and more balancing reserve capacity is located at the distribution level, the distribution system operator needs to co-operate with the transmission system operator responsible for balancing the entire system. *(Key innovations: Co-operation between transmission and distribution system operators)*

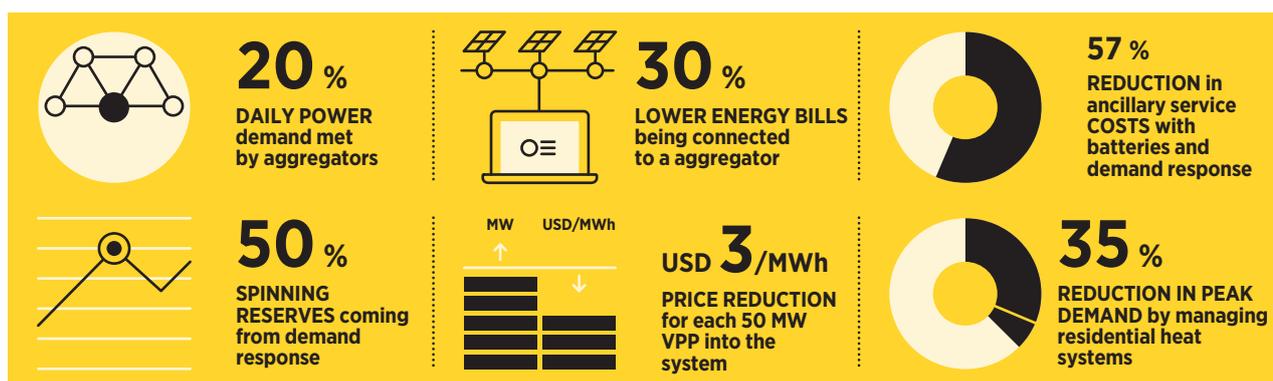
- The amount of voltage or frequency support provided individually by different resources can be small. **Business models** that enable the aggregation of these resources can effectively make them behave like a single, large, predictable source by co-ordinating the behaviour of a large number of distributed devices, using ICT devices (the concept of virtual power plants, or VPPs). A VPP is basically a system that relies on software and a smart grid to remotely and automatically dispatch and optimise the distributed energy resources. In orchestrating distributed generation, solar PV, storage systems, controllable and flexible loads, and other distributed energy resources, VPPs can provide fast-ramping ancillary services, replacing fossil fuel-based reserves. PJM in the US shows that 80% of the distributed energy resource capacity comes through VPPs. *(Key innovation: Aggregators)*

- Digital **enabling technologies** enable distribution automation that is needed to manage the unintended consequences of decentralised assets, such as reverse power flows. However, this may not be enough. Direct control over distributed energy resources, through VPPs, will better enable grid operators to balance intermittency and power flows. Digital systems will support this process by improving the monitoring of end-devices and the data integration among utility systems. Distribution automation and digital systems are already being introduced to the grid, with distributed energy resource management systems (DERMS) and VPPs close behind.

For example all Nordic countries are moving towards the implementation of data hubs for electricity meter data and market processes. Governments and regulators in Denmark, Finland, Norway and Sweden have given transmission system operators the responsibility of introducing a data hub for each of the electricity retail markets. The Danish data hub is fully implemented and handles all communication between suppliers and the distribution system operators. The Norwegian data were scheduled to go live in February 2019. According to the respective national transmission system operators, the Finnish data hub will go live in spring 2021 and the Swedish data hub in the beginning of 2021 (NordREG, 2018).

The data hubs will connect all of the smart meters on the distribution network, making it possible to extract information on what is going on in the network. This will reduce the cost of billing and, more importantly, make it possible to use the information to run the system more efficiently. Aggregators will use this information and create services that can serve both the customers and the grid, extracting more flexibility from consumers. This would digitalise demand in such a way that it would be manageable through markets and aggregators.

Machine learning is still in the experimental stages. Blockchain technology can aid in making the process more efficient. *(Key innovations: Internet of Things; Artificial intelligence and big data; Blockchain)*



Impact on demand:

- **20% of daily power demand can be met and 30% savings on energy bills can be achieved by aggregators in South Australia.**

The South Australian government and Tesla are developing a network of 50 000 home solar PV connected into an aggregator. The VPP is expected to meet around 20% of South Australia's average daily power demand (250 MW). Additionally, the new power plant is expected to lower energy bills for participating households by around 30%, and it will benefit all South Australians with lower energy prices and increased energy stability (Government of Australia, 2018).

- **A field trial conducted with PowerMatcher Suite in the Netherlands showed that peak demand can be reduced by 30% to 35% by managing heat systems (micro CHP and heat pumps) (TNO, 2016).**

Impact on ancillary service procurement:

- **57% reduction in ancillary service procurement in Eastern Australia by allowing the participation of batteries and demand response.**

In Eastern Australia's National Electricity Market (NEM), demand response is playing an increasingly important role in facilitating the renewable energy transition: approximately 180 MW of new demand-response resources have entered the ancillary service markets in the first half of 2018. NEM allowed independent distributed energy resource aggregators to bid into the NEM's Frequency Control Ancillary Services (FCAS) markets for the first time beginning in July 2017. The entry of the new utility-scale battery (known as the Hornsdale Power Reserve) and distributed energy resources into the markets were the major drivers behind a 57% reduction in FCAS costs between the fourth quarter of 2017 and the first quarter of 2018 (Grover, 2018).

- **50% of spinning reserves are coming from demand response in the US ERCOT system, and 10% of resource adequacy needs are covered by demand response in the PJM system.**

PJM has successfully enabled demand response to bid into its ancillary service market to provide regulation services. Also, PJM meets approximately 10% of its total resource adequacy needs from demand response. ERCOT gets half of its spinning reserves from demand response.

Impact on energy costs for consumers:

- **Reduction of USD 3/MWh in the wholesale price for each additional 50 MW of capacity brought into the system with the VPP.**

In South Australia the wholesale price is estimated to drop by around USD 3/MWh for all customers with each additional 50 MW of capacity that is brought onto the system via the VPP. The Australian VPP Tesla proposal could reduce the wholesale price by around USD 8/MWh, or around USD 90 million per year across all South Australian customers, which means 30% of the total energy bill (Frontier Economics, 2018).

Deferred investments in generating capacity:

- **The US Energy Information Administration estimated the cost of a new coal power plant at between USD 2 934 and USD 6 599 per kW depending on the technology used, and the cost of setting up a gas-fired plant at between USD 676 and USD 2 095 per kW. VPPs can provide financial benefits to asset owners of distributed energy resources by maintaining demand and supply balance at a cost of around USD 80 per kW (Enbala, n.d.).**

IMPLEMENTED SOLUTION**The VPP Next Kraftwerke, providing grid services to Elia (Belgium)**

● Belgium has involved demand-response solutions in its daily electricity market operations in a practical manner. The electricity transmission system operator Elia accepts distributed energy resource capacity to compensate for the mismatches between production and peak power demand, in which industrial customers are given primary importance. Transmission and distribution system operators have collaborated to develop a centrally shared IT platform, which enables the sharing of all of the data related to procuring distributed energy resources for flexibility. Through this data hub, all users and generators connected to the distribution/transmission grid can provide flexibility services to the system operators on a daily basis (Elia, 2018).

Distributed energy resource aggregator companies, such as REstore and Next Pool, provide the required capacities to Elia. This is done under stress conditions, in which hundreds of megawatts have already been contracted, in order to add flexibility to Belgian system operations. REstore aggregates flexible industrial capacities – 1.7 GW in total – and constantly monitors the grid load. At peak demand moments, companies in REstore’s portfolio help to maintain grid balance by load shifting.

Through digitalisation, Next Kraftwerke is aggregating 5 000 energy-producing and energy-consuming units in the VPP Next Pool. With a total capacity of over 4 100 MW (not only in Belgium) the VPP trades the aggregated power on different energy spot markets. The VPP contributes substantially to stabilising the grid by smartly distributing the power generated and consumed by the individual units in times of peak load.

Transmission system operators, such as Elia, use control reserve to balance the electricity system. Secondary reserves need to be fully activated within 7.5 minutes and are the most important balancing product for Elia. To test whether the aggregators can provide secondary reserves in a comparable quality as the current units, a pilot

project was conducted in 2017 in which Next Kraftwerke and the other participants proved that VPPs are able to fulfill technical requirements (Trilations, n.d.).

In April 2018 Elia launched its first blockchain pilot project, exploring the opportunities offered by blockchain technology as a payment system to address the business side of such complex, rapid transactions. This would facilitate remunerating the distributed energy resources for the services provided. If the pilot project proves successful it will constitute a major step forward towards establishing a Belgian electricity grid that offers a wide variety of decentralised and sustainable energy sources. This is merely an example of how digitisation can drastically change the energy sector in the coming years/decade.

Sonnen Batterie provides grid services in Germany

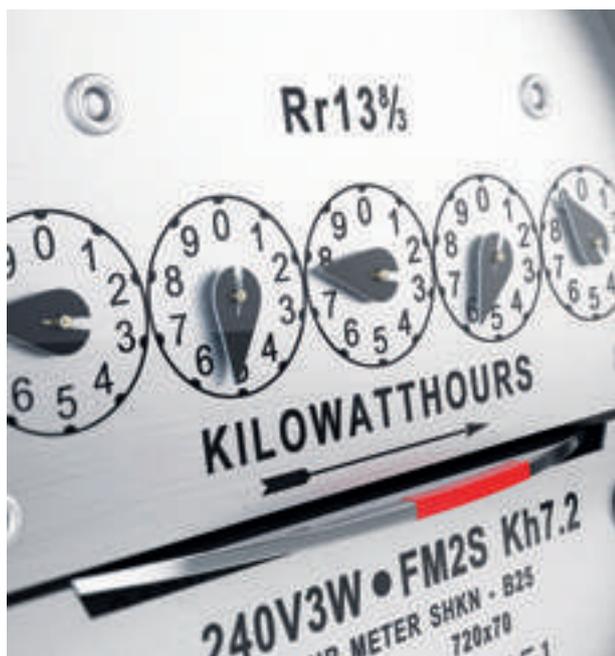
● The sonnenCommunity is an aggregator in Germany consisting of about 10 000 customers with battery storage, solar PV generation, or both. Launched in 2015 the sonnenCommunity was used mostly for peer-to-peer trading within the VPP; however, in summer 2017 the VPP became available to the power grid to provide frequency regulation. Compared to other alternatives, such as pumped hydro storage, this distributed “virtual” storage resource can react very quickly (sub-second), making it a great provider of primary frequency services.

A small part of this storage is made available to the German power grid. This would therefore help reduce wind curtailment, by charging the storage batteries when there is oversupply. This reduces both variability in renewable generation and expensive grid expansion requirements. By being paid for these benefits via the frequency response market, the sonnenCommunity provides battery owners with “free” electricity in return. Since the battery is needed only sporadically, for a few minutes a week, the availability, performance and life span of the battery are practically unaffected.

In May 2017 Sonnen partnered with the German grid operator TenneT to launch the pilot project Sonnen eServices. This project integrated batteries

into the power system via a blockchain solution (developed by IBM). Re-dispatch measures are necessary in Germany, where the wind energy produced in the north cannot be transported to the industrial centres in the south of the country. In this pilot project, a network of residential solar batteries will be made available to help reduce the limitations imposed on wind energy at times of insufficient transport capacity. In 2016 the measures to manage grid congestion cost Germany around EUR 800 million, a large part of which was for wind curtailment (Grey Cells Energy, 2018).

The blockchain presents the operator from TenneT with a view of the available pool of flexibility, ready to be activated with the push of a button. After this, the blockchain records the batteries' contribution. Blockchain technology could be a crucial enabler in documenting, verifying and securing transactions within a future power system composed of millions of small, decentralised power sources, including both prosumers and consumers. The platform is designed to ensure the verifiability and transparency of the transactions made by the small-scale batteries. It simplifies the way that suppliers of locally distributed flexible energy can provide services to support power grid operators in the future. It also is being tested to ensure that it can fulfil TenneT's requirements for data security, restricted access and privacy (TenneT, 2017b).



Tesla's VPP contributes to renewable energy integration and system stability in South Australia

- Tesla proposed the development of a 250 MW VPP – the world's largest built – to contribute to stabilising the Australian state's electricity infrastructure and to improve the security and reliability of the grid in an area where nearly half the electricity comes from wind farms. The initiative will start with a trial in 1 100 public housing homes.

The technology involves four key components:

- Smart meters installed in every participating household to assist in controlling the rooftop solar and battery, and to measure the power flows;
- A network of rooftop solar PV systems installed on public housing (5 kW solar panel system);
- Battery storage installed on public housing in South Australia (5 kW/13.5 kWh Powerwall 2 Tesla battery); and
- A computer system to control the storage, use and transfer of renewable and battery-stored power between houses and the grid, to maximise the value for customers while delivering services to the grid when needed.

The business model is also one of the innovations. The panels and batteries will not carry any upfront charge for the participating households. Instead, it will be funded by selling electricity and with government funds. Officials will provide an AUD 2 million (USD 1.6 million) grant, as well as an AUD 30 million (USD 23.8 million) loan from the state's Renewable Technology Funds.

The impact of such a solution would be considerable in terms of renewable energy integration, with approximately 130 MW of added rooftop solar PV generation capacity and 130 MW/330 GWh of distributed, dispatchable battery storage. This approximately doubles if the roll-out is extended to a similar number of private customers.

In terms of the flexibility added to the system, the participation of 50 000 households in the programme would add 250 MW of peak capacity

3

to the system or, alternatively, reduce the demand on the central grid by 250 MW, freeing the capacity to be supplied to other customers.

In terms of cost reduction, the wholesale price in South Australia is estimated to drop by about USD 3/MWh for all customers, with each additional 50 MW of capacity brought into the system that would not otherwise be operating. This suggests that if only the public housing customers participated in the arrangement, the Tesla proposal could reduce the wholesale price by around AUD 8/MWh, or about AUD 90 million per year, across all South Australian customers.

The savings would be approximately double if the project could achieve its full scale of production of 250 MW. Moreover, the government also has provided estimates showing that it could lower the power bills of those who sign up by 30%.

The additional, distributed, dispatchable battery storage – to be aggregated and managed in a VPP – will improve security and system stability. For example, based on the first full month of trading in December 2018, the Tesla 100 MW battery resulted in about a 75% reduction in the costs being paid by customers for frequency control services. The VPP results could be similar (Frontier Economics, 2018).

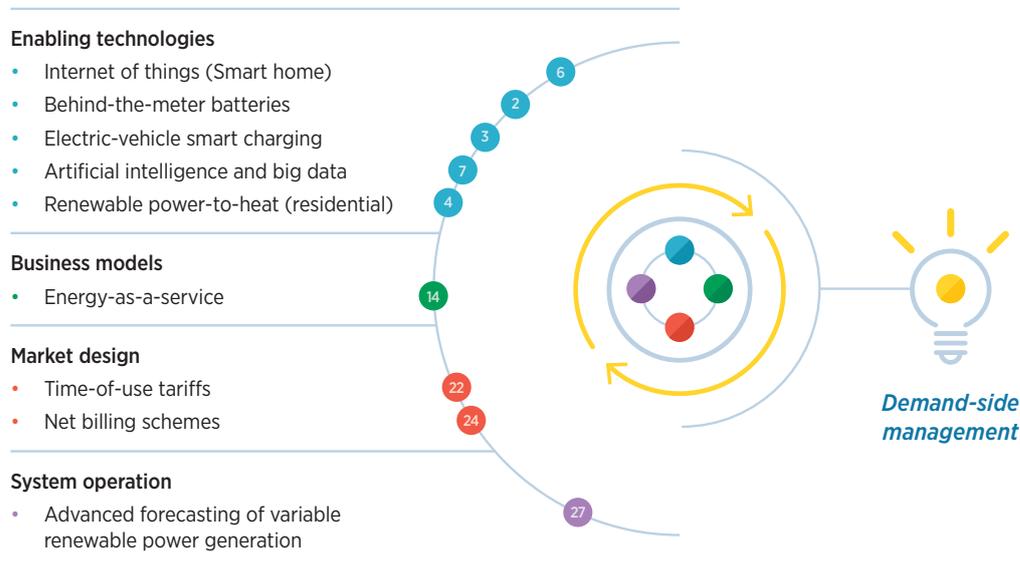
SUMMARY TABLE: BENEFITS AND COSTS FOR AGGREGATING DISTRIBUTED ENERGY RESOURCES FOR GRID SERVICES

Distributed energy resources providing services to the grid	Low	Moderate	High	Very high
BENEFIT				
Potential increase in system flexibility				
Flexibility needs addressed	from seconds to hours			
COST and COMPLEXITY				
Technology and infrastructure costs				
	ICT platform, provided that the distributed energy resources and smart meters are in place			
Required changes in the regulation framework				
Required changes in the role of actors				
	active consumers, distribution and transmission system operators, new players, such as aggregators			
Other challenges	<ul style="list-style-type: none"> Close co-ordination among different stakeholders, including prosumers 			

SOLUTION VII

Demand-side management

Figure 28 Synergies between innovations for enabling demand-side management



● Thanks to **enabling technologies**, automation is one of the most important requirements for demand response and demand-side management, without which customers could not respond to price signals in real time. Digital technologies are emerging in smart homes to facilitate demand-side management. The Internet of Things connects devices such as local battery storage, rooftop solar PV, home appliances and smart meters through the Internet, enabling information gathering and exchange.

Internet of Things is basically composed by digitisation of assets, collection of data about the assets and computational algorithms to control the system formed by the interconnected assets. Cloud-based control systems would enable the management of these devices. Computational algorithms, used to control the system, might be replaced by artificial intelligence. At its core, artificial intelligence is a series of systems that acts intelligently, is able to recognise patterns, draws inferences and makes decisions using its own cognitive judgment, the way humans do. *(Key innovations: Internet of Things; Artificial intelligence and big data)*

● In terms of **market design**, price signals are needed for smart houses to not only increase their energy efficiency, but also to represent a flexibility source for the system. Time-of-use tariffs could be designed to incentivise consumers to shift loads during specific time intervals to support the system and the integration of a high share of VRE. This will allow an increase in consumption when renewable energy generation is available, and a decrease in consumption when there are generation constraints in the system. This has the potential to substantially reduce renewable energy curtailment and improve the system's reliability and predictability.

With real-time pricing, even shorter-term variations in renewable energy output can be balanced with demand response. Under time-of-use tariffs, customers have the choice to adjust their electricity consumption to save on their energy expenses. Automated response is more customer friendly and efficient. In a smart home with rooftop solar PV that can also inject electricity into the grid, a net billing mechanism in place would properly remunerate the renewable energy injected. Under net billing mechanisms, the balance is determined not based on the number of kWh, but on the value

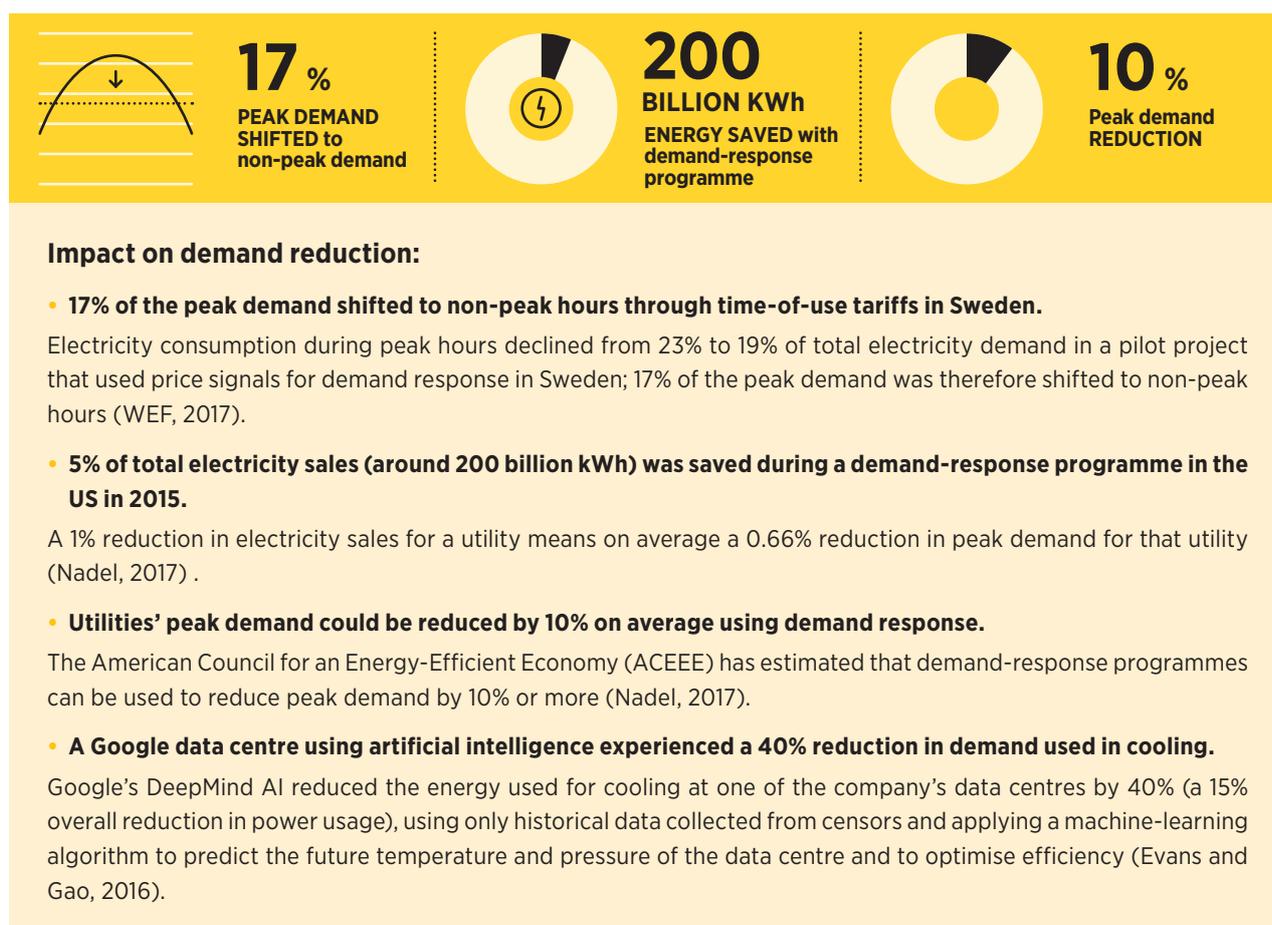
of the kWh consumed or injected into the grid. The invoice issued by the supplier is based on the value of the withdrawn energy, which is reduced by the value of the injected energy.

By making prosumers responsible for their interactions with the grid, the integration of VRE generation into the grid is facilitated. Advanced tools to forecast renewable energy generation would help to decrease uncertainty. *(Key innovations: Time-of-use tariffs; Net billing schemes; Advanced forecasting of variable renewable power generation)*

● **New business models** have emerged with digitalisation at the consumer's end. Energy as a service (EaaS) is an innovative business model where a service provider offers various energy-related services rather than only supplying electricity (i.e., kWh). Using automatic control

systems, distributed energy resources can provide reactive power support for voltage control. The thermostatically controlled demand can be altered in such a way that the set points are adjusted according to the frequency.

Energy service providers can use remotely controlled intelligent devices to manage consumption and reduce the load during peak demand hours, without compromising customer comfort. Smart home solutions can be bundled as an integrated solution that includes monitoring, automation, the controlling of energy consumption, home safety and home intelligence. A recent survey indicates that the number of "connected homes"⁹ or smart homes grew from 17 million to 29 million in the three years from 2015 to 2017, implying a compound annual growth rate of 31% (McKinsey, 2017). *(Key innovation: Energy-as-a-service)*



⁹ A "connected home" is networked to enable the interconnection and interoperability of multiple devices, services and applications, ranging from communications and entertainment to health care, security and home automation.



Impact on energy costs for consumers:

- **15% savings on utility bill with time-of-use tariffs for 350 households.**

Con Edison’s Community Power pilot project would give 350 New York City Housing Authority households access to solar energy for a discounted price. The consumers managed to save 15% on their electricity bills, or around USD 80 (Con Edison, 2018).

- **Up to 40% savings on utility bill using artificial intelligence for demand management.**

BeeBryte, a France- and Singapore-based “software-as-a-service” (SaaS) company, provides cloud-based intelligence software that can monitor real-time load in large commercial and industrial facilities. Using artificial intelligence for weather forecast, occupancy, usage and energy price signals, the software can automatically switch loads such as HVAC systems to battery storage based on time-of-use charges and delivers up to 40% savings in utility bills (BeeBryte, n.d.).

IMPLEMENTED SOLUTION

Reducing renewable energy curtailment – reverse demand-response programme in Arizona

● The Arizona Public Service Company (APS), a utility in the US, experiences demand peaks in summer and mild temperatures with lower demand through the remaining three seasons. As temperatures increase in the summer months, air conditioners represent the main load, which is a good match for solar PV. However, with more moderate temperatures during the remaining nine months of the year, the utility has excess solar PV electricity that often remains unutilised. During some time intervals in the daytime, electricity prices turn negative on account of higher solar generation from the distributed resources. A strategy was needed for load shifting on a daily basis to absorb the excess generation from the renewable energy into the grid.

APS recently proposed a new programme that aims to reduce the need to curtail solar energy during periods of negative pricing. Instead of curtailing renewable production, APS will pay customers to use this energy in order to keep the renewables online and smoothen the load curve. This will be similar to load shifting, but because it is less predictable relative to on-peak/off-peak

price arbitrage (due to the intermittency of the renewables), the APS programme will be specific to dispatchable non-essential loads. APS’s plan includes incentives for smart thermostats, EV charging infrastructure, energy storage and water heater timers, along with a new “reverse demand-response” product that aims to balance system load with excess renewable generation. For example, EVs with smart charging could off-take the free energy when the reverse demand response is activated. During these times, smart appliances (e.g., dishwashers, washing machines, dryers, etc.) can also be run.

APS’s reverse demand response helps to avoid renewables curtailment while also creating a value for the utility’s customers.

Finnish dynamic pricing structure and smart homes

● In Finland, consumers have an option to choose a dynamic pricing tariff structure for electricity. Retail suppliers offer dynamic pricing by choice (without regulation). The price is determined based on the Nord Pool spot price for the price area of Finland. Customers that choose a dynamic pricing tariff structure pay the hourly price, the retailer’s premium and a monthly fixed fee to the retailer that they chose to contract with.

3

By the end of 2017 around 9% (about 340 000) of customers had opted for this tariff structure (Finish Energy Authority, 2018) (Eurelectric, 2017), which allowed them to check electricity prices for each hour of the succeeding day from the chosen retailer’s website. The prices are published based on the spot market timetable. Therefore, the prices for the next day (24 hours), starting from midnight, are finalised at around 2 p.m. The price that the customer pays for a particular time slot would depend on the time of consumption. The customer, like all the other consumers in Finland, requires an hourly metering that he/she can see, one day after the delivery, on the web portal or app of the local distribution system operator.

With the technology available today, it is possible to automatically optimise, for example, lighting, heating, ventilation and the use of white goods according to weather conditions and market prices. Some retailers offer price-optimised heating hours, depending on weather conditions and the actual heating capacity. This enables the current heating system to operate efficiently and helps save up to 15% of heating expenses (Eurelectric, 2017).

Flex PowerPlay – home automation in Australia for solar self-consumption

- Smart buildings are ultimately all about the energy used at the right time in the right place. Flex PowerPlay, a smart home energy platform launched in 2017 in Australia consists of three elements: solar panels, a home battery and a monitoring system. The Energy App allows users to simply switch between appliances and automatically control power loads, helping control energy and its costs. Optimisation solutions like this will be essential for users to get the most out of their solar system and reduce electricity bills.

Users can monitor their power generation and use it in real time on a smartphone, laptop or tablet. PowerPlay, working with smart technology-enabled appliances, can be programmed to turn the lights on when darkness falls and off again when daylight returns. Users also can remotely control the air conditioner, television and sound systems. The platform not only shows the exact amount of real-time energy generation, but also allows consumers to automatically optimise the consumption.



Other case studies: Energy as a service for demand-side management

Con Ed, a utility in New York, offers a rebate of USD 85 to customers for enrolling in its Demand Response programme. The customers allow the utility to adjust their thermostat for a maximum of 10 times each year (Con Edison, 2016).

PassivSystems, in the UK, provides home energy monitoring and energy management solutions by integrating home technologies (e.g., storage heaters, heat pumps) with the Passiv platform and back-end systems in an Internet-connected solution. It demonstrates that the energy usage in homes could be managed on an aggregated level in response to various energy tariffs and demand-side incentives provided by the grid and network operators (DECC, n.d.).

Similarly, STEM, a US-based energy services provider, helps commercial and industrial customers reduce their energy bills by using the energy stored in their batteries during periods of peak demand. The company combines the battery storage with a cloud-based analytics system to identify the best time to draw energy from the battery storage (Colthorpe, 2017). STEM

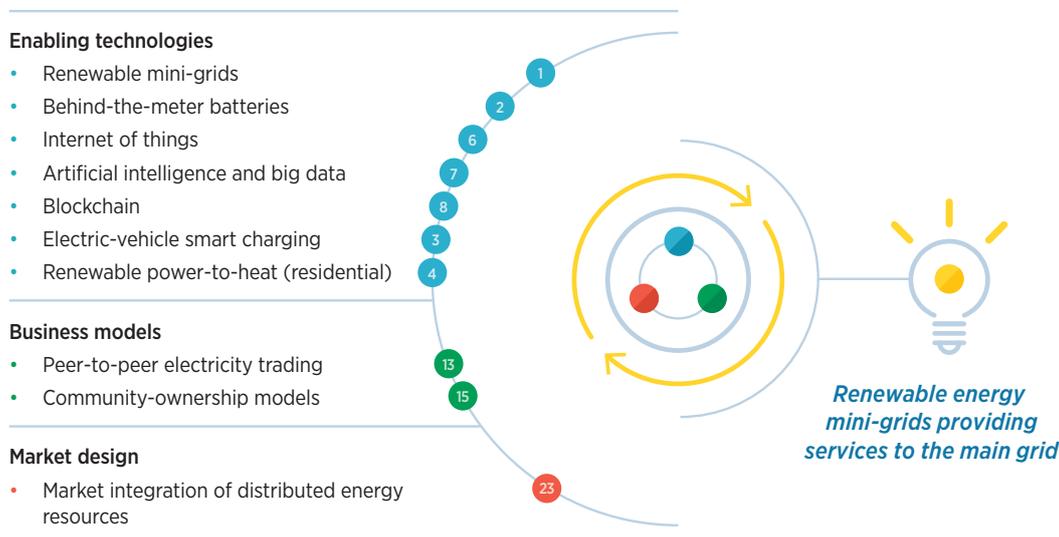
uses artificial intelligence-enabled technology to maintain a consistent level of energy usage, thus helping businesses control their demand charges (Pickerel, 2018).

“Battery as a service” is another variation of the EaaS business model, which provides storage systems for customers to store energy during periods of low demand and to draw from that stored energy during periods of peak demand. For instance, the European energy service provider E.ON has developed a Solar Cloud for solar PV owners to store the surplus energy supply through a cloud solution. This virtual electricity account can be accessed not only for energy demand at home, but also in other places. The key advantage of power clouds is that consumers do not have to invest in a physical battery. Customers can also save on their energy bills by avoiding peak-use charges (E.ON, 2018). In 2018, in the German market alone, there were more than 1.6 million operators of solar systems. According to E.ON, and based on data from the Sunroof co-operation between E.ON and Google, another 10 million roofs in Germany are suitable for installing PV systems. Such services therefore have great market potential.

SUMMARY TABLE: BENEFITS AND COSTS OF DEMAND-SIDE MANAGEMENT

Demand-side management	Low	Moderate	High	Very high
 BENEFIT				
Potential increase in system flexibility	[Progress bar from Low to Very High]			
Flexibility needs addressed	from minutes to days			
 COST and COMPLEXITY				
Technology and infrastructure costs	[Progress bar from Low to Moderate]			
	smart meters, ICT			
Required changes in the regulation framework	[Progress bar from Moderate to High]			
	price signals to consumers			
Required changes in the role of actors	[Progress bar from Low to Moderate]			
	active consumers - automation as facilitator			
Other challenges	<ul style="list-style-type: none"> • Consumers participation and guaranteed privacy 			

SOLUTION VIII

Renewable energy mini-grids providing services to the main grid
Figure 29 Synergies between innovations for enabling mini-grids to provide services to the main grid


● As an **enabling technology**, renewable mini-grids are integrated energy infrastructures combining loads and renewable energy resources. Mini-grids combine power demand with distributed energy resources into a single controllable entity that can be operated separately from the grid. Mini-grids enable renewable energy deployment in both connected areas (allowing local generation to provide independence from the main grid at times) and developing areas, where distributed generation can power remote communities. *(Key innovation: Renewable mini-grids)*

All types of distributed energy resources may be connected to a mini-grid, including distributed generation plants such as rooftop solar PV, battery thermal management, EVs, residential heat pumps and demand response, among others. *(Key innovations: Behind-the-meter batteries; Electric-vehicle smart charging; Renewable power-to-heat)*

● These assets, connected to the mini-grid, can be individually owned by consumers or shared by a community. Community ownership (CO) models are **innovative business models** that enable the sharing of ownership and management energy-related assets, such as energy generation systems,

energy storage systems, energy efficiency systems, and district cooling and heating systems. CO models allow the sharing of costs, enabling participants to own assets with lower investment amounts. This encourages people to unite and act on energy and other socio-economic challenges that are specific to their local areas and communities. It also encourages solidarity and cooperation within communities. *(Key innovation: Community-ownership models)*

Often, mini-grids can enable peer-to-peer (P2P) electricity trading between participants. The P2P concept involves a platform-based business model of an online marketplace where consumers and distributed energy suppliers transact electricity at the desired price. This energy can be bought by any consumer with whom there is a direct connection. An emerging innovation that facilitates P2P transactions is blockchain. *(Key innovations: Peer-to-peer electricity trading; Blockchain)*

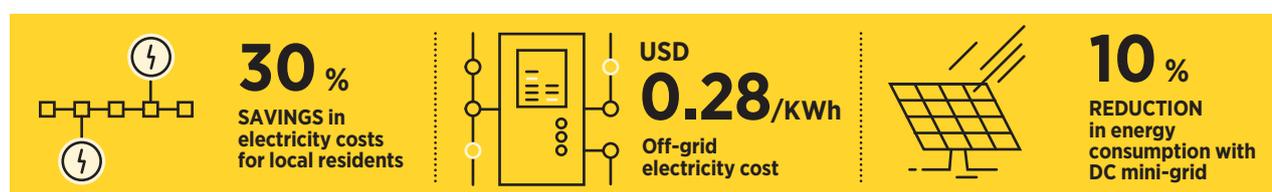
● If connected to the distribution network, the mini-grid can provide flexibility services to the main grid if the **market design** allows. Recent breakthroughs are positioning renewable energy mini-grids as an innovative solution, as these

advancements can facilitate the provision of ancillary services to the main grid and improve efficiency and cost effectiveness. Intelligent sensors can be employed for monitoring the operations of the national grid, to automatically switch between the national grid and the mini-grid.

In switching between grids, DC mini-grids offer an additional advantage as they can quickly connect/disconnect from the national grid. They do not need frequency synchronisation, unlike AC mini-grids, thereby ensuring a continuous supply of electricity for critical applications such as large data centres. Additionally, mini-grids can help in reducing the congestion in interconnections between the mini-grid and the national grid. These systems can enable demand-side response by choosing to connect with the national grid during periods of low demand and disconnecting from the national grid during periods of peak demand. For these services to be properly remunerated, distributed energy resources that are connected to the mini-grid need to participate in wholesale markets. *(Key innovation: Market integration of distributed energy resources)*

● However, matching local demand with local generation in a mini-grid requires the complex tools of an operator. Only digital **enabling technologies** allow a mini-grid to automatically forecast demand, adjust generation, optimise reserves, control voltage and frequency, and connect or disconnect from the main grid (if possible). The more effectively these sources are balanced, the cheaper the generation costs for the mini-grid and the higher the revenue from the additional services it can provide to the main grid. *(Key innovations: Internet of Things; Artificial intelligence and big data)*

Companies such as Power Ledger and LO3 Energy, and research initiatives like The Energy Collective, have been experimenting with P2P trading with local mini-grids using blockchain technology. With smart contracts, trades can be made automatically throughout the network using price signals and real-time renewable energy production data. Companies are now working on intelligent grids that use digitalisation and smart contracts to automate the monitoring and redistribution of the mini-grid energy.



Impact of mini-grids:

- **30% savings in electricity costs for local residents in a mini-grid in Germany that feeds the excess electricity generated into the grid.**

The village of Feldheim owns and operates a local mini-grid system consisting of solar-, wind- and biomass-based generation sources and a battery storage system. The solar plant produces over 2 700 MWh per year, the biogas plant can produce 4 GWh per year, and the wind turbines have a capacity of 74.1 MW. Excess electricity generated is fed into the national grid. Additionally, the mini-grid uses its battery storage system to provide flexibility services for frequency control to the main grid. As a result of the mini-grid system, local electricity costs have come down by over 30% (Eid, 2016; Guevara-Stone, 2014).

- **Plug-and-play mini-grid in Bulgaria can deliver off-grid electricity at a cost of USD 0.28/kWh.**

Bulgaria's International Power Systems has developed Exeron, a plug-and-play system that can effectively switch between multiple energy sources such as solar PV panels, wind and a battery system. This system can enable mini-grid operators to remotely monitor and control the total load and also helps improve the overall efficiency of the mini-grid system (Exeron, 2018). The system results in significant savings in operational expenses and can provide off-grid electricity at a cost of USD 0.28/kWh.

• **A mini-grid system is providing reliable and clean back-up to the Indian grid.**

IBM has installed solar PV-powered DC mini-grids for its data centre in Bangalore, India. The system can provide 50 kW of DC for 330 days a year and result in a 10% reduction in energy consumption as compared to AC power (IBM, 2011). The mini-grid system provides a reliable and clean back-up to the grid.

IMPLEMENTED SOLUTION

Connected mini-grids in the Netherlands

● In the Netherlands mini-grid pilot projects have been undertaken to focus on sustainable and smart energy management. These pilot projects, also referred to as the “SIDE system” (Smart Integrated Decentralised Energy system), are an integration of various renewable energy-based technologies for electricity and heating. The local mini-grids comprise solar PV for generating electricity and solar thermal systems, electric boilers and heat pumps for generating heat. A SIDE network uses an intelligent management system to integrate different components and to balance local supply and demand, reducing costs. For example, solar panels collect energy when the sun shines, and charge EVs. Any surplus power is either stored in a battery or sent by the system to power other houses in the community. The study data show that SIDE systems are less expensive than the conventional grid-powered systems in the long run and do not require expensive infrastructure upgrades (Wood, 2018).

The local mini-grid also is connected to the national grid and allows the feeding of excess power generated in the mini-grid into the national grid. Results from the pilot project showed that the cost of electricity was reduced greatly due to the solar PV, while the cost of heating also declined, albeit slightly, due to the cheaper solar thermal systems (de Graaf, 2018).



Connected mini-grids in Australia

● The Australian Renewable Energy Agency (ARENA) will be investing USD 8.7 million towards a USD 21.9 million 30 MW/8 MWh battery storage facility adjacent to the Wattle Point Wind Farm. This battery system will use local wind power and solar PV power to create a mini-grid system. The mini-grid system would provide fast response during outages in the main grid and reduce congestion on the interconnector linking South Australia with Victoria. The mini-grid also can island the local network using 90 MW of wind farm and solar PV modules (AGL, 2017).

Brooklyn Microgrid

● Brooklyn Microgrid, developed by the New York-based start-up LO3 Energy, is a pilot microgrid using blockchain technology that is intended initially to be a “virtual microgrid” operating over existing wires and eventually to include physical resiliency. Residents and businesses that produce electricity locally can sell their surplus to a network that is connected to other neighbourhood participants. The microgrid has the role of interconnecting the users in a reliable way, either using the main grid network or using a private community network if available.

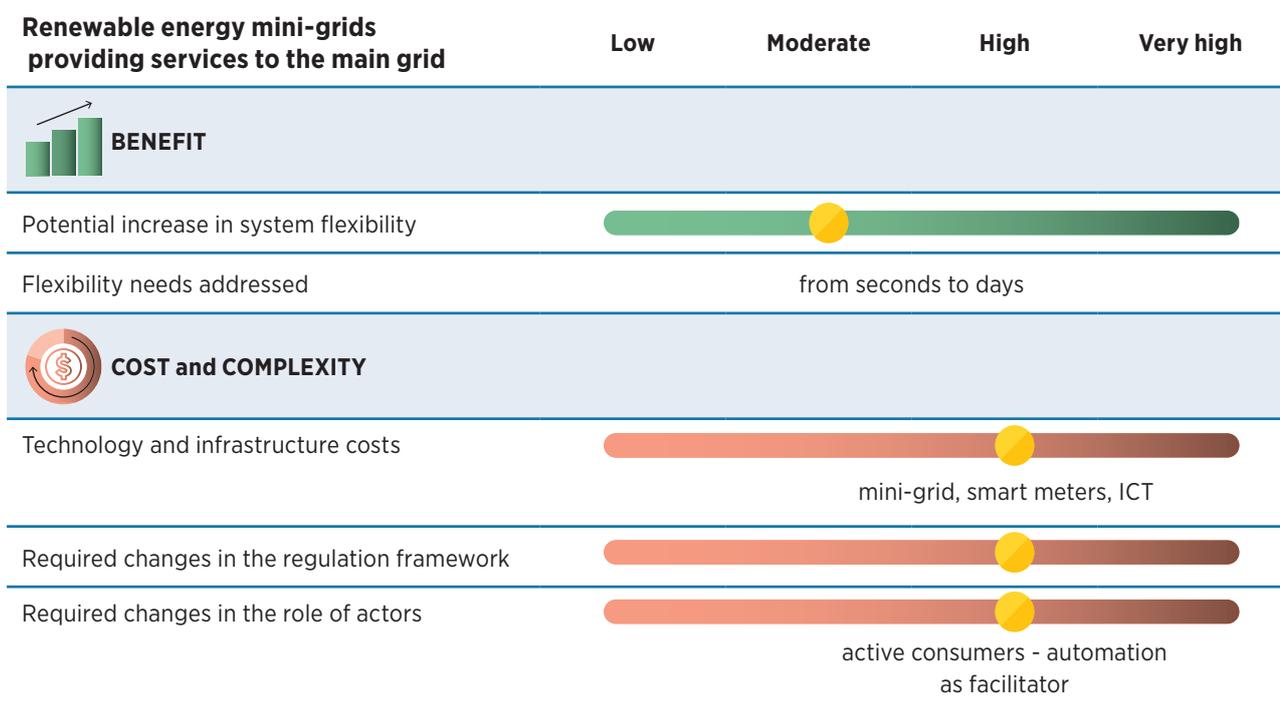
The platform therefore allows peer-to-peer transactions that take advantage of blockchain. The software records and accounts for every unit of energy produced by members’ energy systems. A Smart Contracts application makes surplus units of energy available on the TransActive Grid market to be bought and sold by local community members, with payments through their utility bills. The pricing in these contracts is market driven and based on the supply-demand curve. A fluctuating amount of supply is available from the sellers, while the producers set their bid price, and the trade represents a match between the two. The prosumers (producers and consumers) also

may deal with typical suppliers if their bid is not high enough for local, clean energy. The current installation covers more than 50 participants in Brooklyn.

The concept of a smart microgrid using blockchain was brought in with two key objectives. First, it offers an alternate option for residents and businesses to monetise their surplus power.

Residents with solar PV panels previously have been able to sell excess energy to utility companies, but they are limited to a single consumer at a pre-set price. Additionally, when a blackout occurred in the area, their PV systems would be switched off despite their capability to generate their own power. Since Superstorm Sandy caused a series of blackouts across the US in 2012, the reliability of the grid has been called into question.

SUMMARY TABLE: BENEFITS VERSUS COSTS OF MINI-GRID SOLUTIONS

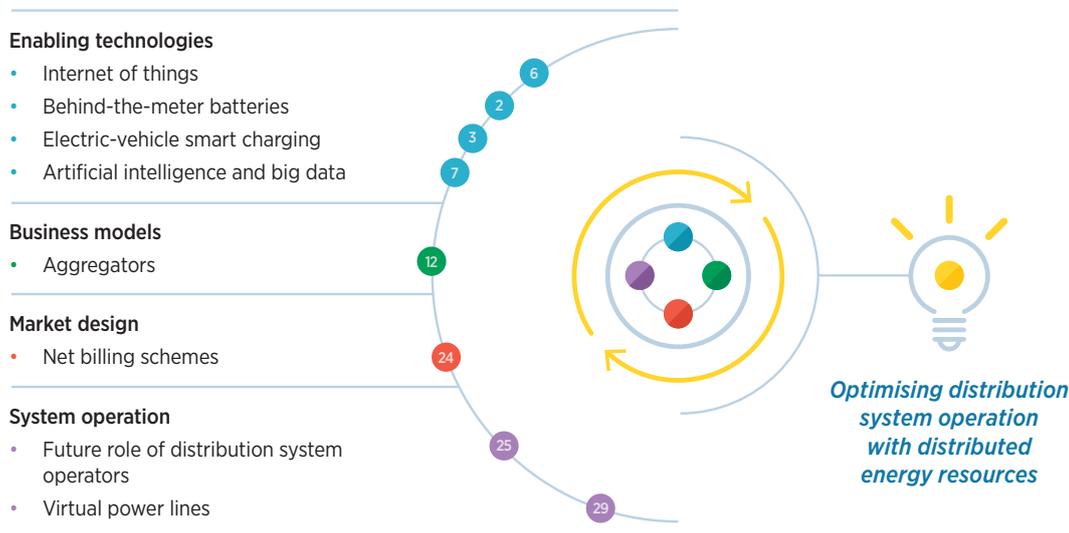


3

SOLUTION IX

Optimising distribution system operation with distributed energy resources

Figure 30 Synergies between innovations for optimising distribution system operation with distributed energy resources



The increasing penetration of distributed generation has led to an unpredictable and reverse flow of power in the system, which can affect the traditional planning and operation of distribution and transmission networks. To effectively manage the distributed energy resources connected to the distribution network, distribution companies need to become active system operators instead of being mere network managers, much as the transmission system operators are. As distribution system operators, these companies should be able to procure flexibility services from their network users, such as peak shaving and voltage support. By mandating distributed energy units to comply with certain communication requirements and dispatch signals, distribution companies can actively operate these technologies, or at least send them price signals, in order to undertake peak load and manage the congestion in the network.

● With the deployment of **enabling technologies**, such as EVs, and the new load that they connect to the grid, distribution system operators also can manage EV charging stations smartly to leverage on the extra storage capacity connected to the

grid. Optimal combinations and harnessing synergies among different distributed energy resources can greatly increase system flexibility. Battery storage systems, deployed by end consumers, can store the surplus energy produced from renewable sources such as solar PV or can be charged using grid electricity when it is cheap. Batteries can then be discharged at the request of the distribution system operator, during peak time intervals, to fulfil demand. (*Key innovations: Electric-vehicle smart charging; Behind-the-meter batteries*)

Meeting peak demand through locally stored energy reduces the need to draw power from the transmission system operators, thereby decreasing grid congestion and deferring network investments. Using distributed energy resources to avoid investment in the grid is also known as “virtual power lines”. For instance, UK Power Networks, a distribution network operator in the UK, recently announced its plan to create London’s first virtual power plant, comprising solar panels and a fleet of batteries across 40 homes in the city. A trial concept was conducted in February 2018,

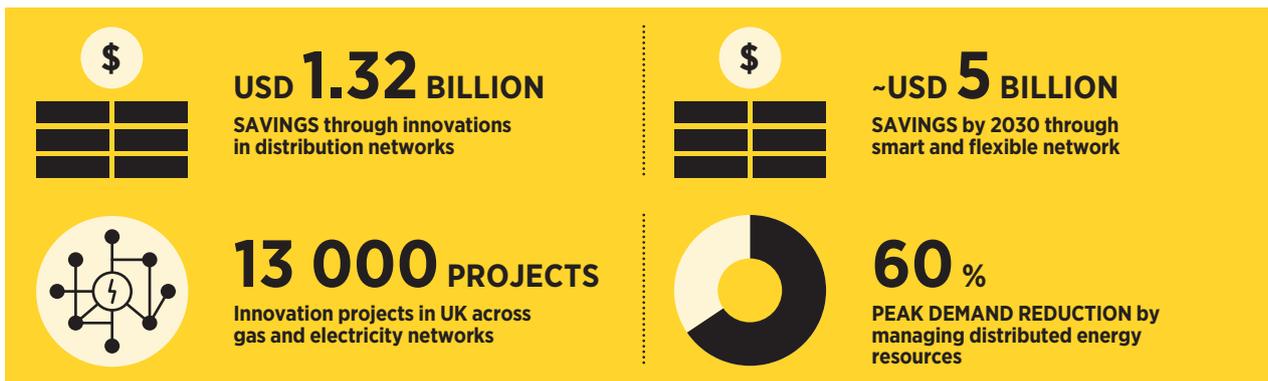
wherein a fleet of 45 batteries was used to meet peak demand. The project is expected to provide an alternative to the traditional approach of increasing network capacity to meet peak demand (Hill, 2018). *(Key innovations: Virtual power lines; Aggregators)*

Active network management must be adopted as an alternative to conventional grid reinforcement in order to efficiently integrate distributed generation. Regulatory mechanisms that aim to foster the new roles of the distribution companies and their active interaction with distributed energy resources include non-firm connection agreements, bilateral flexibility contracts and local markets. A European Commission proposal from November 2016 mandates Member States to ensure that the regulation enables and encourages distribution companies to procure flexible services from network users (EC, 2016a). This can be done via bilateral contracts between agents and distribution system operators, or through economic incentives (prices with some locational/temporal differentiation). In the UK, a form of variable network access for distributed generation, known as a non-firm connection agreement, allows the distributor to temporarily curtail the power injected or withdrawn by the end-user, for security reasons. *(Key innovation: Future role of distribution system operators)*

A well-designed compensation mechanism to help minimise the negative impacts and maximise the value of distribution generation for the overall system is net billing. Under this scheme, compensation for the injected renewable energy is based on time- or location-varying tariffs. Consumers can respond to price signals and help in grid balancing, thereby reducing grid congestion. *(Key innovation: Net billing schemes)*

To become grid and system operators, distribution companies will need to adopt enhanced use of information and communication technologies and innovative systems to solve network constraints. The emergence of many advanced digital technologies – such as sensors, smart meters, artificial intelligence and robotics – has unlocked new and efficient ways of network management. These solutions comprise, among others, automated voltage control or automatic grid reconfiguration to reduce the loading of a distribution feeder by transferring a part of the distributed generation feed-in to a neighbouring one. Grid networks enabled by such technologies are often referred to as “smart grids”. *(Key innovations: Internet of Things; Artificial intelligence and big data)*





Impact on cost savings by optimising distribution operation:

- **USD 1.32 billion in cost savings achieved through innovations in energy networks in the UK.**

Innovations by distribution network operators in the UK – including creating smarter networks, improving transmission-distribution processes related to connections of distributed generation, planning and shared services, assessing the gaps in customer experience and considering changing the requirements of transmission and distribution systems – has enabled close to USD 1.32 billion in cost savings for consumers, which will be realised between 2018 and 2023 (Engerati, 2018). Western Power Distribution, a distribution system operator in the UK, estimates the total cost of the transition to be USD 150 million, considering recurring costs such as licences and new employees (Engerati, 2018).

- **Up to ~ USD 5,16 billions (GBP 4 billion) of savings can be released by 2030 in the UK through a smart and flexible network that enables distribution system operators to easily access flexible assets on the grid.**

Open Utility is developing an online marketplace platform that would allow distribution system operators to access location-specific flexible sources. These operators will play a critical role in actively balancing local smart grids and facilitating the roll-out of distributed generation, storage and EVs. Open Utility’s resource optimisation algorithms, delivered via an intuitive online service, lower barriers to entry and manage the deployment of localised flexibility in a highly efficient and scalable way (BEIS, 2018).

- **Since 2004 over 1 300 innovation projects have been delivered across both gas and electricity networks in the UK,** allowing network operators to better understand how to integrate new energy technologies such as EVs, renewable distributed generation and decarbonised sources of gas into the energy system (Northern Powergrid, 2018).

Impact on peak demand reduction:

- **60% peak demand reduction from the grid by managing distributed energy resources, achieved by a distribution network in the UK.**

UK Power Networks, a distribution company in the UK, will install a fleet of battery systems on around 40 homes across London that are already fitted with rooftop solar PV arrays. In total a combined capacity of 0.32 MWh will be installed via modules coupled with 8 kWh batteries. The batteries would be aggregated into a virtual power plant, which could reduce the evening peak by 60% through remote discharge of batteries (Willuhn and Brown, 2018). The peak times (a couple of hours per weekday) could account for 93% of the “distribution use of system costs”; encouraging consumers to reduce their energy usage during peak times is key.

Note: The original figure of GBP 1 billion was converted to USD based on the United Nations operational rate of change on 10 July 2018.

IMPLEMENTED SOLUTION

UK Open Networks project

- Open Networks is a project launched in the UK by the Electricity Networks Association, a national trade association representing transmission and distribution networks. The project is expected to lay the foundation for the transition of distribution network operators to the role of distribution system operators. Its objectives include developing improved transmission/distribution system operator processes, planning of shared services and a need-gap assessment for customers (Engerati, 2018).

Western Power Distribution, a distribution network operator in the UK, has released a four-point plan for its transition into a distribution system operator. This includes expanding and rolling out smart network solutions to higher voltages, contracting with aggregators and customers for various services, transmission/distribution system operator co-ordination, and ensuring the integrity and safety of the lower-voltage networks (Engerati, 2018).

Piclo online marketplace in the UK

- Open Utility is developing an online marketplace, called Piclo, to enable distribution system operators to access location-specific flexible resources. These operators will play a critical role in actively balancing local smart grids and facilitating the roll-out of distributed generation, storage and EVs. A smart and flexible network could reduce the UK's emissions from electricity generation and realise a savings of up to EUR 4 billion by 2030, but only if the distribution system operators can quickly and easily access flexible assets on the grid. Open Utility's resource optimisation algorithms, delivered via an intuitive online service, lower the barriers to entry and manage the deployment of localised flexibility in a highly efficient and scalable way.

The trial saw good engagement by customers and sellers, with stakeholders logging in regularly to check the details of the electricity transactions. Piclo matches generation and consumption according to preferences and locality, providing customers with data visualisations and analytics. It has provided a transparent, easy-to-use mechanism for its subscribers to offer renewable energy to consumers wanting to source from a renewable generator. Daily, weekly and monthly visualisation proved to be very useful in understanding the energy demand, as well as the "distribution use of system" (DUoS) charges that are meant to cover electricity distribution costs. Understanding that peak times (a couple of hours per weekday) could account for 93% of the DUoS costs encouraged consumers to reduce their energy usage during these times (Open Utility, 2016). Customer feedback showed that distance from the generators, rather than technology, was a key factor in determining the supplier. Customers preferred local suppliers to distant ones. In the context of the Cornish local energy market, four consumers in Cornwall consumed 54% of the Cornish generation.

New York's Reforming the Energy Vision

- The state of New York has developed a roadmap titled "Reforming the Energy Vision (REV)", under which the New York Public Service Commission has mandated six large investor-owned utilities to undertake several measures to integrate distributed energy resources. These include creating charging systems for EVs, creating online marketplaces for energy products and services, building virtual power plants and enabling the connectivity of distributed energy resources to the grid, and developing storage on demand, among others. The costs of these products and services will be recovered through the modification of tariff structures. Utilities have already launched multiple demonstration projects (New York State, 2018).

3

SUMMARY TABLE: BENEFITS AND COSTS OF OPTIMISING DISTRIBUTION SYSTEM OPERATION WITH DISTRIBUTED ENERGY RESOURCES

Optimising distribution system operation with distributed energy resources	Low	Moderate	High	Very high
BENEFIT				
Potential increase in system flexibility				
Flexibility needs addressed	from minutes to days			
COST and COMPLEXITY				
Technology and infrastructure costs				
	smart meters, ICT			
Required changes in the regulation framework				
	new incentives and regulatory framework for distribution system operators			
Required changes in the role of actors				
	new role of distribution system operators			
Other challenges	• Grid instability management			



3.4 SYSTEM-WIDE FLEXIBILITY SOLUTIONS

Some enabling technologies can support a range of different applications, enhancing flexibility in several different parts of the system.

Utility-scale battery solutions are able to address the intraday variability of renewable energy generation, providing flexibility on:

- **The supply side:** Storage batteries, coupled with VRE plants, can counter-balance their output. Despite the impressive decrease in battery costs in recent years, this solution is still at the high end of the cost scale. It can have a direct impact on the flexibility of the generation plant itself, but its impact on the reliability of the system depends on the adoption of solutions for all variable generators.
- **The grid:** Although battery storage systems gained momentum from their potential benefits in firming renewable power output and facilitating its integration, their advantages go beyond that, providing wider services to the grid such as load shifting, frequency regulation and reserves. To become a fully competitive option, battery costs still need to decrease. However, regulatory adjustment to allow batteries to provide ancillary services could provide a new revenue stream for them and encourage their wider adoption. As a fast-responsive technology, the impact on system flexibility is high.

Reducing congestion: Using batteries to reduce congestion in the grid and allowing the deferment of investments in the network is also an emerging solution for some transmission system operators. As most such projects are in the pilot stage, the impact of battery

usage on system flexibility is not well defined. Additionally, existing regulations can impose restrictions, for example, on transmission system operators owning batteries.

Power-to-X solutions, such as power-to-hydrogen and power-to-heat, are able to address the short-term variability of renewable energy generation and also can help address seasonal variability, providing the option to store energy over longer periods of time. It also is a system-wide solution that offers flexibility on the supply side, provides grid services and avoids grid congestion:

- **The supply-side:** Power-to-X can decouple generation from demand by converting surplus renewable generation into heat or hydrogen. Both have a great impact on providing the needed flexibility for integrating high shares of renewable generation, but at different costs for different maturity levels of technologies.
- **The grid:** As a flexible load, the electrolyser can offer grid balancing services provided that it is of sufficient capacity and responsiveness to participate in power balancing markets. Since hydrogen can be converted back to electricity to provide constant power when the renewable source is unavailable, it helps to stabilise the grid (EC, 2016b). Additionally, the electrolyser can be cycled up and down rapidly, to be used as a flexible load providing low-cost balancing services to the power system.
- **Reducing congestion:** Power-to-hydrogen and power-to-heat can be used to store the renewable energy produced when the grid is too congested and this power cannot be transmitted directly to demand centres.

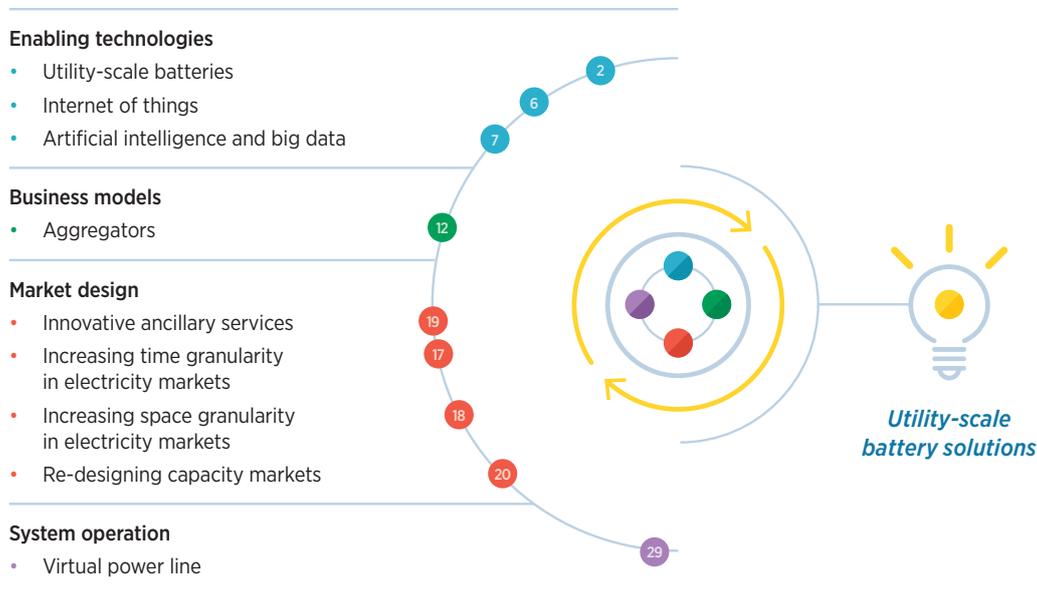


3

SOLUTION X

Utility-scale battery solutions

Figure 31 Synergies between innovations with utility-scale batteries



● As **enabling technologies**, utility-scale batteries facilitate the integration of renewables from several fronts. First, they can help cope with the variability of renewables by storing energy in cases of excess generation, avoiding curtailment and supplying electricity to the grid when resources are scarce. Second, they are flexible and fast-responding technologies that help to maintain the balance in the system when sudden changes occur. Batteries provide stability and reliability services that become critical with the penetration of renewables, such as a need for faster frequency regulation and voltage control. *(Key innovation: Utility-scale batteries)*

● In terms of **business models**, a utility-scale battery can, depending on its size, function as a single market player, or it can serve as part of an aggregator. *(Key innovation: Aggregators)*

Supply-side flexibility: Battery storage system coupled with VRE power plants

Coupling a specific VRE generation source with a battery reduces the variability of the power output at the point of the grid interconnection,

thus facilitating better integration of the renewable energy into the grid. The battery storage system can smoothen the output of VRE sources and controls the ramp rate (MW per minute) to eliminate rapid voltage and frequency fluctuations in the electrical grid. Further, due to the smoothening of the generation, renewable energy generators can increase compliance with their generation schedules and avoid the payment of penalty charges for any deviation in generation output. Generation smoothening also would allow renewable energy generators to take better positions in the market-based auctions for energy/capacity, due to the increased certainty and availability of round-the-the-clock energy. If a significant amount of renewable capacity installation is planned in an electricity system, the deployment of battery storage systems along with such renewable capacity also can be devised.

Furthermore, large-scale battery storage can be coupled with aggregated local distributed generation plants such as rooftop solar PV. These battery storage systems are connected to the utility network and can be controlled directly by

the utility or by aggregators working on behalf of utilities. The stored electricity can be used later in the locality when the demand exceeds the supply. A pilot is being implemented in Walldorf, Germany, with a 100 kW battery system connected to 40 households (GTAI, 2018).

Grid flexibility: Battery storage systems providing services to the system

Battery storage systems can be used to provide services to the grid due to their fast-response capability. Ancillary grid services, such as primary (fast) frequency regulation, secondary frequency regulation, voltage support and capacity reserve, among others, will grow in significance as VRE penetration increases, although they have different dynamics in terms of performance, varying by the market and the time of year. Some applications require high power for short durations (e.g., fast frequency regulation response), while others call for power over longer periods (e.g., firm capacity supply). These different services imply various charge/discharge cycles. Each technology, therefore, is likely to find different market segments where it can compete on performance and cost (IRENA, 2018a).

Table 2 shows the suitability of various battery technologies for different applications, followed by details about some of these services.

- In terms of **market design**, a critical issue for electricity storage that will assist in its economics is the ability to derive multiple value streams by providing a range of services with one storage system. This will enable the “stacking” of the revenue streams and will improve the project revenues. In many countries, this will require changes in the market structure and regulations, or require the creation of new markets for ancillary grid services, and the introduction of more granular markets to reward individual services more directly (e.g., primary and secondary frequency reserves, firm capacity, etc.). This will open up new opportunities for their deployment, given that battery storage will increasingly offer competitive services to these markets. At the same time, renewable capacity firming or time-shift services from battery storage technologies will also expand. *(Key innovations: Innovative ancillary services; Increasing time granularity in electricity markets; Increasing space granularity in electricity markets;; Re-designing capacity markets)*

Table 2. Suitability of various battery technologies for different grid applications

APPLICATION	TYPE OF BATTERY			
	Lithium-ion	Lead acid	Sodium-sulphur	Flow batteries
Load shifting – reducing excess renewable energy curtailment	Suitable	Suitable	Suitable	Suitable
Frequency restoration reserves	Suitable	Unsuitable	Unsuitable	Unsuitable
Capacity reserves	Suitable	Suitable	Suitable	Potentially suitable
Transmission and distribution system upgrade deferral	Suitable	Suitable	Suitable	Potentially suitable
Voltage support	Potentially suitable	Unsuitable	Unsuitable	Unsuitable
Spinning reserve	Potentially suitable	Suitable	Potentially suitable	Potentially suitable

Note: “Suitable” means that the battery type has been used for the respective application at the pilot or the commercial level.

“Potentially suitable” means that the battery type has the potential to be used for the respective application, but with few or no installations. “Unsuitable” means that the battery type is unlikely to be suitable for the respective application.

Source: Adopted from HDR, 2017.

3

In many countries, the participation of energy storage systems in electricity markets is not allowed. A wide range of revenue streams for storage providers is enabled by clear regulations defining the ownership models and the operating models. This can include participation in wholesale electricity markets, the sale of frequency response services to system operators or participation in capacity markets. For example, in 2016 the UK grid operator awarded contracts for 201 MW of its first “enhanced frequency response” tender, which is directed towards storage systems.

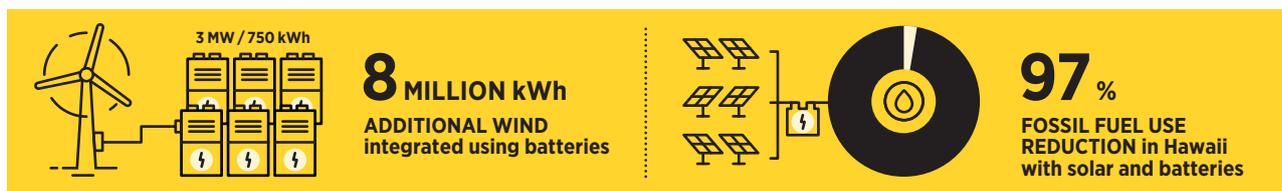
In the US the Federal Energy Regulatory Commission (FERC) voted to remove barriers to the participation of electricity storage resources in the capacity, energy and ancillary service markets operated by the regional transmission organisations and the independent system operators. This order will allow utility-scale batteries to help support the resilience of the bulk power system. In February 2018 FERC passed a rule to allow storage providers to participate in US wholesale electricity markets (FERC, 2018). Another recent FERC order allows energy storage systems to participate in capacity markets, mandating system operators to revise tariffs and establishing rules that recognise the physical and operational characteristics of energy storage systems (Walton, 2018).

Systems around the world are already including storage in their planning efforts. For example, in the Californian power system, the California Public Utilities Commission mandated that the three big utilities must have 1 325 MW of energy storage in operation by 2020. Similarly, Asia Pacific, North America and Western Europe are expected to be the leading markets for utility-scale energy storage capacity for ancillary services through 2026, accounting for more than 32 GW (Colthorpe, 2018).

Battery storage system used for decongesting the grid

- To support **system operation**, large-scale storage systems can be deployed at different points in the distribution and transmission network to store excess power during non-peak hours. These systems can then be discharged to meet load requirements in the local area during peak hours, without the need for transporting electricity through congested grid lines, thereby reducing network congestion and creating “virtual power lines”.

In this case, batteries are not merchant assets but network assets, owned by the grid operator and used exclusively for managing the grid. For example, Terna, a transmission system operator in Italy, is deploying a pilot battery storage project of 35 MW on part of its 150 kV grid in southern Italy for grid congestion management (Terna, n.d.). RTE, the French transmission system operator, is carrying out a similar initiative called the Ringo project. (See *Innovation Brief: Virtual power lines*)



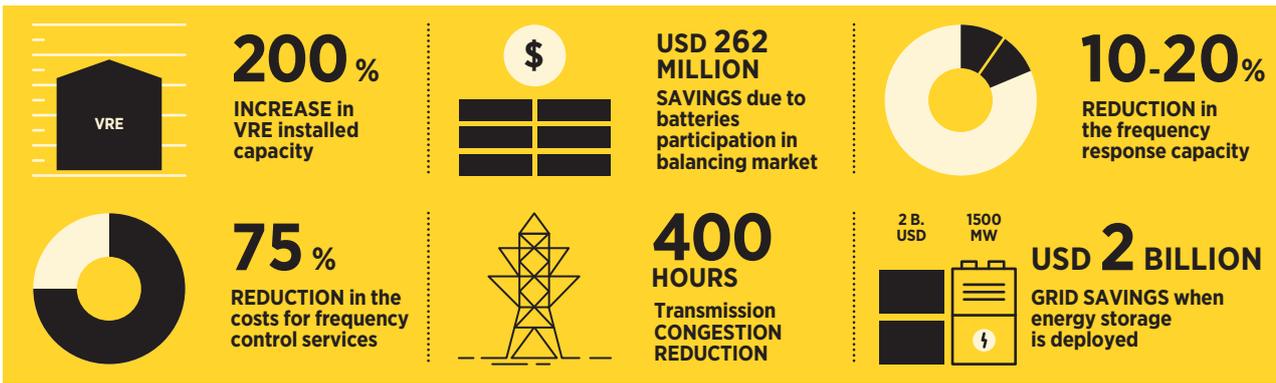
Impact on VRE integration:

- **8 million kWh of additional wind integration was enabled in Alaska using battery storage.**

In Alaska a local utility called Kodiak Electric Association, in collaboration with Berlin-based energy storage firm Younicos, has installed an advanced lead-acid battery storage system of 3 MW / 750 kWh with a 4.5 MW wind power project, resulting in additional wind integration of 8 million kWh (IRENA, 2015).

- **Solar and batteries are expected to reduce fossil fuel use by 97% on the island of Hawaii.**

In 2014 Aquion Energy, an energy storage system provider, completed installation of a 1MWh battery system as part of an off-grid solar microgrid at Bakken Hale on the island of Hawaii. The system is designed to generate 350 MWh per year. This is expected to reduce fossil fuel usage by 97% and carbon dioxide emissions by more than 5 000 metric tonnes (ESA, 2014).



Impact on system operation:

- **200% increase in VRE installed capacity, 70% decrease in ancillary service procurement costs and 20% decrease in balancing market size in Germany.**

In Germany, alongside conventional generators, renewable energy generators, battery storage systems and industrial loads have been allowed to participate in the balancing markets since 2009. In the period 2009-2015 the balancing market size decreased by 20% (in GW), and ancillary service procurement costs by transmission system operators decreased by 70%, while in the same period the system stability increased and the installed capacity of VRE increased by 200% (Wang, 2017).

- **Around USD 262 million in cost savings for consumers** due to the deployment of the sub-second Enhanced Frequency Response by National Grid in the UK, which allows the participation of batteries in balancing markets. Contracts were awarded to more than 200 MW of battery storage in July 2016 (National Grid, 2017).
- **10% to 20% reduction in the frequency response capacity procurement expected by PJM.**

PJM, a power transmission operator in the US, has deployed energy storage systems that are providing cost-efficient frequency response, reducing the use of fossil fuel generation. PJM has forecasted that a 10% to 20% reduction in frequency response capacity procurement could result in USD 25 million to USD 50 million in savings for its consumers (HDR, 2017).

- **75% reduction in the costs for frequency control services from a utility-scale battery in Australia.**

Based on the first full month of trading in December 2017 the Tesla 100 MW battery resulted in about a 75% reduction in the costs being paid by customers for frequency control services (Frontier Economics, 2018).

Impact on transmission network:

- **400 hours of congestion reduced and savings up to USD 2.03 million on fuel costs per year.**

A high-level demonstration study for mitigating transmission congestion using a 4 MW / 40 MWh battery storage system with four hours of storage showed that the New York Independent System Operator (NYISO) can save up to USD 2.03 million in fuel costs and reduce almost 400 hours of congestion (IEEE, 2017).

- **USD 2 billion in savings when about 1 500 MW of energy storage is deployed.**

A draft study commissioned by the state of New York estimates over USD 2 billion in savings if the state deploys about 1 500 MW of energy storage in lieu of traditional grid solutions by 2025 (NYSERDA, 2018).



3

IMPLEMENTED SOLUTION

Large battery in Australia, coupled with a wind plant providing services to the system

● In 2017, the US company Tesla commissioned a lithium-ion battery storage capacity of 100 MW/129 MWh at the 315 MW Hornsdale Wind Farm in South Australia. The battery storage facility was installed to firm up the power generated from the Hornsdale Wind Farm and simultaneously provide ancillary services to the Southern Australia grid. A battery capacity of 70 MW is connected to the grid for providing grid services, and the remaining 30 MW is to be used for firming up the renewable power generated at the wind farm. The latter is designed to hold up to three-to-four hours of energy (McConnell, 2017).

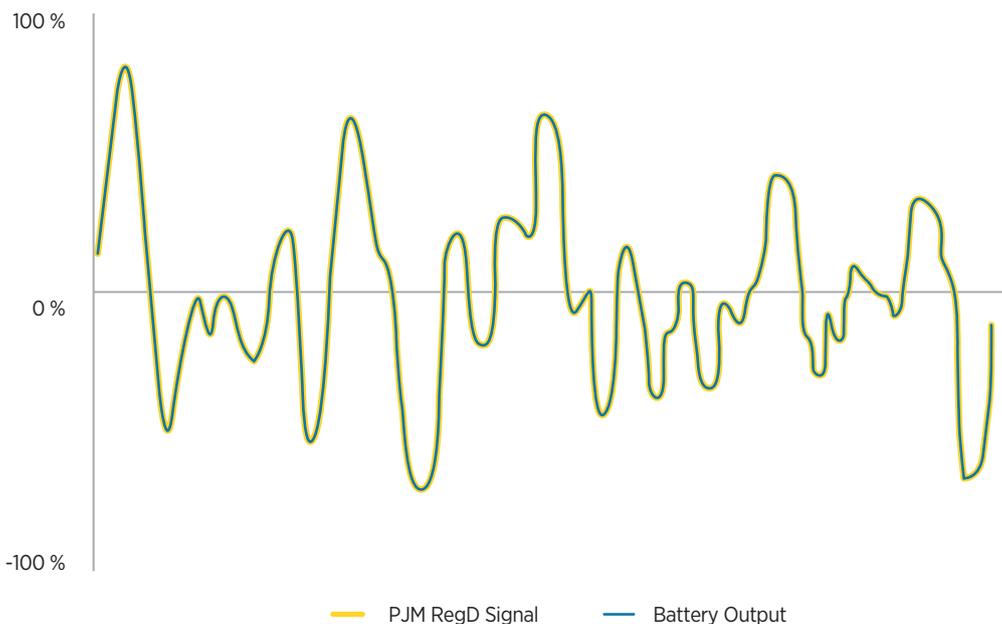
In addition the Australian Energy Market Commission changed the market rules, allowing energy storage to provide ancillary services and thus opening an additional opportunity for storage in the country (Stone, 2016).

Large battery provides ancillary services to PJM in the US

● Driven by FERC’s mandate to independent system operators to pay for the performance of the frequency providers, Renewable Energy Systems (RES), a UK-based firm, built a 4 MW/2.6 MWh battery storage system that provides frequency regulation services to PJM, a regional transmission operator in the US (RES, 2016).

Frequency regulation is the injection and withdrawal of power on a second-by-second basis to maintain the grid frequency at the nominal level. The primary resources used for regulation – coal-fired steam plants and combined-cycle gas plants – are relatively slow at ramping and therefore cannot follow a fast-moving signal well. Realising this, FERC instituted Order 755, which requires the independent system operators to “pay for performance”. This resulted in energy storage systems receiving much higher revenue per megawatt for regulation than that received by traditional resources (RES, 2016).

Figure 32 PJM regulation services signal and battery response



Source: RES, 2016.

PJM assesses the frequency regulation market participants largely on how quickly and accurately they can respond to a PJM-provided signal. The battery installed by the UK firm continues to earn a very high performance score, having been programmed and designed with maximum speed of response and accuracy when providing frequency regulation. Figure 32 shows the signal received from PJM and how accurately RES's storage system responds to it.

Batteries facilitate the integration of renewables: they are flexible and fast-responding and can cope with the variable generation and help maintain the balance in the system

Solar PV – wind – storage hybrid solution for Graciosa Island, Portugal

● Graciosa, a Portuguese island, has traditionally met its energy requirements through fossil fuel imports and diesel-based generation. However, the new Graciosa Hybrid Renewable Power Plant – comprising a 1 MW solar PV plant, a 4.5 MW wind plant and a 6 MW/3.2 MWh battery storage system – has helped reduce the island's reliance on imported fossil fuel while also reducing its greenhouse gas emissions.

The project's generated energy will be sold to the local utility, EDA. The project also uses the Greensmith Energy Management System (GEMS) software, which optimises energy generation based on various factors such as weather forecasts, load patterns, etc. Renewable energy consumption on the island is expected to increase from 15% to 65% of total energy consumption while eliminating the need for around 17 000 litres of diesel per month. The plant can currently meet 70% of local demand (Anteroinen, 2018).

SUMMARY TABLE: BENEFITS AND COSTS OF UTILITY-SCALE BATTERY SOLUTIONS

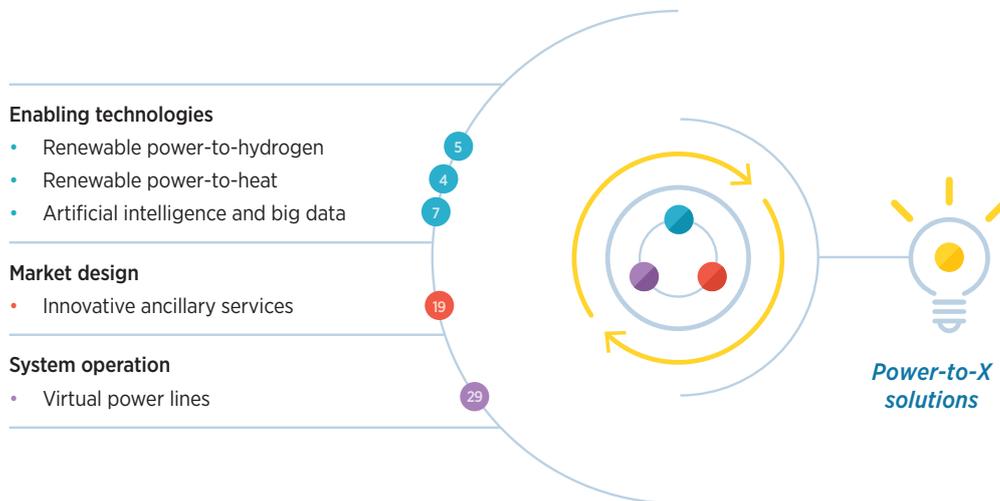
Utility-scale battery solutions	Low	Moderate	High	Very high
BENEFIT				
Potential increase in system flexibility	[Progress bar from Low to High]			
Flexibility needs addressed	from seconds to hours			
COST and COMPLEXITY				
Technology and infrastructure costs	[Progress bar from Low to High]			
Required changes in the regulation framework	send right incentives to the new player that can generate, store and consume electricity			
Required changes in the role of actors	[Progress bar from Moderate to High]			
Other challenges	<ul style="list-style-type: none"> Standards to be developed between DSOs and Battery providers 			

3

SOLUTION XI

Power-to-X solutions

Figure 33 Synergies between innovations for power-to-X solutions



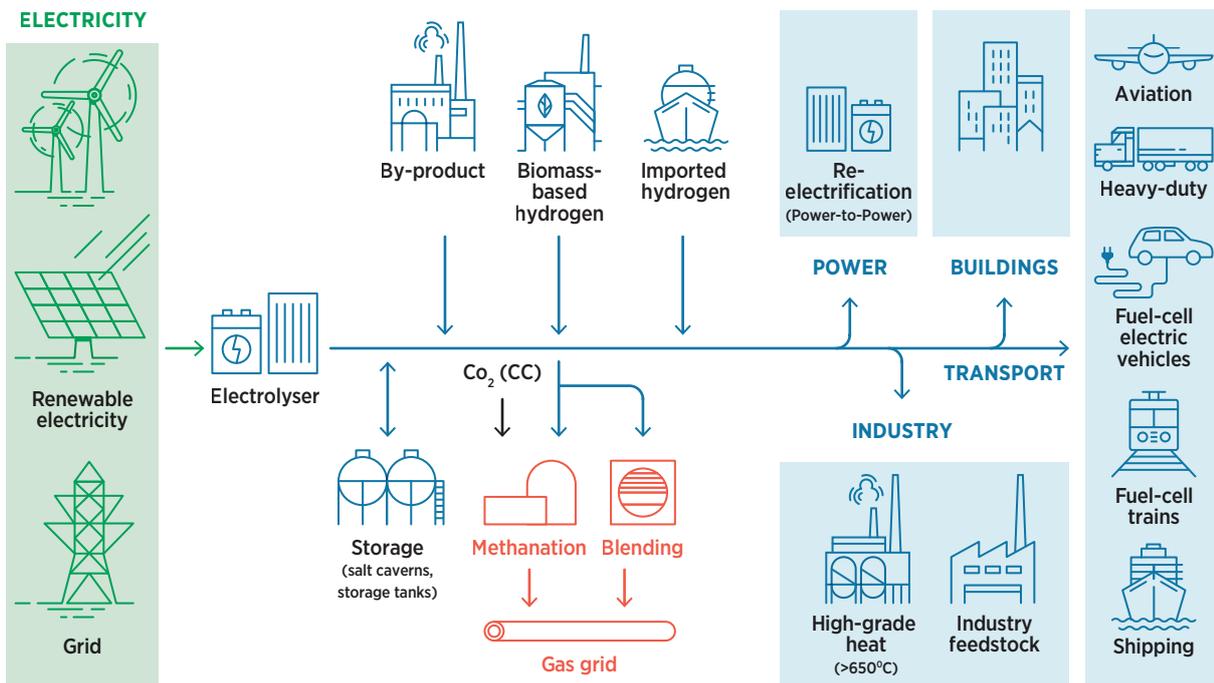
● Apart from using batteries as **enabling technologies**, electricity can be stored by being converted into hydrogen or heat. The value of storage is also given by its potential to decouple generation from demand, thus facilitating the integration of high shares of VRE and avoiding curtailment of the generation surplus. While intraday variations can be better managed with batteries, the electrification of other sectors shifts the demand from these sectors to the power sector. If well managed, this can add significant flexibility to the system.

The process of converting the power generated from solar and wind sources to different types of energy carriers for use across multiple sectors, or to be reconverted back into power, has the potential to greatly increase the flexibility of the power grid. It builds an optional place to put the temporary surplus of power from VRE and reduces carbon by displacing fossil fuel energy sources in other sectors.

Power-to-hydrogen

Power-to-hydrogen is the process of using electrolysis to split water into hydrogen and oxygen using electricity. Hydrogen is a versatile, clean and safe energy carrier that can be used as a fuel for power or as a feedstock in industry. It can be stored and transported as a liquid or a gas and can be combusted or used in fuel cells to generate heat and electricity. Therefore, hydrogen might play a key role in the seasonal storage of renewable electricity, while also having the potential to decarbonise other sectors when used for other applications, such as mobility applications, industrial uses or injection into the gas grid (see Figure 34).

Power-to-gas is the process of converting renewable energy to gaseous energy carriers such as hydrogen or methane. Power-to-gas also uses electrolysis to generate hydrogen from renewable power, which is then reacted with carbon dioxide in the presence of bio-catalysts to produce methane. Synthetic methane can be used as a direct replacement for fossil natural gas, for example in marine transport or power generation. It also is a low-cost way to arrange seasonal energy storage or to transport energy in large quantities by using existing infrastructure.

Figure 34 Integration of VRE into end-uses by means of hydrogen


Source: IRENA, 2018d.

A similar concept is power-to-liquid fuels, in which hydrogen generated from electrolysis is reacted with carbon dioxide to produce liquid fuels such as synthetic crude, gasoline, diesel and jet fuel. These electrofuels (liquid fuels produced from renewable power) can replace fossil fuels without the need to change end-use technologies (IRENA, 2018d). Also, hydrogen can be used as feedstock to produce bulk chemicals, such as methanol or ammonia, that are used in the industry sector (a concept known as power-to-chemicals).

Using hydrogen for energy storage provides unique opportunities. Hydrogen can be produced during times of excess renewable electricity and it can be converted back to electricity to provide power when the renewable source is unavailable, helping stabilise the utility grid. Additionally, the electrolyser can be cycled up and down rapidly to be used as a flexible load providing low-cost balancing services to the power system. (*Key innovation: Renewable power-to-hydrogen*)

● Innovation in **system operation** could consist in using power-to-hydrogen as a solution to defer network investments. Some of the best wind resources are located offshore or in rural areas. Wind energy can be converted into hydrogen, which can be liquefied and transported to regions with energy deficits or demand centres. This facilitates wind power development without requiring large investments in a new transmission capacity. (*Key innovation: Virtual power lines*)

High investments and policy support are needed to adopt this solution. The Power-to-X alliance in Germany is investing up to EUR 1.1 billion to facilitate the production of green hydrogen and synthetic methane.

Power-to-heat

● Another **enabling technology**, renewable power-to-heat, involves using the electricity produced from renewable energy sources to generate heat through heat pumps or large electric boilers. Heat pumps use electricity to transfer heat from

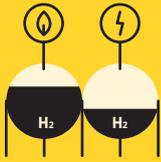
surrounding heat sources (air/water/ground) to buildings. Heat pumps can be used for demand-side management applications, such as load shifting and peak shaving. Renewable power-to-heat solutions can be implemented as either centralised or decentralised solutions. In the case of centralised heating systems, heat pumps or large-scale electric boilers generate heat, which is then transmitted to several buildings through a network of pipes. These systems are also known as district heating systems. Decentralised systems consist of heat pumps or electric boilers for heating individual buildings or residences. *(Key innovation: Renewable power-to-heat)*

Power-to-heat systems can use the excess electricity supplied from these sources to address heating needs and avoid the curtailment of renewable energy generation. For instance, the Inner Mongolia Autonomous Region in China had about 22.3 GW of installed wind power at the end of 2014, but also had very high curtailment levels due to transmission constraints, among other reasons (9% wind curtailment in 2014; 15% wind curtailment in 2015 (Zhang, 2016)). To avoid curtailment, the Chinese National Energy Administration is installing electric boilers with a capacity of 50 MW, which can be used to generate heat using excess renewable energy for the district heating system that conventionally has depended on inefficient coal boilers. The project is targeted for completion in 2020 and aims to generate about 2.8% of yearly planned district heat generation (IRENA, 2017).

The Swedish utility company Vattenfall will be investing around EUR 100 million over two years to build three power-to-heat units with a combined heating capacity of 120 megawatts-thermal. These units will use excess wind energy to heat water, which in turn will transmit heat to residences and commercial buildings. These units are expected to be operational by 2019, at which point a unit in a coal-fired plant with a total capacity of 330 MWh will be shut down, reducing the use of fossil fuels in heating applications (Vattenfall, 2017).

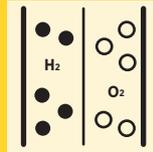
Thermal storage can store energy for days or even months to help address seasonal variability in supply and demand. This is of particular benefit for energy systems in regions that have a significant difference in heating and/or cooling demands between seasons. Surplus heat produced with renewables in the summer can be stored in thermal storage, which then can be used to meet winter heating demand, thereby reducing the need for non-renewable sources of heat during peak times. Thermal storage also can be used to store natural cold in winter, to then supply space cooling during the summer (IRENA, forthcoming b). Key technologies for seasonal storage are aquifers or other forms of underground thermal energy storage.





HYDROGEN STORAGE

Could provide heat and electricity for homes from otherwise curtailed VRE



ELECTROLYSER

For utility-scale grid stabilisation services

Impact of power-to-hydrogen:

- **Storing solar and wind excess electricity in California using hydrogen would provide heat for up to 370 000 homes or provide enough electricity for up to 187 000 homes.**

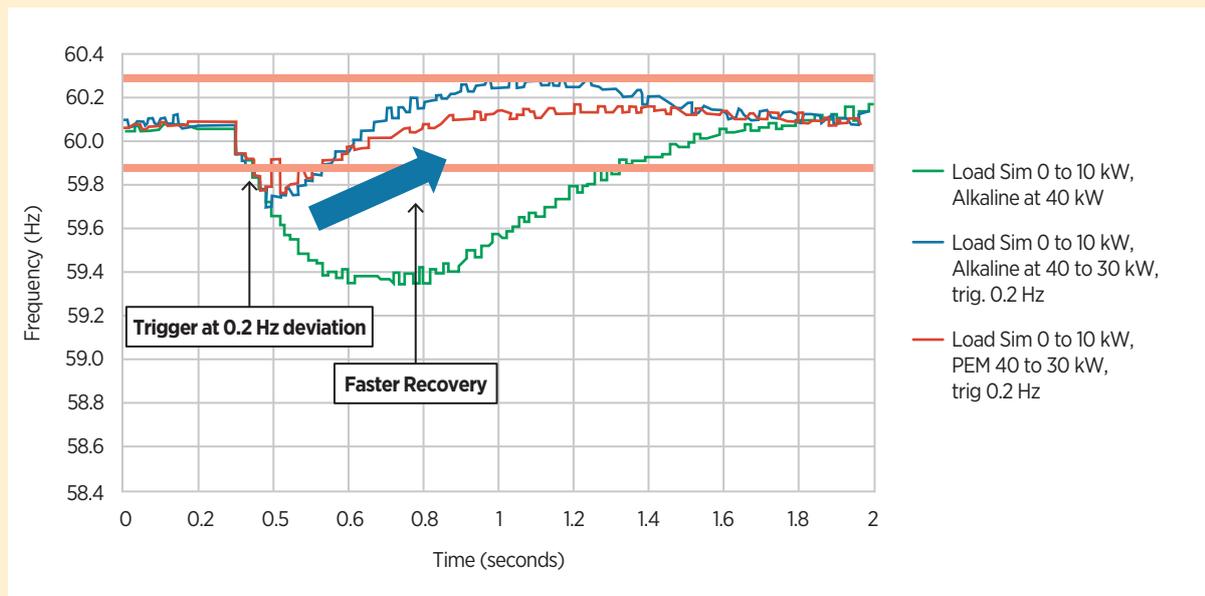
A study by Lawrence Berkeley National Laboratory claims that between 2017 and 2025, between 3 300 GWh and 7 800 GWh of solar and wind energy will be curtailed in California. Hydrogen gas made from excess electricity could be used to power fuel cell cars and trucks, or it could be blended with natural gas and used in anything that is gas fired. If all of the excess solar and wind energy that the study predicts will be curtailed in California were converted to methane and stored as renewable natural gas, it would provide enough energy to heat up to 370 000 homes or provide enough electricity for up to 187 000 homes (Sempra, 2017).

- **Electrolyser technology for utility-scale grid stabilisation services.**

Hydrogenics Corporation completed a trial in 2011 with Ontario’s Independent Electricity System Operator aimed at demonstrating the use of electrolyser technology for utility-scale grid stabilisation services. Experimental analysis done by the US National Renewable Energy Laboratory also shows that electrolysers can rapidly change their load point in response to grid needs and at the same time accelerate recovery in case of frequency deviation (Gardiner, 2014).

Figure 35 shows the result of the experiment conducted. A load simulator was used to generate harmonics on the grid (green line in figure), which reduces the frequency below the lower limit of 59.8 hertz (Hz). A control signal is generated when the frequency reaches a defined point, and that signal is transmitted to the electrolysers to reduce power consumption. The red and blue lines in the figure show the response of the electrolyser (by reducing the power consumption) once the frequency dips by 0.2 Hz. The time taken for such response is less than a second, enabling the electrolyser to provide such services. Commercial tenders from power companies are demanding fast response times including sub-second enhanced frequency response. Revenues from grid balancing payments serve to reduce the cost of hydrogen production via electrolysis (ITM Power, 2015; NREL, 2012).

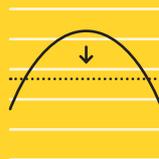
Figure 35. Use of electrolyser for fast frequency response



Source: NREL, 2017.


5 %

Heat demand supplied by electric boiler from excess wind generation


47 - 61 %

REDUCTION IN PEAK LOAD using EVs and heat pumps

Impact of power-to-heat:

- **Electric boiler with heat storage unit reducing curtailment during the night and providing ancillary services in Germany.**

The town of Lemgo in Germany implemented a 5 MW electric boiler in 2012 to contribute to district heating services. The electric boiler draws excess power from the grid during night time and generates revenue by providing this ancillary service. The electric boiler is accompanied by a heat storage unit that enables it to match supply and demand for heat. As per estimates, the electric boiler can compete with the existing combined heat and power plants during the 500 peak-load hours that occur every year. The boiler generated 27 terajoules or 7.5 GWh of heat, which comprised 5% of total heat supply in Lemgo in 2012 (IRENA, 2017c).

- **A project in Denmark demonstrated that a 47% to 61% reduction in peak load could be achieved using EVs and heat pumps.**

The ability to reduce peak load by adding flexibility to residential heating demand was demonstrated as part of the eFlex project conducted by DONG Energy (now Orsted) in Denmark (DONG Energy, 2012). The project assessed the potential peak load reduction by using heat pumps attached to smart devices that can control its functioning, exposed to price-based demand-response programmes. The system was designed so that the heat pump would reduce its consumption or shut off during peak demand intervals (if the house is sufficiently heated) and turn back on during low demand intervals. The study indicated that optimising the heat pump's performance resulted in reducing the peak load by 47% to 61%, depending on the time of day and prevailing temperature conditions.

IMPLEMENTED SOLUTION

POWER-TO-HYDROGEN DEMONSTRATION PROJECTS

HyStock, the Netherlands

- HyStock is a project developed by EnergyStock, a subsidiary of the Dutch gas transmission system operator Gasunie, and is the first power-to-gas facility in the Netherlands. The project consists of a 1 MW proton exchange membrane (PEM) electrolyser together with a 1 MW solar field that will supply part of the electricity required to generate hydrogen from water. The HyStock 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 then can be inserted into storage cylinders and transported to end-users. The project also is investigating how this electrolyser could provide benefits to the power sector by, for example, providing ancillary services to the grid (EnergyStock, 2018).

HyBalance, Denmark

- HyBalance is a Denmark-based project that demonstrates the use of hydrogen in the energy system. Under this project, excess wind power is used to produce hydrogen by electrolysis, which helps to balance the grid. The hydrogen that is produced is then used in the transport and industrial sectors in Hobro, Denmark. The project is expected to help identify potential revenue streams from hydrogen as well as changes in the regulatory environment that are required to improve the financial feasibility of power-to-hydrogen.

H2Future, Austria

- H2Future consists of a 6 MW electrolyser, proposed to be installed at the Voestalpine Linz steel production site in Austria, and is expected to study the use of the electrolyser to provide grid balancing services such as primary, secondary and tertiary reserves, while also providing hydrogen to the steel plant. The hydrogen would be produced using electricity generated during off-peak hours to take advantage of time-of-use power prices.

REFHYNE, Germany

- The REFHYNE project consists of a 10 MW electrolyser, established at a large oil refinery in Rhineland, Germany, to provide the hydrogen required for refinery operations. The electrolyser is expected to replace the existing supply from two steam methane reformers. At the same time, it is expected to balance the internal electricity grid of the refinery and to provide primary control reserve services to German transmission system operators. The pilot is expected to be evaluated after two years, and the data collected is expected to explore the conditions under which the electrolyser can become financially viable. This project also includes a study of a 100 MW electrolyser at the Rhineland refinery, for large-scale analysis (FCH JU, 2018).

GRHYD, France

- A consortium led by ENGIE is demonstrating the GRHYD hydrogen energy storage project in France. France aims to meet 23% of its gross end-user energy consumption from renewable sources by 2020, so the GRHYD project aims to convert the surplus energy generated from renewable energy sources to hydrogen. The hydrogen produced is blended with natural gas – called Hythane(1) – and incorporated into the existing natural gas infrastructure. The project aims to demonstrate the technical, economic, environmental and social advantages of mixing hydrogen with natural gas as a sustainable energy solution (ENGIE, 2018).

POWER-TO-HEAT PROJECTS

Heat Smart Orkney project, Scotland

- A wind power-to-heat scheme is being implemented as part of the Heat Smart Orkney project, which secured funding of GBP 1.2 million through the Scottish Government’s Local Energy Challenge fund. Households will be provided with energy-efficient heating devices that will draw the excess power generated from the community-owned wind turbine, otherwise meant to be curtailed. The household heating devices will be connected to the Internet and will get switched on when the wind turbine receives a curtailment signal.

Power-to-heat expansion in Denmark

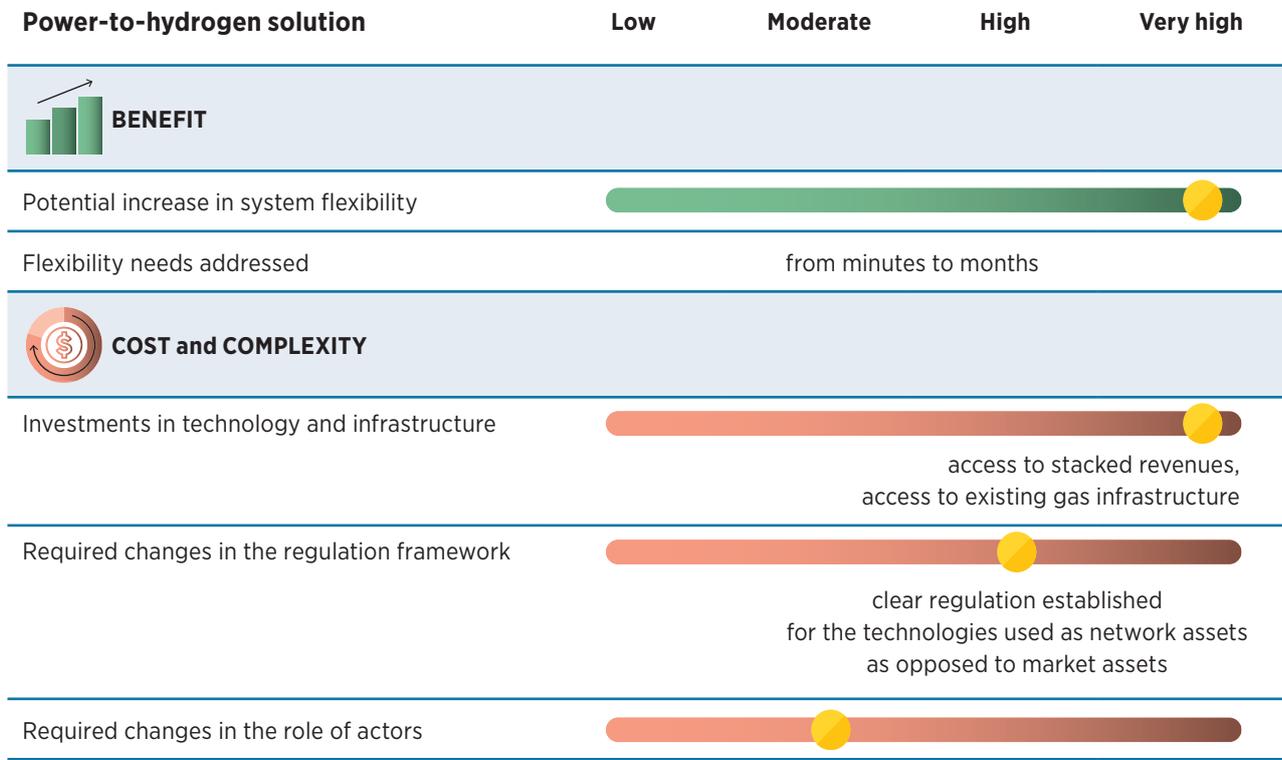
- In 2015 the city of Aarhus, Denmark, expanded the capacity of an existing CHP plant by adding an 80 MW electric boiler and a 2 MW electric heat pump to provide district heating services to the neighbourhood. The plan was to expand the heat pump’s capacity to up to 14 MW after assessing the performance of the existing heat pump (IRENA, 2017). The electric boiler and the heat pump are designed to utilise the excess wind generation in western Denmark, typically the greatest in winter and coincident with the increased demand for heat.



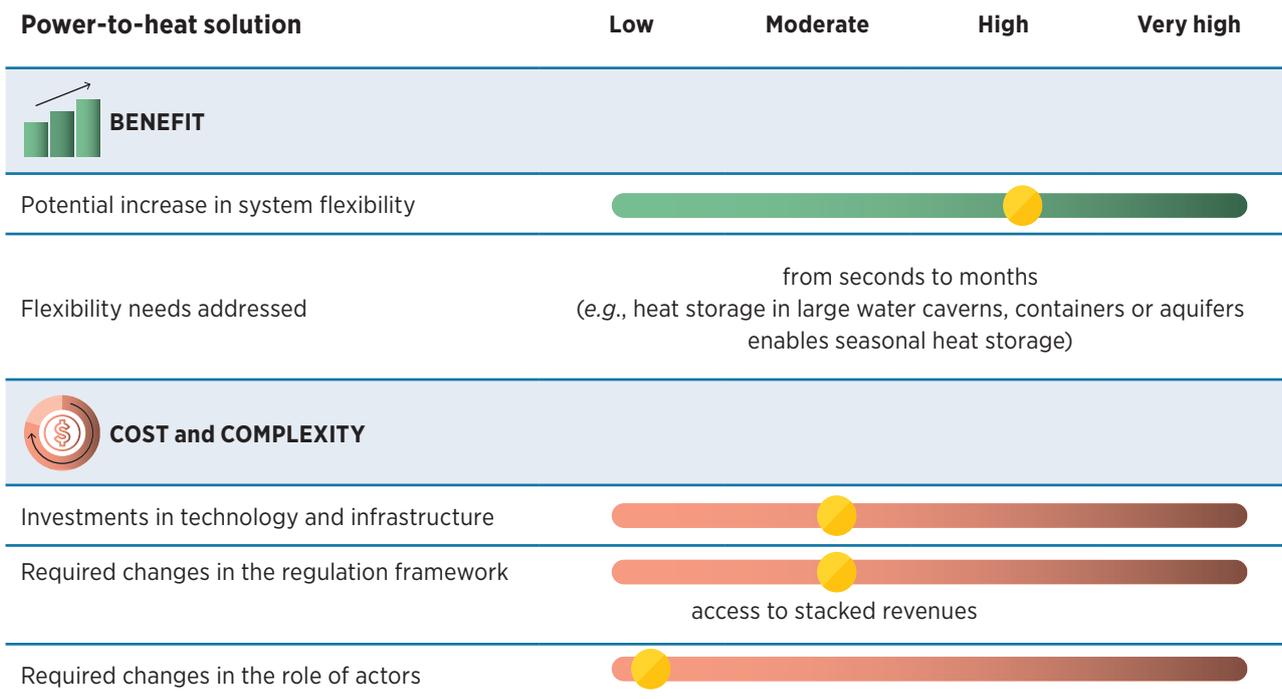
3

SUMMARY TABLE: BENEFITS AND COSTS OF POWER-TO-X SOLUTIONS

POWER-TO-HYDROGEN SOLUTION



POWER-TO-HEAT SOLUTION





4

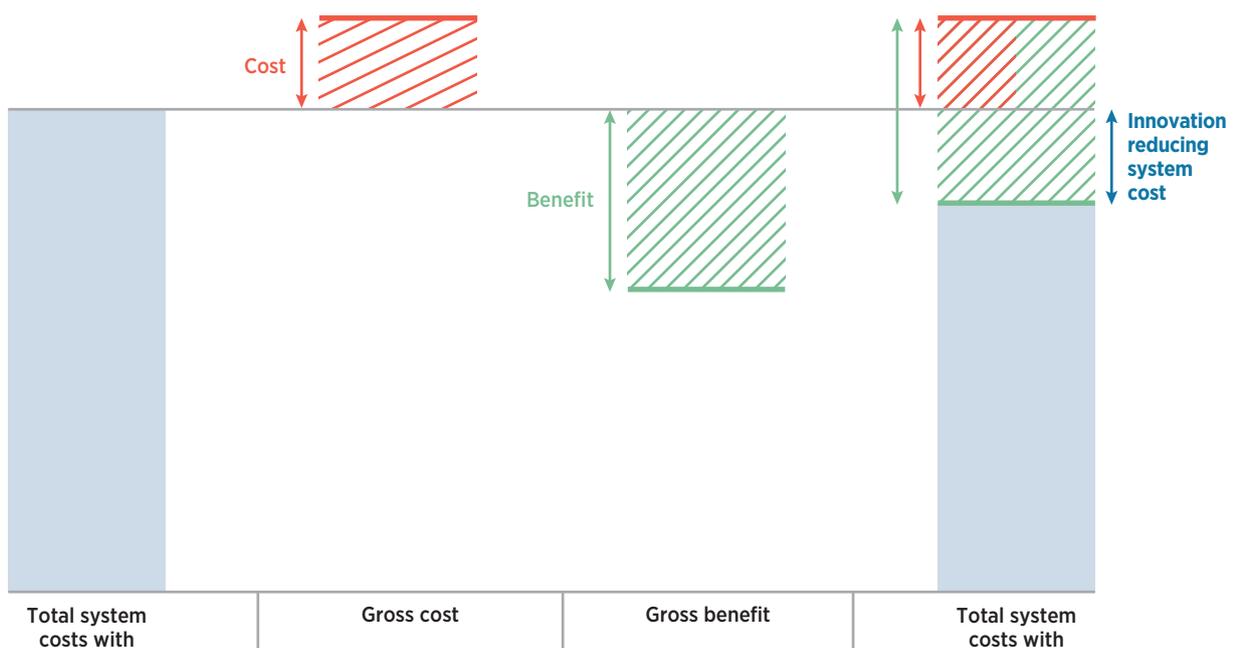
IMPACT ASSESSMENT OF SOLUTIONS



The innovations for integrating high shares of VRE into power systems focus on increasing flexibility in the system while reducing the costs of system operation. In the EU, for example, 50% of the electricity cost is system integration costs. The flexibility of a power system – the extent to which the system can adapt the pattern of electricity generation and consumption to keep supply and demand in constant balance (IRENA, IEA and REN21, 2018) – is directly related to its ability to accommodate VRE generation at the lowest possible cost.

With an objective to achieve 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. Lack of proper planning for VRE integration in power systems may result in high constraints that increase system costs. Sound planning – anticipating system requirements and emerging flexibility solutions – increases the benefits from low-cost VRE generation (IRENA, 2017b), as depicted in Figure 36.

Figure 36 Innovation that maximises system benefits



4

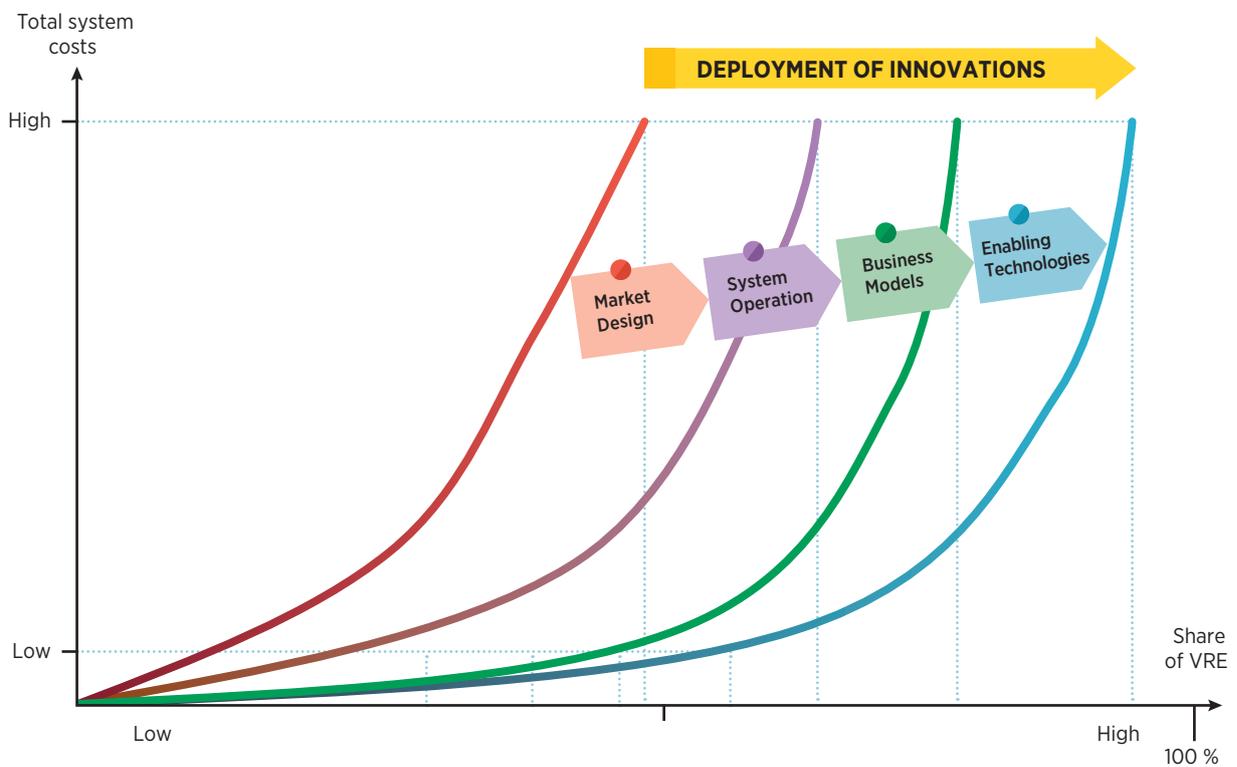
IRENA analysis concludes that investments in grid infrastructure reinforcement and the implementation of other flexibility options for VRE integration are of a similar order of magnitude to the total investments required in additional renewable energy generation technologies. These investments may add up to USD 18 trillion for the period from today to 2050 in a scenario in line with the Paris Agreement and the limited flexibility options being implemented (IRENA, 2018b). Innovation efforts in power systems can decrease the integration cost through solutions that increase flexibility in the system, as illustrated in Figure 37.

Of course, each solution has different implementation costs, challenges and benefits. However, the solutions that will support the integration of renewables, and their costs, will depend on the specific system context, and there is no one-size-fits-all solution. Depending on the system’s characteristics, some solutions may be more relevant than others. As described in Chapter 3, eleven solutions were identified that

could unlock flexibility on the supply side, in the grids, on the demand side and in the system as a whole. This is depicted in Figure 38.

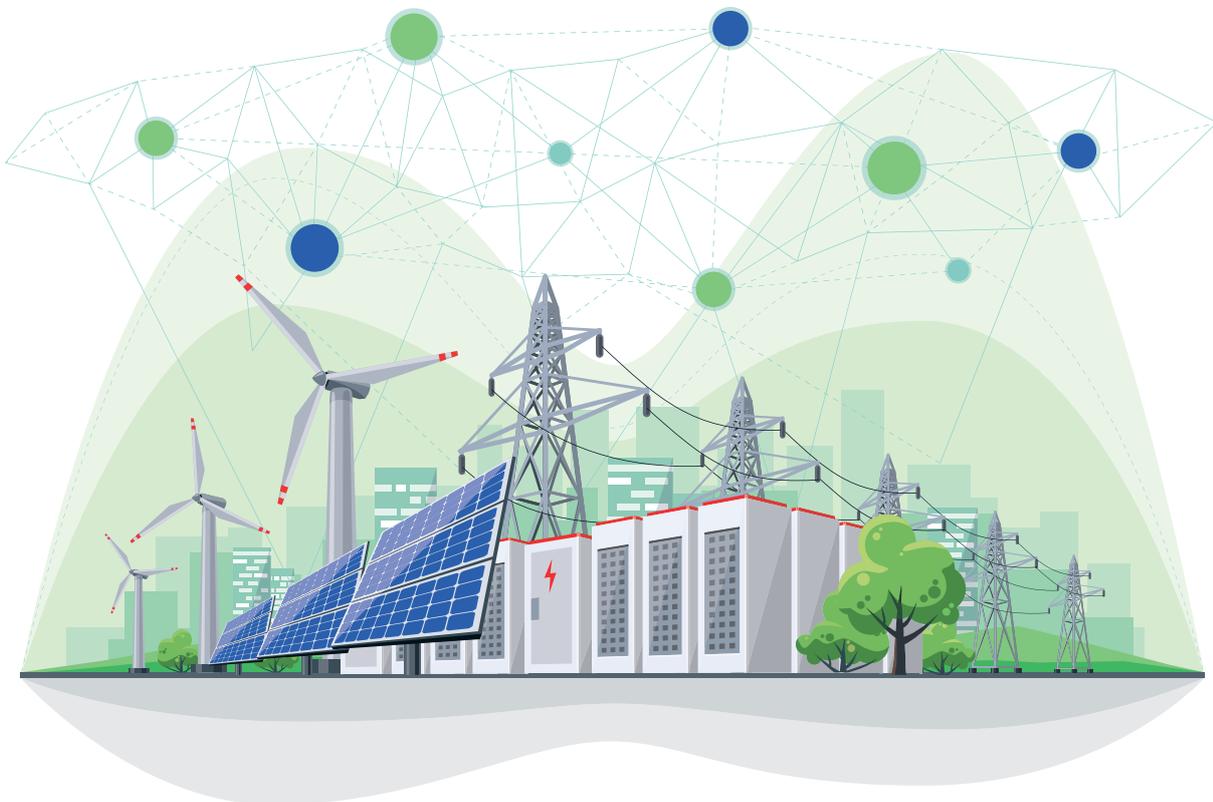
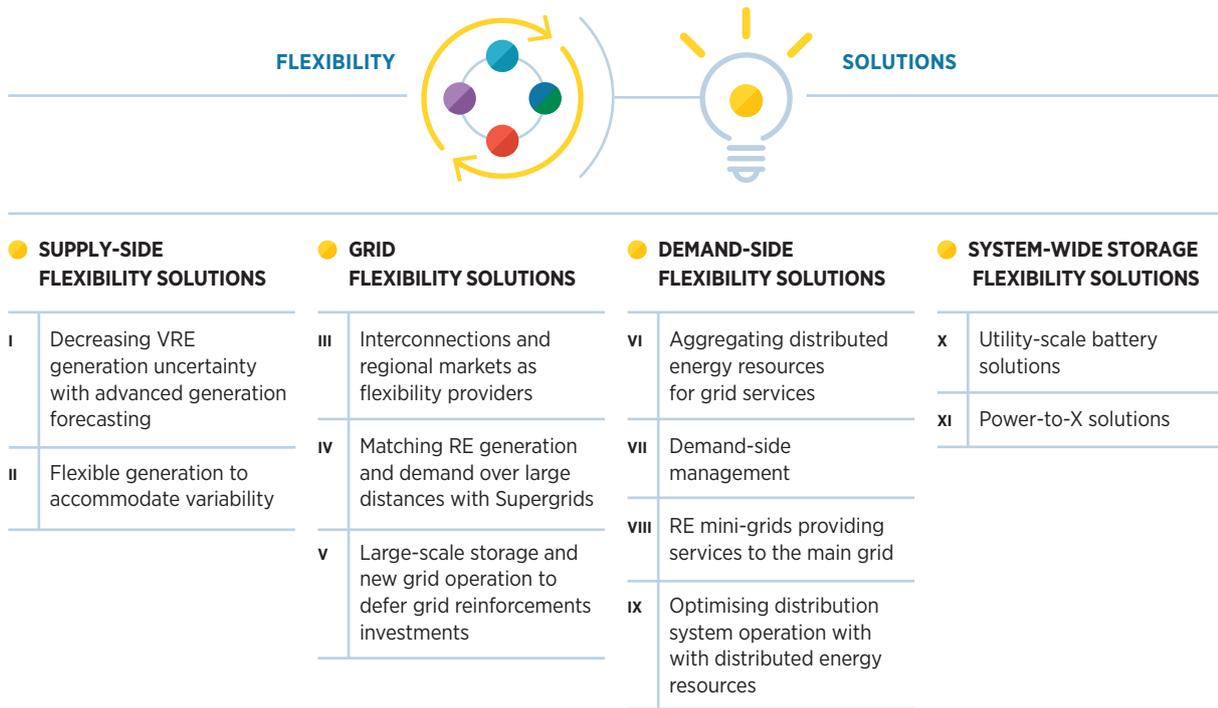
This concluding chapter guides policy makers about solutions that could be the most easily adopted to increase the flexibility in their system. It is structured in two main parts. In the first part, an overview of the solutions is provided, summarising their benefits, costs and other implementation challenges that policy makers should be aware of and address when implementing such solutions. The second part of the chapter provides further guidance for policy makers on the solutions that might be most relevant to their context, and those that have limited applicability. For this, several predefined indicators, which define power systems and country contexts, have been used: 1) population density in cities, 2) seasonality, 3) interconnections, 4) the geographical dispersion of VRE resources and demand, and 5) load profile versus VRE profile.

Figure 37 Innovation reducing total system costs for high shares of VRE



The more innovative solutions are implemented, the higher the share of VRE integrated and the lower the system costs

Figure 38 Solutions that unlock the system's flexibility



4

**4.1 KEY SOLUTIONS:
IMPLEMENTATION CHALLENGES
VERSUS FLEXIBILITY POTENTIAL**

Each of the key solutions identified targets different flexibility needs, ranging from the second and minute levels, used for balancing services in real time, to the hour and day and days levels, used for optimising the operation of available VRE generation. Longer-term flexibility needs, such as weeks and months, are used in more seasonal contexts.

Most supply-side and grid solutions address very short-term flexibility needs, used for real-time operations – usually centralised services provided by flexible generators, utility-scale batteries and interconnections through regional markets. On the other hand, solutions that unlock flexibility on the demand side, mostly decentralised sources, provide minutes-to-hours flexibility for optimising the operation of the available generation sources. Hydrogen, but also heat storage, can store energy for up to months, thus providing seasonal flexibility. Table 3 outlines the key solutions and the flexibility needs addressed by them.

Table 3. Flexibility needs addressed by the solutions

	FLEXIBILITY NEEDS ADDRESSED IN TIME SCALE					
	second	minute	hour	day	week	month
Decreasing VRE generation uncertainty with advanced weather forecasting						
Flexible generation to accommodate variability						
Interconnections and regional markets as flexibility providers						
Matching renewable energy generation and demand over large distances with supergrids						
Avoiding grid reinforcement using large-scale storage technology						
Avoiding grid reinforcement with the innovative operation of existing lines						
Aggregating distributed energy resources for grid services						
Demand-side management						
RE mini-grids providing services to the main grid						
Optimising the distribution system operation with distributed energy resources						
Utility-scale battery solutions						
Power-to-hydrogen solution						
Power-to-heat solution						

Secondly, regardless of the specific flexibility need addressed in time scales, solutions also have a different impact on the overall flexibility of the system. In general terms, they can be compared to each other – assuming that all of them would be implemented in the exact same system.

Also, the implementation of solutions poses different challenges, from investments needed in technology and infrastructure development to other kinds of obstacles, such as regulatory challenges, complexity rising from the co-ordination of multiple stakeholders and/or possible changes in the roles of the main actors, to challenges created by the political environment, international settings, etc. In general terms, the solutions that need the least investments in technology or infrastructure are the ones based primarily on innovations in system operation and market design, which can incentivise old and new

actors to effectively respond to the new system’s conditions, based on the existing assets. Table 4 illustrates the high-level challenges that may appear for different solutions and innovations.

Figure 39 compares the solutions in terms of their flexibility potential and the costs, while Figure 40 compares the solutions in terms of the non-technological challenges. While there is no “silver-bullet” solution that has a very high impact with low cost and lesser challenges, Figure 39 shows that the investment required by a solution is generally directly proportional to the potential flexibility of the solution. However, the same proportionality does not hold true for the non-technical challenges, as illustrated by Figure 40. This is because each solution has diverse challenges, and it becomes difficult to compare one with another in an absolute way. Each of them comes from the specificities of the geo-political and power system context.

Table 4. Challenges for implementing different innovations and solutions

	INVESTMENT REQUIRED	CHALLENGES
<p>Enabling technologies</p> 	<ul style="list-style-type: none"> • High in hardware investment 	<ul style="list-style-type: none"> • Operation of enabling technology
<p>Business models</p> 	<ul style="list-style-type: none"> • Limited in hardware, but high in software (investment in personnel and software may be needed) 	<ul style="list-style-type: none"> • Change in regulation may likely be needed • New Digital technologies need to be implemented (like sensors and predictive models)
<p>Market design</p> 	<ul style="list-style-type: none"> • Limited in hardware, but high in software (e.g., investment in software in power exchanges and market participants) 	<ul style="list-style-type: none"> • Change in the regulatory framework • Political challenges • International co-operation may be needed • Co-ordination between several different stakeholders • Changing roles of the actors in the power sector • Because of winners and losers, may take time to agree and implement
<p>System operation</p> 	<ul style="list-style-type: none"> • Limited in hardware, but high in software (new software, tools, control systems may be needed) 	<ul style="list-style-type: none"> • Availability of data • Data handling • Change in regulations may be needed

4

Figure 39 Solutions’ flexibility potential versus technology costs needed

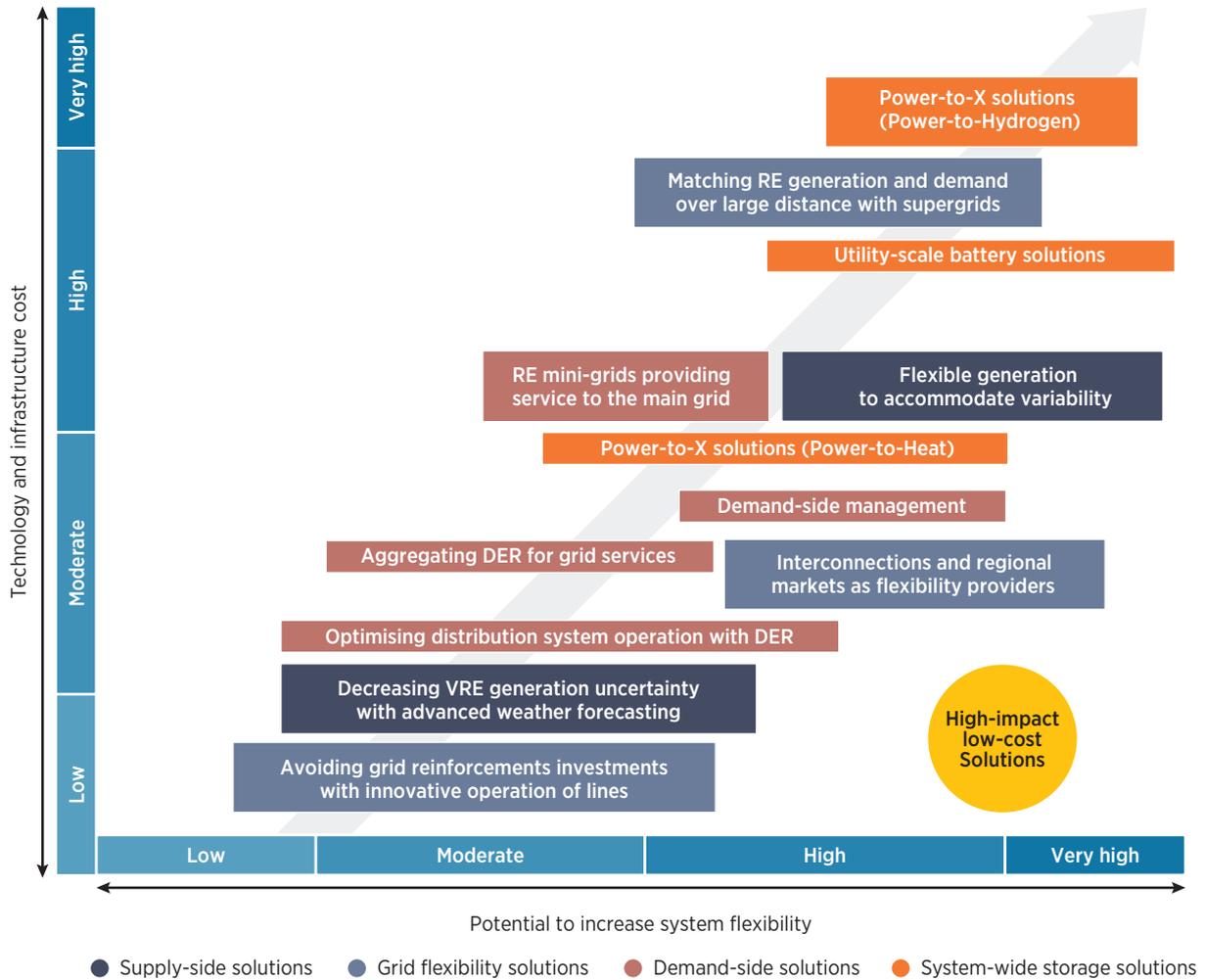


Figure 39 shows a high correlation between the technology and infrastructure costs that solutions require and their potential impact to increase system flexibility. Large-scale batteries, supergrids and the electrolyser for power-to-hydrogen applications are costly technologies and are part of solutions with high and very-high flexibility impact. However, many other solutions offer significant flexibility to unlock at lower costs. Each system needs to assess the level of flexibility needed and the synergies that can be created within its own context.

Importantly, potential synergies exist among the solutions, which would result in lower investments when implementing them together. For example, investments in digital technologies to enable distributed energy resources to provide services

to the grid would help at the same time for demand-side management purposes. Investments 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 even enabling distribution system operators to better optimise the operation of the system by taking advantage of these technologies.

Also, an important variable in this assessment is given by the system context and set-up. For example, if the system is well interconnected, better regulation and operation of the interconnections would enable regional markets with no significant investment in infrastructure. However, if interconnections are not in place, the costs could significantly increase. The same applies for the

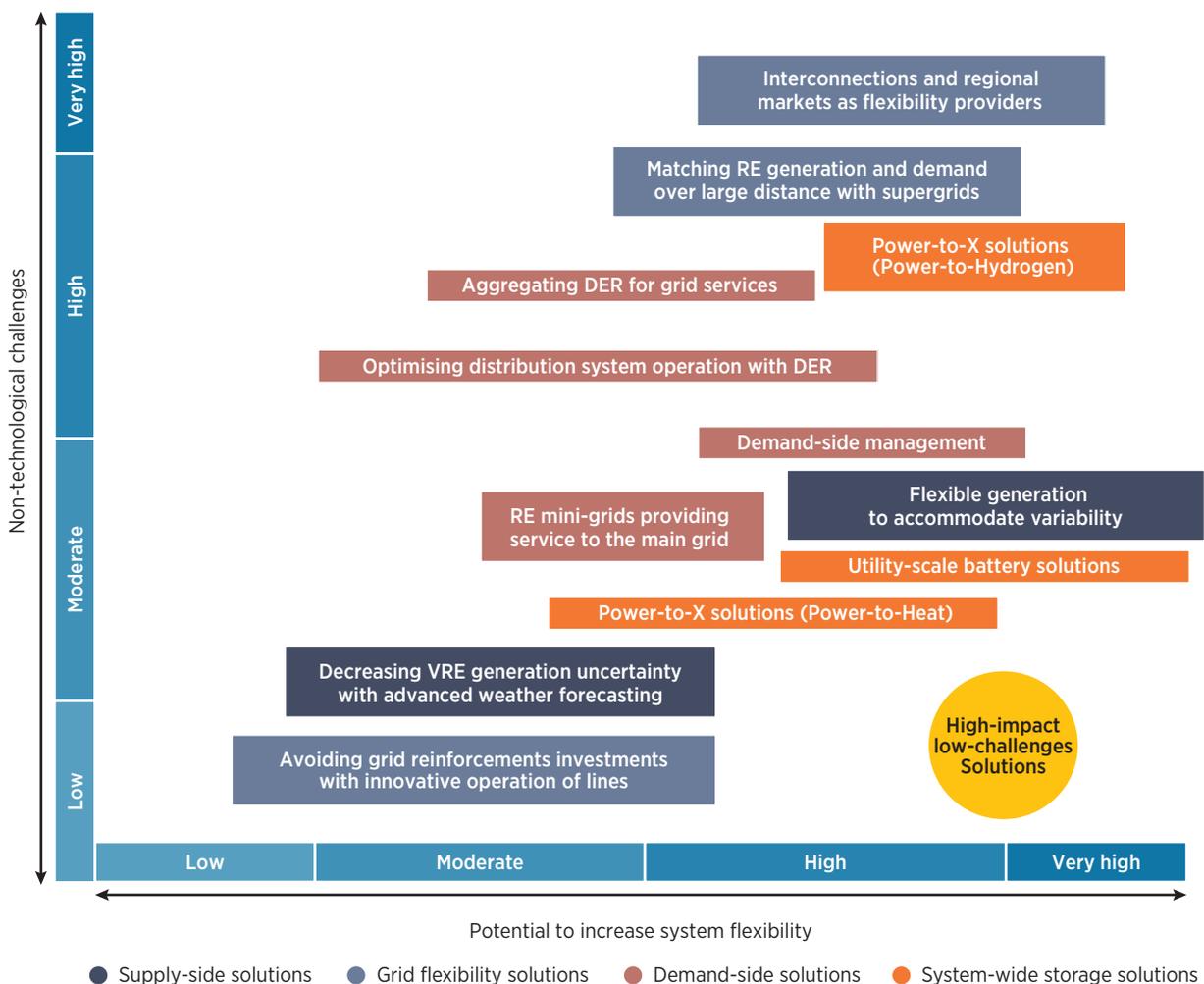
solution for increasing flexibility to accommodate variability of wind and solar generation. When a system already has in its capacity mix flexible power plants, such as large hydro reservoirs or flexible gas plants, a change in operation is needed to harness the full flexibility potential. Otherwise, more costly refurbishment of the conventional capacity fleet would be needed.

Figure 40 provides an overview of non-technological challenges in comparison with the potential flexibility unlocked by solutions. Regulatory changes required are an important aspect considered, with a lot of weight in the case of utility-scale battery solutions or incentivising flexible generation to accommodate variability. In this context, regulation and market design are

important to send the right incentives for flexible operation of the energy resources.

On top of regulatory changes, another important aspect that makes the solution more challenging to implement is the changing roles and responsibilities of actors involved. For example, demand-side flexibility solutions involve changing the role of consumer and changing consumption patterns. For integration of distributed energy resources and allowing them to provide services to the system and the grid, changes in the role of the transmission system operator and, more importantly, the distribution system operator are required. Changing the roles of actors is a significant challenge, as the right incentives and business models are needed to justify the shift.

Figure 40 Solutions' flexibility potential versus non-technological challenges



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

On the other hand, the political set-up and the international environment are often a great challenge when it comes to external co-operation, setting cross-systems roles and responsibilities and putting the regional benefit ahead of the national one. These are among the most significant burdens for establishing well-functioning regional markets or even exchange agreements through interconnections.

Exploring the impact from each solution The list below enumerates the insights and captures the key messages from Figures 39 and 40.

- **Avoiding or reducing investments in grid reinforcement, with innovative operation of power lines** refers to *dynamic line rating*, which implies that more VRE could be allowed through the grid when the temperature decreases or other environmental conditions allow it without compromising on safety. This is therefore a solution that does not require additional investments and has considerable potential to reduce VRE curtailment due to grid congestion. It also involves only one actor: the transmission system operator. The change in operational parameters can be done according to the timeline and accuracy of the weather forecast, usually from hours to weeks in advance.

In Europe, where the temperature varies considerably between summer and winter, 11 transmission system operators have dynamic line rating in operation. For example, TenneT in Germany uses meteorological data from its own stations (ambient temperature, wind speed), and Terna in Italy uses temperature sensors directly at the conductor (ENTSO-E, 2015).

- **Advanced weather forecasting** tools have a great potential to decrease the uncertainty of VRE generation. Although they do not reduce the variability of wind and solar generation, the improved certainty of the generation helps to schedule the system operation and account for the variability better. Advanced weather forecasting tools are already developed and are continuously improving with an added digital component. Artificial intelligence would enhance such tools and boost their accuracy, at increased cost. However, the implementation of this solution is relatively straightforward, as it is a tool used by generators and/or system operators for scheduling the system's dispatch. The main challenge comes from the availability of historical data, which is usually measured and kept by big players in the sector, while small generators do not have access to it. The development of an open platform for such data would enable this solution to realise its full potential.

In Germany, three transmission system operators – Amprion, TenneT and 50 Hertz – are working with the German Meteorological Service and the Fraunhofer Research Institute to improve the weather and power forecasts for wind turbines and solar PV plants. They develop new forecast products, especially focused on grid stability. Real-time data from solar panels and wind turbines around Germany are fed into an algorithm that calculates the renewable energy output for the next 48 hours (IRP Wind, 2016).

*More generally, Figures 39 and 40 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 also may 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.*

- **Demand-side solutions** have a great potential to unlock flexibility in the system. These solutions can be both implicit – with the demand response based on the time-of-use tariffs (or wholesale prices) for consumers (*demand-side management*) – and explicit, allowing the participation of distributed energy resources in the markets and exposing them to the dispatch based on wholesale market conditions (*providing services to the grid*). From a technological point of view, applying these solutions to small-scale resources requires the deployment of smart meters and smart appliances that enhance demand response through automation, in order to connect and enhance communication between the small distributed energy resources and the smart appliances. This is especially true for small consumers and households. Industrial consumers may respond to price signals without a high degree of digitalisation.

Also, the deployment of distributed energy resources, such as solar PV or behind-the-meter batteries and EVs, are providing the opportunity for prosumer participation in the wholesale or local markets. These technologies are deployed based on a bottom-up approach, with their widespread adoption being a result of technological advancements and innovative business models. Therefore, major investments in technology and infrastructure would not be needed from a policymaker point of view, but adapting regulation is required to harness the benefits and services that the already existing technologies, connected to the consumer's point, can provide to the system. Adapting regulations to provide the right price signals, proper valuing and remunerating of the new flexibility services, and enabling the participation of new players in the wholesale markets are required.

Besides the regulatory challenges, these solutions involve the co-ordination of many actors, changing also their roles: prosumers and distribution and transmission system operators. While *demand-side management* can be implemented in any context, the *participation of distributed energy resources in the wholesale*

market, or in the ancillary service market – to provide services to the grid – requires a liberalised market, both at the wholesale and the retail level. Distributed energy resources also can be used for the provision of system/ancillary services for the transmission system operator, or provision of services for the distribution system operator (to defer network reinforcement). In these two cases, a liberalised market is not a requirement, as this could be dealt with through direct contracts with the transmission and distribution system operators.

Belgium has involved demand-response solutions in its daily electricity market operations in a practical manner. The transmission system operator accepts the distributed energy resource capacity to compensate the mismatches between production and peak-power demand, in which industrial customers are given vital importance. In Finland, dynamic pricing structures and smart homes enabled demand-side management at the household level.

- **Existing distributed energy resources also could be managed to best benefit the distribution grid.** Similarly, taking advantage of the already connected assets, distribution system operators can optimise the operation of their networks, directly or indirectly, through price signals. A distribution system operator needs to expand its role and responsibilities in managing the new resources connected to the distribution network and optimising their operation according to the *grid constraints*.

This requires **new innovative regulation for the distribution system operators**, based on performance rather than costs, as well as new operationally complex procedures. It includes incentive regimes that support buying services (operating expenditures, OPEX) instead of building assets (capital expenditures, CAPEX). It also requires **review of the basic terms of access to and charging for use of the networks**. Western Power Distribution, a distribution company in the UK, has released a four-point plan to optimise its network operation: this includes expanding and rolling

out smart network solutions to higher voltages, contracting with aggregators and customers for various services, and co-ordination between transmission and distribution system operators, while ensuring the integrity and safety of the lower-voltage networks (Engerati, 2018). Local flexibility marketplaces are already being developed to allow distribution system operators to procure flexibility and thereby defer network upgrades (e.g., Agder Energi).

- Another solution involves **clustering all the distributed energy resources into a mini-grid** that is able to self-operate and communicate with the main grid, whenever needed, based on real-time circumstances. This solution requires a robust IT system and digitalisation, connecting all the devices of the mini-grid with each other. In the Netherlands, mini-grid pilot projects have been undertaken to focus on sustainable and smart energy management. Such a mini-grid uses an intelligent management system to integrate different components and to balance local supply and demand, reducing costs. For example, solar panels collect energy when the sun shines and charge EVs; any surplus power is either stored in a battery or sent by the system to power other houses in the community.
- **Regional markets and interconnections**, along with **flexible conventional** generation to offset uncertainty, are important to improve overall system flexibility. Both solutions are based on market design innovations, which require a changing regulation framework to better value the flexibility services and to enable the easy trading of these services across systems, respectively. According to the system's current configuration, investments also might be needed. For example, in a system with existing flexible generation options, such as large hydro reservoirs or gas generators, regulations to properly remunerate the flexible behaviour of the plants may be sufficient. However, in systems based on less-flexible generation, such as coal or nuclear plants, technological enhancements and refurbishment of the plants might be required in addition to the new regulations.

For example, in Denmark, where the generation mix consists of wind and thermal sources, thermal power plants were retrofitted to ramp on average 4% per minute, instead of the typical 1%, in response to the demand for flexibility in the production fleet, expressed through power price fluctuations throughout the day. Improved ramping properties allow the plant to increase or decrease participation in the market faster and follow the volatility in power prices. Similarly, the minimum load is as low as 15% in some Danish thermal power plants, whereas the standard if this property is not optimised is 30% to 40% (Energinet, 2018).

While regional markets can unlock huge amounts of flexibility, interconnections are a pre-requisite. When investments in interconnections are needed, the challenges and costs of implementing such a solution increase. Also, regional markets require a (reasonably) harmonised market design across the region. This can imply different challenges for implementation: the need for strong institutional arrangements and a regional mindset and trust between the involved parties, with participants putting the regional security of supply ahead of national needs and interests. Regional markets all over the world, including in Europe, Central America, Africa and the US, are facing the same challenges and same benefits from VRE integration. In the long run, despite difficulties in international co-operation, these will need to form part of the solution for renewable energy integration and for meeting the Paris climate protection targets. International negotiations can take time, and such discussions should begin sooner rather than later.

- **Power-to-heat solutions** are heavily dependent on the operation of heat pumps and large electric boilers. As technologies, they have reached a mature commercialisation stage. Now, digital components would help to optimise their operations and aid flexibility in the power system. For example, the Scottish government has secured funding of GBP 1.2 million for a wind power-to-heat scheme. Households will be provided with energy-efficient heating devices that will draw the excess power generated from

the community-owned wind turbine, otherwise meant to be curtailed. The household heating devices will be connected to the Internet and will get switched on when the wind turbine receives a curtailment signal.

- Solutions based on technologies in the early stages of commercialisation – such as **utility-scale battery storage** and the electrolyser used for **power-to-hydrogen solutions** – are the ones that are most costly at the moment, thus requiring risky investment that comes at the point of mass roll-out but before costs fall. These solutions are still in an early stage of commercialisation. Battery costs are slightly lower – and their implementation and operation are more straightforward than those of power-to-hydrogen solutions – because of high levels of deployment over the last decade. On the other hand, adapting regulation is needed for utility-scale batteries, as they are new actors that can both consume, generate and store electricity. Their behaviour in the system should be incentivised to best benefit both the players and the system.

For example, a battery storage facility of 100 MW/129 MWh has been installed in South Australia to firm up the power generated from the Hornsdale Wind Farm and simultaneously to provide ancillary services to the grid.

Converting the renewable power to hydrogen, using an electrolyser, is only one part of the solution. Storing and further using the hydrogen in other applications, or converting it back into power, requires other technologies, proper infrastructure and operational procedures to be in place. In Austria, H2Future projects proposed installing a 6 MW electrolyser at the Voestalpine Linz steel production site. This project will study the use of the electrolyser to provide grid balancing services, such as primary, secondary and tertiary reserves, while also providing hydrogen to the steel plant. Hydrogen would be produced using electricity during off-peak hours to take advantage of time-of-use power prices. The hope is that by scaling the sizes of electrolysers and with mass production, their costs will decrease significantly.

Unlocking existing flexibility is the first action to take with innovations

- The solution based on **supergrids** has the highest implementational complexity, for several reasons. First, it is a less-developed technology, at least with regard to meshed HVDC grids with DC breakers. Only a few pilot projects have been implemented across the world. Second, electricity trading between different countries involves economic and political agreements, which might increase the complexity of this solution. Issues regarding regulation and standardisation, as well as ownership, rights and revenue allocation also might emerge.

As part of the German Energiewende, HVDC grids were built to integrate offshore wind power with the German grid. In April 2015 TenneT, a German transmission system operator, commissioned SylWin1, currently the world's longest offshore grid connection. SylWin1 connects three wind power plants 70 kilometres off the coast. With SylWin1, with an output of 864 MW, the wind farms can feed large quantities of wind power into the German grid via an HVDC connection. To transport the energy generated by a total of 232 wind turbines to the onshore converter station, a distance of 205 kilometres must be bridged: 160 kilometres of submarine cable and 45 kilometres of land cable, supplying more than 1 million households with clean wind energy (TenneT, 2018).

On the other hand, not only Europe, China and North America but also a growing number of other regions in the world are pushing forward international interconnections and markets (e.g., the Gulf Cooperation Council and the African power pools as well as South America, India with its neighbours, East Asia and others). International trading rules have been developed and refined over decades, and different parts of the world are actively trying to learn from one other in this field.

4

Table 5 Summary Table.

Legend: ● ● ● ● low impact/cost/challenge ● ● ● ● very high impact/cost/challenge

 SOLUTIONS	Potential increase in system flexibility	Technology and infrastructure costs	Required regulatory changes	Required changes in the role of actors	Other challenges
Decreasing VRE generation uncertainty with advanced weather forecasting	● ● ● ●	● ● ● ●	● ● ● ● providing VRE balance responsibility would improve their forecast	● ● ● ●	availability of weather historical data for small players
Flexible generation to accommodate variability	● ● ● ●	● ● ● ● if refurbishment of thermal plants are applicable	● ● ● ●	● ● ● ●	improved modelling tools and data availability
Interconnections and regional markets as flexibility providers	● ● ● ●	● ● ● ● if interconnections are not in place	● ● ● ● depends on the degree of market integration	● ● ● ● co-ordination between transmission system operators and market players in different markets	political challenges regional mindset and trust
Matching renewable energy generation and demand over large distances with super grids	● ● ● ●	● ● ● ● cost of supergrid	● ● ● ● agreed regulatory frameworks between the connected regions	● ● ● ●	international, political co-operation needed
Avoiding grid reinforcement using storage technology	● ● ● ●	● ● ● ● varies with the storage technology used	● ● ● ● clear regulation established for the technologies used as network assets as opposed to market asset	● ● ● ● new tasks for the transmission and distribution system operators	
Avoiding grid reinforcement with innovative operation of the existing lines	● ● ● ●	● ● ● ● potential cost of the control system	● ● ● ●	● ● ● ●	

 SOLUTIONS	Potential increase in system flexibility	Technology and infrastructure costs	Required regulatory changes	Required changes in the role of actors	Other challenges
Distributed energy resources providing services to the grid		 ICT platform, provided that the DERs and smart meters are in place		 active consumers, distribution and transmission system operators, new players such as aggregators	involves co-ordination between stakeholders, including prosumers
Demand side management		 smart meters, ICT	 price signals to consumers	 active consumer – automation as a facilitator	consumers participation and guaranteed privacy
Renewable energy mini-grids providing services to the main grid		 mini-grid, smart meter, ICT			
Optimizing the distribution system operation		 smart meters, ICT	 new incentives, regulatory framework for distribution system operators	 new role for distribution system operators	Grid instability management
Utility-scale battery solutions		 depends on scale and costs dropping	 send the right incentives to the new player that can generate, store and consume electricity		Standards to be developed between DSOs and battery providers
Power-to-hydrogen solution		 cost of electrolyser, retrofitting gas infrastructure pipelines	 access to stacked revenues, access to existing gas infrastructure		
Power-to-heat solution					

4.2 INDICATORS ON THE SUITABILITY OF SOLUTIONS

The solutions identified differ in both the complexity of implementation and the flexibility needs addressed, as explained in the previous section. However, not all solutions are as relevant in every context. Therefore, policy makers have to carefully assess each solution according to the specific context in which it is to be implemented. This section aims to guide policy makers on which solutions, and which kinds of innovations, would be more relevant based on five indicators.

This is not a “how-to” guide but a rather an attempt to indicate what, from the innovation landscape, could fit better in one context or another. Its intent is to help policy makers narrow down their options and consider which solution(s) to investigate more thoroughly. For each of the indicators, solutions with limited applicability have been presented, along with the recommended ones.

To illustrate how the solutions can be relevant to different circumstances, five indicators have been chosen:

- 1 Population density in cities: high-density population/low-density population
- 2 Seasonality: four seasons/no seasons
- 3 Interconnection possibilities: interconnected systems/isolated systems
- 4 Spatial proximity of VRE sources and demand centres: demand centres close to VRE sources/demand centres far from VRE sources
- 5 Time match between VRE generation and load profile: VRE generation matches demand (flat net load)/VRE generation does not match demand (net load with peaks).

The solutions that are impacted by each of the indicators are discussed below.

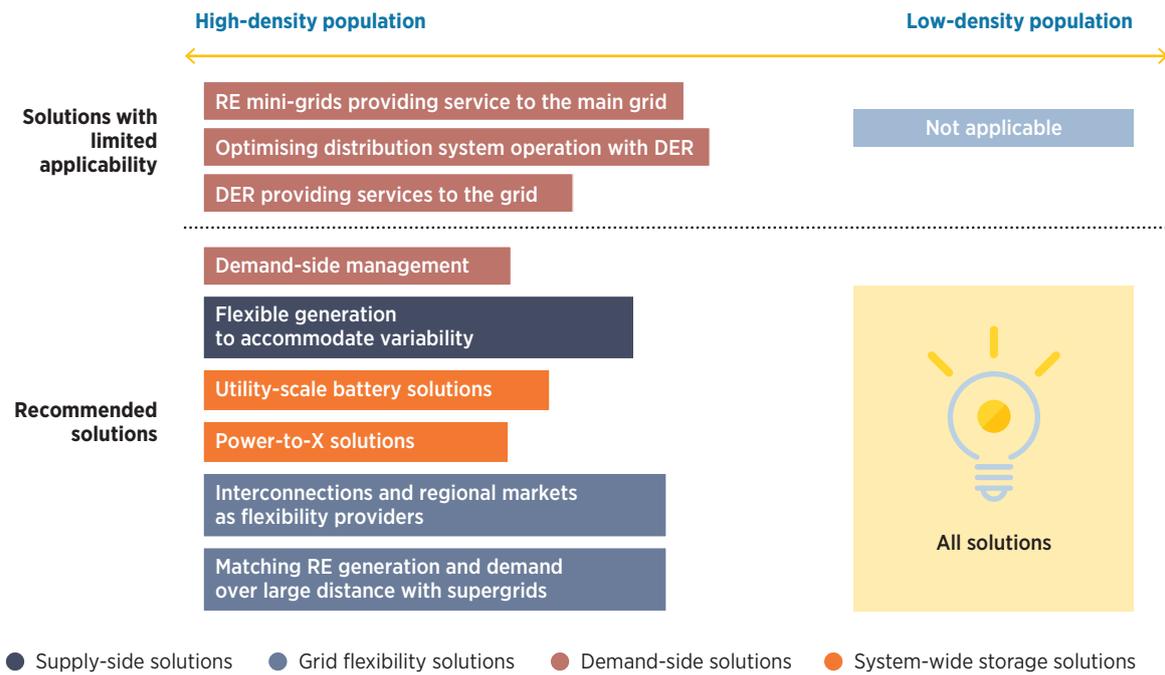
1. Population density in cities

The population density in cities is an important indicator for assessing the level of decentralisation that is physically and practically possible. Decentralised solutions are not feasible options in heavily populated cities where people live in skyscrapers or very busy neighbourhoods (e.g., New York, Bogota, São Paulo, Paris, etc.), since there is little space in the consumer’s house to add batteries, solar PV panels on the roofs or an EV plug. *Demand-side management*, meaning demand response based on time-of-use tariffs or direct load control, is the only demand-side flexibility option that can be unlocked in such contexts. Given the load size in such busy settlements, this solution can have a great potential impact.

It therefore is implied that most renewable energy projects would be large-scale projects deployed outside cities. *Flexibility from existing conventional generation* and storage solutions (from *utility-scale batteries* or *converting renewable power into hydrogen or heat*) would be of great importance in integrating high shares of VRE. Grid flexibility solutions are also important for high-density population areas, where a strong grid and the interconnections with neighbouring systems are available. Consuming more renewable energy in cities is achieved mainly through improved power market and interregional renewable energy trading. *Supergrids* could be a solution for bringing renewable energy to these demand centres, over long distances.

On the other hand, for cities or areas with low population density, the availability of physical space enables decentralised solutions to be deployed. This could unlock deployment of distributed generation, such as solar PV panels, together with flexibility sources on the demand side; behind-the-meter battery storage, EV smart charging, residential heat pumps and mini-grids can all offer valuable services to the main grid.

Figure 41 Solutions guide according to population density in cities



2. Seasonality

Seasonality is an important indicator for the flexibility needs of a power system. Whereas short-term flexibility needs are present regardless of the context, long-term flexibility is needed mostly in systems that have temperature variations throughout the year.

Countries with seasonal variations have much higher electricity and energy demand in some seasons than others (in regions with cold winters, energy demand in winter is much higher than in summer because of heating needs, whereas in regions with very hot summers and mild winters, energy demand is higher in the summer due to air conditioning usage). Therefore, long-term storage would enable saving the surplus renewable power generated in the season with lower demand to use it in the season with higher demand.

Power-to-X solutions, in particular power-to-hydrogen, can address this challenge, as hydrogen can be stored for longer periods of time, albeit so far at very high costs and energy losses. Hydrogen can serve as a long-term storage medium with the capability of storing energy for several months. For example, Germany has 30% higher energy demand in winter than in summer, but renewable

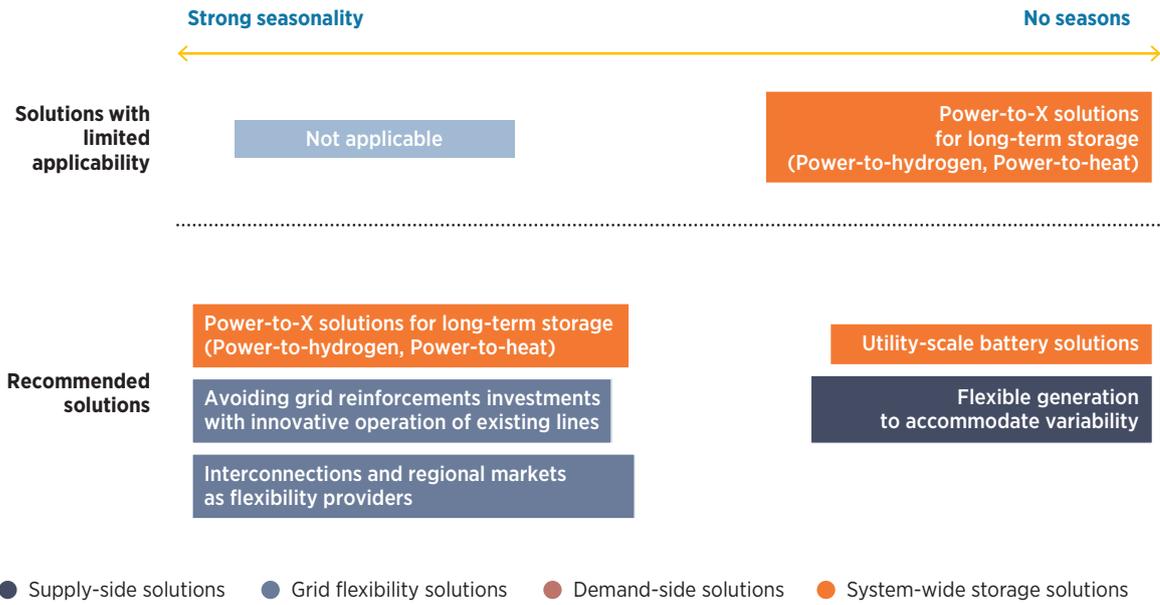
energy sources generate around 50% lower power in winter than in summer (Hydrogen Council, 2017). Currently, storing power in the form of hydrogen is not economical. However, by 2030 the economies of scale are expected to drive costs down. How hydrogen could fit into an overall 2050 decarbonised energy system in Europe is a question of increasing interest and studies. Some power-to-heat technologies, such as aquifers or other underground thermal storage, can store energy for up to six months.

On the grid side, *dynamic line rating* is an innovation that makes use of the changes in temperatures and other environmental conditions, enhancing the grid’s capability to transmit more power in periods with lower temperatures, high wind speed, less solar radiation, etc.

All of these solutions have limited applicability in areas where temperature and VRE availability are constant throughout the year. In these contexts, long-term flexibility might not be needed, and the focus should be primarily on short-term flexibility only. *Utility-scale battery storage* is a solution that can address short-term system flexibility in the entire system, although other such solutions are suitable as well.

4

Figure 42 Solutions guide according to seasonality



3. Interconnections

Interconnections are powerful flexibility providers in a power system. When a system is very large or well interconnected, the establishment of *regional markets* to capture the synergies among different power systems and enlarge the balancing area is a solution that deserves policy makers’ attention. Also, when interconnections are not in place but are possible to build, they should be considered. There is also the issue of how correlated the VRE resources are within the wider interconnected region or the large system, and how the interconnections should be operated to take best advantage of different wind/solar patterns in different locations. A close-to-real-time operation of regional markets would be of benefit to increase flexibility.

This solution is not applicable in an isolated, small system, where interconnections with other systems are neither existent nor possible to build. A solution to connect an isolated system with another, more distant system, with which synergies can be harnessed, is through a *supergrid*.

However, in these isolated systems, the flexibility should come entirely from within the system itself. Options to consider in this case are to *incentivise conventional generation to be more flexible, storage solutions* (either through batteries or power-to-X options) or unlocking demand-side flexibility.

4. Spatial proximity of VRE sources and demand centres

Rather than focusing on flexibility options, this indicator guides policy makers towards solutions that bring the VRE generation from areas rich in resources to the demand centres. When such synergies are possible, *supergrids* are one of the emerging options that transport electricity over long distances with low losses. Creating *regional markets* for capturing the synergies and complementarities among different VRE generation profiles and load profiles is also a powerful option. When the grid connecting the VRE generation with the demand is congested, there are several innovative solutions to *defer reinforcement investments while avoiding VRE curtailment* (using either storage applications or dynamic line rating).

However, when areas with good VRE resource spots coincide with demand centres, deploying local VRE generation projects and other distributed energy resources would increase both renewable energy consumption and demand-side flexibility in the system.

4

5. Time match between VRE generation and load profile

The net load profile is the difference between the VRE generation profile and the load profile. When the VRE generation profile does not match the load profile, flexibility in the system is required to meet the net load, when it peaks. Options to increase system flexibility, in this case, come from across the entire value chain of electricity, including increasing the ramp-up and ramp-down capabilities of conventional plants, balancing the system via interconnections and regional markets, and demand-side management options and storage solutions.

Recommended solutions in any context

As illustrated in this chapter, there is no one-size-fits-all solution. All solutions have different levels of complexity in their implementation and address different needs in terms of flexibility, based on the specificities of the system. However, of the 11 key solutions identified, 2 can be considered in almost all circumstances: *decreasing VRE generation uncertainty with advanced forecasting*, and *demand-side management*. More accurate generation forecasting of VRE power plants would decrease uncertainty and enable better integration of renewable energy in any system. Similarly, improvements in demand-side management and an effective load response to price signals can unlock demand-side flexibility regardless of the context.

Figure 45 Solutions guide according to the net load profile

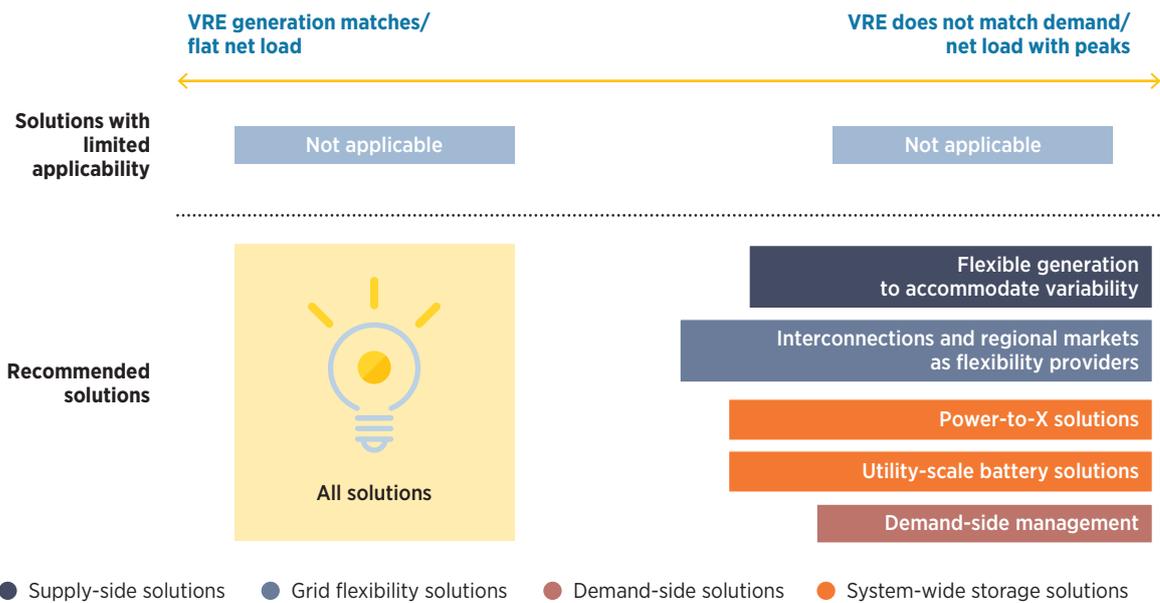


Figure 46 Solutions for all contexts





5 SUMMING UP: EIGHT-STEP INNOVATION PLAN



Innovation is the engine powering the energy transformation, and the pace of innovation around the world is accelerating. A multitude of innovation solutions are being trialled and adopted in a wide range of countries for a wide range of applications across energy systems. The power sector has been leading the way with rapid cost reductions in the key renewable energy technologies of solar and wind and accelerating adoption in many power systems.

At higher shares of VRE, flexibility becomes an increasingly valuable characteristic in power systems. As VRE shares expand, policies need to adapt to the changing system conditions. In an age of inexpensive VRE, the success of integration strategies is crucial for high shares of VRE to translate into low-cost electricity for consumers (IRENA, IEA and REN21, 2018).

The future is upon us: already, we can see a number of changes that are happening:

- **Generation:** Large, inflexible thermal generation is progressively being replaced by smaller-scale renewable generation, much of which is not commercially flexible (zero marginal cost) and which is weather dependent (non-energy-price-responsive resources). In the short term, existing conventional generators need to become more flexible, with improved ability to provide a faster ramping capacity to react to increasing volatility of net load. In the long term, flexibility also will come from demand management and increased grid interconnectivity.
- **Sector coupling/demand:** A trend of electrification of end-use sectors, such as electrification of transport (EVs) and potentially of the heating sector, will eventually develop, greatly increasing the load on distribution networks. These new loads could be relatively high capacity/low energy if not managed, but they are inherently flexible: electrification technologies include battery or thermal storage that could help smooth out the demand pattern to match the availability of generation and the capacity of the distribution grid. This optimal contribution to system flexibility will only happen if their integration is properly managed and if customers accept that their use patterns are not solely their personal choice.
- **Energy storage:** Battery technology is becoming increasingly affordable. Even domestic users, especially households with solar PV systems that want to maximise self-consumption, are installing batteries at scale, due to personal preference over economics. Distribution grid operators are turning to mid-scale batteries to avoid network upgrades. Also, power-to-X applications that are supporting sector coupling (power-to-heat and power-to-hydrogen) are emerging, with great potential to store energy in different forms.
- **Distribution grid:** The growing awareness about “predict and provide” for network capacity (predict the load and provide the available capacity, to balance supply and demand) will become unsustainable, especially with

5

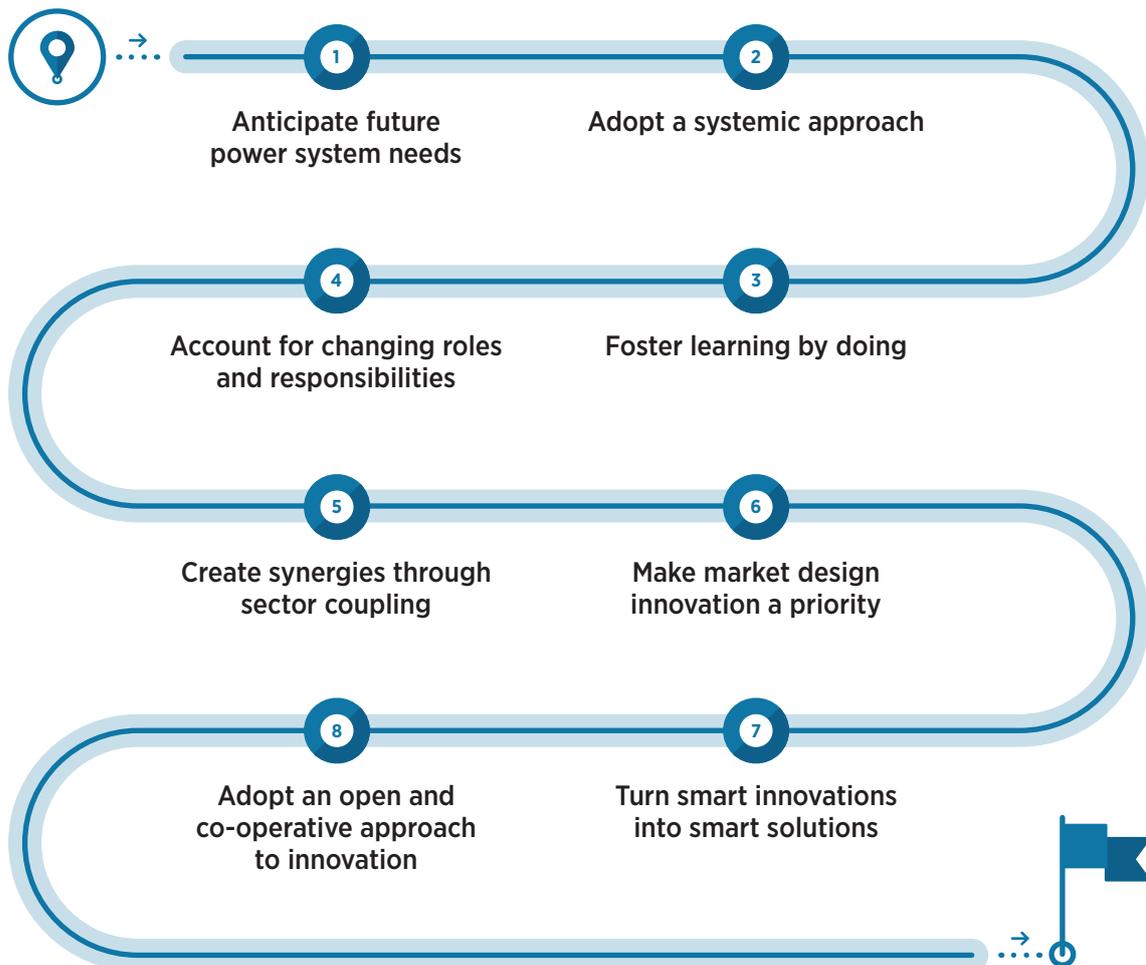
electrification. Flows on distribution networks will become less predictable. Also, distribution system operators will need better visibility on lower-voltage parts of their networks, and better tools for control.

- **Aggregation/demand response:** A space is growing for increasing demand response, including Improved technology readiness, the availability of suitable market or ancillary service products and marketplaces or platforms, and new business models and actors. Active energy consumers, often called prosumers because they both consume and produce electricity, are changing the dynamics of the sector, with great potential to unlock demand-side flexibility.

THE EIGHT-STEP INNOVATION PLAN

The strong business case for VRE technologies, such as wind and solar PV, are positioning those at the core of the transformation. Innovations being trialled in front-running countries show that power systems can operate 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 in integrating VRE. To bridge the gap, the following recommended actions could be implemented by countries.

Figure 47 The eight-step innovation plan for power sector transformation



1 Develop far-sighted policy frameworks that 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 look at the quick wins alone. They need to look ahead to a time when renewable energy deployment has been successful, and design the markets and systems around this future.

2 Adopt a systemic approach, drawing together innovations in technology, market design, business models 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 this report show that solutions tailored to the country context 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 so support the energy transformation. Potential synergies among the different solutions also exist, which can result in lower investments when implementing them together.

3 Foster learning by doing through ongoing trial and demonstration.

We cannot predict a unique archetype of the power system of the future. Innovation necessarily involves failing, but energy systems cannot fail – the lights must stay on, and we need to understand what 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 bring solutions. There is a need for the 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 Account for changing roles and responsibilities in the operation of the power system.

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 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, as it fosters flexibility at relatively low cost.

Market design solutions for VRE have shown to be very impactful and low-cost solutions, making them a first option 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 the value is moving from providing kilowatt-hours to providing flexibility to accommodate more low-cost VRE. The glue that holds this together is a market that prices energy and balancing services properly and that

remunerates all actors that are able to provide flexibility. Proper planning accounting for the energy transformation would result in holistic and cost-effective market designs. Otherwise, solutions based on quick wins with a patches approach 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 Create synergies between renewable power supply and electric mobility, heating and cooling.

Valuable synergies can be harnessed between renewable power and the decarbonisation of end-use sectors through sector coupling. 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 using digital technologies.

Digital innovations (artificial intelligence, the Internet of Things, blockchain, etc.) are starting to significantly impact power systems

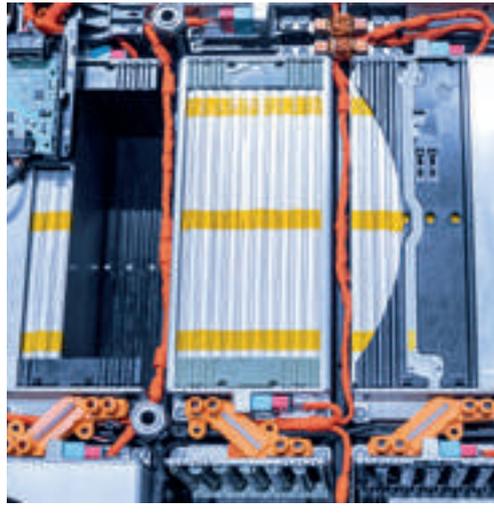
in many different ways. The implications for established models and actors and the risks are not yet fully understood. Technologies exist, but smart applications are still limited. Energy systems should make far more use of the “smartness” that digital innovations enable. Notably, other industrial sectors have applied digital technologies at (close to) full potential, providing knowledge that could be 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 other industrial segments that were not considered part of the energy sector could bring great opportunities to harness the synergies. Innovation should be coupled with a sustainable and inclusive approach.

This report shows that policy frameworks that encompasses these elements are well positioned to transit a successful power sector transformation. A multitude of innovative solutions to facilitate the integration of VRE, which a decade ago may have seemed like science fiction, are now being implanted or trialled around the globe. The solutions emerging can be tailored to suit most power systems. With the insight from this report and its accompanying online resources, energy system planners and decision makers can seriously contemplate plans for a renewable-powered future.





REFERENCES

- ABB** (2017), “India to build longest 800kV UHVDC transmission line”, *T&D World*, <https://www.td-world.com/overhead-transmission/india-build-longest-800kv-uhvdc-transmission-line>.
- ACEG** (2017), “Texas as a national model for bringing clean energy to the grid”, Americans for a Clean Energy Grid, <https://cleanenergygrid.org/texas-national-model-bringing-clean-energy-grid/>.
- ACER** (2016), *ACER Market Monitoring Report 2015 - Electricity and gas retail markets*, Agency for the Cooperation of Energy Regulators, Ljubljana, Slovenia.
- ACER** (2018), *ACER/CEER - Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2017 - Electricity Wholesale Markets Volume*, Agency for the Cooperation of Energy Regulators, Ljubljana, Slovenia.
- AGGARWAL, S. AND R. ORVIS** (2016), *Grid flexibility: Methods for modernizing the power grid*, Energy Innovation, San Francisco, California.
- AGL** (2017), “Wattle Point Wind Farm”, <https://www.agl.com.au/about-agl/how-we-source-energy/wattle-point-wind-farm>.
- AGORA ENERGIEWENDE** (2017), *Flexibility in thermal power plants*, Agora Energiewende, Berlin.
- ALEN PAVLINIĆ, V. K.** (2017), “Direct monitoring methods of overhead line conductor temperature”, *Engineering Review*, Vol. 37(2), pp. 134-146.
- ANTEROINEN, S.** (2018), “Graciosa on the path to 100% renewable energy”, Wärtsilä, <https://www.wartsila.com/twentyfour7/energy/graciosa-on-the-path-to-100-renewable-energy>.
- ARENA** (2018), “Hydrogen to be trialled in NSW gas networks”, Australian Renewable Energy Agency, <https://arena.gov.au/news/hydrogen-to-be-trialled-in-nsw-gas-networks/>.
- AVALLONE, E. D.** (2018), *Flexible ramping product: Market design concept proposal*, New York Independent System Operator.
- BADE, G.** (2018), “Storage will replace 3 California gas plants as PG&E nabs approval for world’s largest batteries”, *Utility Dive*, <https://www.utilitydive.com/news/storage-will-replace-3-california-gas-plants-as-pge-nabs-approval-for-worl/541870/>.
- BASKIN, J. S.** (2016), “Xcel tames variability of wind power”, *Forbes*, <https://www.forbes.com/sites/jonathansalembaskin/2016/06/30/xcel-tames-variability-of-wind-power/#2d-2f70263bdd>.
- BEEBRYTE** (n.d.), BeeBryte website, <https://beebryte.com>.
- BEIS** (2018), UK Department of Business, Energy and Industrial Strategy website, <https://www.gov.uk/government/organisations/department-for-business-energy-and-industrial-strategy>.
- BEIS** (2017), “Smart meters”, UK Department for Business, Energy and Industrial Strategy, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/662089/2017-Q3-smart-meters-quarterly-report.pdf.
- BETA, E. M.** (2016), “SAPP experience on regional power market development & operation”, presentation, <https://sari-energy.org/wp-content/uploads/2016/03/Session-3-Mr-Musara-BETA-SAPP.pdf>.

- BIG HIT** (2018), “About the project”, <https://www.bighit.eu/about>.
- 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/>.
- BNEF** (2017), *Digitalization of energy systems*, Bloomberg New Energy Finance, London, UK.
- BRIDGE TO INDIA** (2017), “Southern region to lead India in grid integration of renewable energy – Bridge to India”, *PV Tech*, <https://www.pv-tech.org/guest-blog/southern-region-to-lead-india-in-grid-integration-of-renewable-energy-bridg>.
- CAISO** (2018a), “Day-ahead market enhancements”, California Independent System Operator, <http://www.caiso.com/informed/Pages/StakeholderProcesses/Day-AheadMarketEnhancements.aspx>.
- CAISO** (2018b), “Flexible ramping product”, California Independent System Operator, <http://www.caiso.com/informed/Pages/StakeholderProcesses/CompletedClosedStakeholderInitiatives/FlexibleRampingProduct.aspx>.
- CAISO** (2018c), *Western EIM benefits report – Second quarter 2018*, California Independent System Operator, Folsom, California.
- CAM** (2019), *Branchenstudie Elektromobilität 2019*, Center of Automotive Management, Bergisch Gladbach, Germany, <http://www.auto-institut.de/e-mobility-studien.htm>.
- CARLINI, E. M., F. MASSARO AND C. QUACIARI** (2013), “Methodologies to uprate an overhead line. Italian TSO case study”, *Journal of Electrical Systems*, Vol. 9(4), pp. 422-439.
- CEA** (2018), *National Electricity Plan (Volume I) – Generation*, Central Electricity Authority, Ministry of Power, Government of India, New Delhi, India.
- CEC** (2018), “Total system electric generation”, California Energy Commission, https://www.energy.ca.gov/almanac/electricity_data/total_system_power.html (accessed 4 December 2018).
- COCHRAN, J., D. LEW AND N. KUMAR** (2013), *Flexible coal: Evolution from baseload to peaking plant*, US National Renewable Energy Laboratory, Golden, Colorado.
- COLTHORPE, A.** (2018), “Navigant: Energy storage PCS becoming a ‘crowded market’”, *PV Tech*, <https://www.pv-tech.org/news/navigant-energy-storage-pcs-becoming-a-crowded-market>.
- COLTHORPE, A.** (2017), “Stem connects 1MW aggregated virtual power plant in Hawaii”, *Energy Storage News*, <https://www.energy-storage.news/news/stem-connects-1mw-aggregated-virtual-power-plant-in-hawaii>.
- CON EDISON** (2018), “Con Edison’s ‘Community Power’ to bring solar energy to 350 NYCHA households”, <https://www.coned.com/en/about-con-edison/media/news/20180925/con-edisons-community-power-to-bring-solar-energy-to-350-nycha-households>.
- CON EDISON** (2016), “Register your smart thermostat and get up to \$135”, [https://www.coned.com/en/save-money/rebates-incentives-tax-credits/rebates-incentives-tax-credits-for-residential-customers/bring-your-thermostat-and-get-\\$85](https://www.coned.com/en/save-money/rebates-incentives-tax-credits/rebates-incentives-tax-credits-for-residential-customers/bring-your-thermostat-and-get-$85).
- CORFO** (2018), *Opportunities for the development of a solar hydrogen industry in the Atacama and Antofagasta regions: Innovations for 100% renewable energy system*, Chilean Solar Committee (CORFO), Santiago, Chile.
- CUFFARI, B.** (2018), “Offshore vs. onshore wind farms”, AZoCleantech, <https://www.azocleantech.com/article.aspx?ArticleID=704>.
- DE CLERCQ, G. AND C. STEITZ** (2017), “Energy firms battle startups to wire Europe’s highways for electric cars”, *Reuters*, <https://www.reuters.com/article/us-electricity-autos-charging/energy-firms-battle-startups-to-wire-europes-highways-for-electric-cars-idUSKCN1BQ0JG>.
- DE GRAAF, F.** (2018), *New strategies for Smart Integrated Decentralized Energy systems*, Metabolic, Amsterdam, the Netherlands.
- DEA** (2015), *System integration of wind power – Experiences from Denmark*, Danish Energy Agency, Copenhagen.

- DECC** (n.d.), *Energy Entrepreneurs Fund projects, Phases 1&2*, Department of Energy & Climate Change, UK.
- DIW** (2013), *The benefit of coordinating congestion management in Germany*, German Institute for Economic Research, Berlin.
- DONG ENERGY** (2012), *The eFlex Project Main Report DONG Energy*.
- DU, P., R. BALDICK AND A. TUOHY** (eds.) (2017), *Integration of Large-Scale Renewable Energy into Bulk Power Systems*. Cham: Springer International Publishing, <https://doi.org/10.1007/978-3-319-55581-2>.
- DWD** (2018), “Weather forecasts for renewable energy – A challenge”, Deutscher Wetterdienst, https://www.dwd.de/EN/research/weather-forecasting/num_modelling/07_weather_forecasts_renewable_energy/weather_forecasts_renewable_energy_node.html (accessed 16 November 2018).
- E.ON** (2018), “E.ON brings innovation to the energy market: Storing solar power without batteries”, <https://www.eon.com/en/about-us/media/press-release/2018/eon-brings-innovation-to-the-energy-market-storing-solar-power-without-batteries.html>.
- EC** (2016a), *Proposal for a directive of the European Parliament and of the Council on common rules for the internal market in electricity*, European Commission, Brussels.
- EC** (2016b), “FCH-02-7-2016 – Demonstration of large-scale rapid response electrolysis to provide grid balancing services and to supply hydrogen markets”, European Commission CORDIS, https://cordis.europa.eu/programme/rcn/700832_en.html (accessed 3 December 2018).
- EHPA** (2018), “Press release: Ongoing growth: heat pump sector continues its positive contribution to Europe’s energy and climate targets”, European Heat Pump Association, <https://www.ehpa.org/about/news/article/press-release-ongoing-growth-heat-pump-sector-continues-its-positive-contribution-to-europes-ene/>.
- EIA** (2018a), “Frequently asked questions: What is U.S. electricity generation by energy source?” US Energy Information Administration, <https://www.eia.gov/tools/faqs/faq.php?id=427&t=3>.
- EIA** (2018b), *Assessing HVDC transmission for impacts of non-dispatchable generation*, US Energy Information Administration, Washington, D.C.
- EIA** (2017), “Frequently asked questions: How many smart meters are installed in the United States, and who has them?”, US Energy Information Administration, <https://www.eia.gov/tools/faqs/faq.php?id=108>.
- EID, C. et al.** (2016), “Market integration of local energy systems: Is local energy management compatible with European regulation for retail competition?” *Energy*, Vol. 114, pp. 913-922.
- EIM** (2018), “About”, Western Energy Imbalance Market, <https://www.westerneim.com/Pages/About/default.aspx> (accessed 29 November 2018).
- EIRGRID** (2016), *DS3 Programme operational capability outlook 2016*, EirGrid Group, Dublin.
- EL PERIÓDICO DE LA ENERGÍA** (2018), “Wible, el servicio de car-sharing de KIA y Repsol comienza a funcionar en Madrid”, <https://elperiodicodelaenergia.com/wible-el-servicio-de-car-sharing-de-kia-y-repsol-comienza-a-funcionar-en-madrid/>.
- ELIA** (2018), “Deployment of a datahub shared by all system operators to support electrical flexibility”, Elia, Brussels, http://www.elia.be/-/media/files/Elia/PressReleases/2018/20180308_SYN_Persbericht_Datahub_EN.pdf.
- ENBALA** (n.d.), *Virtual power plants: Coming soon to a grid near you*, Enbala, Vancouver, British Columbia, <https://cdn2.hubspot.net/hubfs/1537427/Chapter1.pdf?submissionGuid=859d63d0-7af0-4c64-9cb3-1e1e3c0bd3d4>.
- ENERGINET** (2018), *Nordic power market design and thermal power plant flexibility*, Energinet, Fredericia, Denmark.

- ENERGYSTOCK** (2018), “The hydrogen project HyStock”, <https://www.energystock.com/about-energystock/the-hydrogen-project-hystock>.
- ENGERATI** (2018), “UK networks: Making the switch from DNO to DSO”, <https://www.engerati.com/article/uk-networks-switch-dno-dso-western-power-distribution>.
- ENGIE** (2018), “The GRHYD demonstration project”, <https://www.engie.com/en/innovation-energy-transition/digital-control-energy-efficiency/power-to-gas/the-grhyd-demonstration-project>.
- ENTSO-E** (2015), *Dynamic Line Rating for overhead lines – V6*, European Network of Transmission System Operators, Brussels.
- EPE AND BMWI** (2017), *Untapping flexibility in power systems*, EPE and Bundesministerium für Wirtschaft und Energie, Brasilia and Berlin.
- EPEX SPOT** (2019), Products Intraday Continuous, EPEX SPOT, Paris, https://www.epexspot.com/en/product-info/intradaycontinuous/intraday_lead_time
- EPEX SPOT** (n.d.), *15-minute intraday call auction*, EPEX SPOT, Paris, <https://www.epexspot.com/document/29113/15-Minute%20Intraday%20Call%20Auction>.
- ESA** (2014), “Providing 100% renewable power to large residence on protected Kona coast”, Energy Storage Association, <http://energystorage.org/energy-storage/case-studies/providing-100-renewable-power-large-residence-protected-kona-coast>.
- ETO, J. H., B. C. LESIEUTRE AND D. R. HALE** (2005), *A review of recent RTO benefit-cost studies: Toward more comprehensive assessments of FERC electricity restructuring policies*, Lawrence Berkeley National Laboratory, Berkeley, California.
- EURELECTRIC** (2017), *Dynamic pricing in electricity supply – A Eurelectric position paper*, Eurelectric, Brussels.
- EVANS, R. AND J. GAO** (2016), “DeepMind AI reduces Google data centre cooling bill by 40%”, DeepMind, <https://deepmind.com/blog/deepmind-ai-reduces-google-data-centre-cooling-bill-40/>.
- EXERON** (2018), “Exeron – Applications”, <https://exeron.com/applications/applications-xgrid> (accessed 17 October 2018).
- FCH JU** (2018), “Launch of REFHYNE, world’s largest electrolysis plant in Rhineland refinery”, Fuel Cells and Hydrogen Joint Undertaking, <https://www.fch.europa.eu/news/launch-refhyne-worlds-largest-electrolysis-plant-rhineland-refinery> (accessed 16 November 2018).
- FELIX, B.** (2017), “Total ready for price war as it enters French retail power market”, *Reuters*, <https://www.reuters.com/article/us-total-gas/total-ready-for-price-war-as-it-enters-french-retail-power-market-idUSKBN1CA1JP>.
- FERC** (2018), *Open Commission Meeting Staff Presentation, Item E-1*, US Federal Energy Regulatory Commission, Washington, D.C., <https://www.ferc.gov/industries/electric/indus-act/rto/02-15-18-E-1-presentation.pdf>.
- FERNANDEZ, E. et al.** (2016), “Review of dynamic line rating systems for wind power integration”, *Renewable and Sustainable Energy Reviews*, Vol. 53, pp. 80-92.
- FINNISH ENERGY** (2017), *Finnish Energy’s position on the features of next-generation electricity meters*, Finnish Energy, Helsinki.
- FINNISH ENERGY AUTHORITY** (2018), *National Report 2018 to the Agency for the Cooperation of Energy Regulators and to the European Commission*, Energy Authority, Helsinki.
- FRAUNHOFER ISE** (2018), *Power generation in Germany – Assessment of 2017*, Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany.
- FRONTIER ECONOMICS** (2018), *South Australia’s Virtual Power Plant*, Frontier Economics, Melbourne, Australia.
- GARDINER, M.** (2014), *Hydrogen energy storage: Experimental analysis and modeling*, US Department of Energy, Washington, D.C.

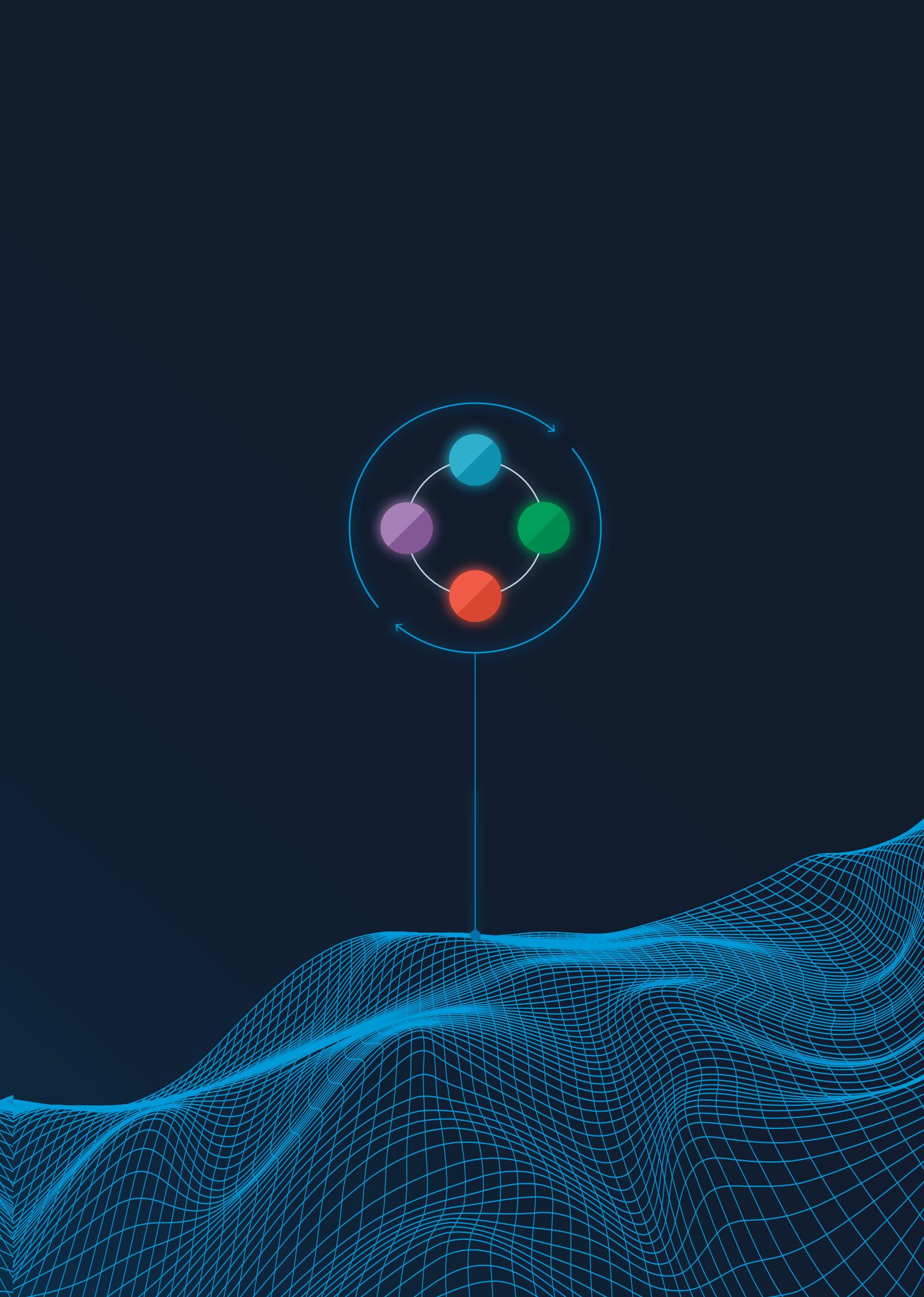
- GLOBALDATA** (2018), “Global smart meter market expected to see huge rollout”, Global Data, <https://www.power-technology.com/comment/global-smart-meter-market-expected-see-huge-rollout/>.
- GOVERNMENT OF AUSTRALIA** (2018), South Australia’s Virtual Power Plant website, <https://virtualpowerplant.sa.gov.au/> (accessed 29 November 2018).
- GREY CELLS ENERGY** (2018), “Sonnen’s ‘Community’: Aggregating domestic battery storage”, <https://greycellsenergy.com/examples/sonnens-community-aggregating-domestic-battery-storage/>.
- GROVER, M.** (2018), “Demand response is disrupting Australia’s ancillary services markets”, RenewEconomy, <https://reneweconomy.com.au/demand-response-disrupting-australias-ancillary-services-markets-43382/>.
- GTAI** (2018), *The energy storage market in Germany*, Germany Trade & Invest, Berlin.
- GUEVARA-STONE, L.** (2014), “Why a small German village bet big on renewables”, GreenBiz, <https://www.greenbiz.com/blog/2014/02/13/rural-german-village-feldheim-power-clean-energy>.
- HDR** (2017), *Battery energy storage technology assessment*, Platte River Power Authority, Fort Collins, Colorado.
- HILL, J. S.** (2018), “Solar & batteries to power London’s first ‘virtual power station’”, CleanTechnica, <https://cleantechnica.com/2018/06/26/solar-batteries-to-power-london-first-virtual-power-station/>.
- HYDROGEN COUNCIL** (2017), *How hydrogen empowers the energy transition*, Hydrogen Council.
- HYDRO TASMANIA** (2014), *King Island Renewable Energy Integration Project*, Hydro Tasmania, <http://www.kingislandrenewableenergy.com.au/project-information/overview>
- IBM** (2011), “IBM rolls out first solar array designed for high-voltage data centers and industrial use”, <https://www-03.ibm.com/press/us/en/pressrelease/35891.wss>.
- IEA** (2018a), *World energy outlook 2018*, International Energy Agency, Paris.
- IEA** (2018b), *Energy storage: Tracking clean energy progress*, International Energy Agency, Paris.
- IEEE** (2017), “Large scale storage and demand resources – Enabler of transmission delivery? ”, presentation, Institute of Electrical and Electronics Engineers Power & Energy Society, Piscataway, New Jersey, <https://pdfs.semanticscholar.org/presentation/3648/25caf9687eb-3c483a14578bb54e5fedf1b64.pdf>.
- IEEFA** (2018), *Power-industry transition, here and now. Wind and solar won't break the grid: Nine case studies*, Institute for Energy Economics and Financial Analysis, Cleveland, Ohio.
- IPCC** (2018), *Global Warming of 1.5 °C*, Intergovernmental Panel on Climate Change, Geneva.
- IRENA** (forthcoming a), *Innovation outlook: Smart charging for EVs*, International Renewable Energy Agency, Abu Dhabi.
- IRENA** (forthcoming b), *Innovation outlook: Thermal energy storage*, International Renewable Energy Agency, Abu Dhabi.
- IRENA** (2018a), *Renewable power generation costs in 2017*, International Renewable Energy Agency, Abu Dhabi.
- IRENA** (2018b), *Global energy transformation: A roadmap to 2050*, International Renewable Energy Agency, Abu Dhabi.
- IRENA** (2018c), *Power system flexibility for the energy transition. Part 1: Overview for policy makers*, International Renewable Energy Agency, Abu Dhabi.
- IRENA** (2018d), *Hydrogen from renewable power: Technology outlook for the energy transition*, International Renewable Energy Agency, Abu Dhabi.
- IRENA** (2017a), *Electricity storage and renewables: Costs and markets to 2030*, International Renewable Energy Agency, Abu Dhabi.
- IRENA** (2017b), *Adapting market design to high shares of variable renewable energy*, International Renewable Energy Agency, Abu Dhabi.

- IRENA** (2017c), *Renewable energy in district heating and cooling: A sector roadmap for REmap*, International Renewable Energy Agency, Abu Dhabi.
- IRENA** (2015), *Battery storage for renewables: Market status and technology outlook*, International Renewable Energy Agency, Abu Dhabi.
- IRENA, IEA AND REN21** (2018), *Renewable energy policies in a time of transition*, International Renewable Energy Agency, International Energy Agency and Renewable Energy Policy Network for the 21st Century, Abu Dhabi and Paris.
- IRP WIND** (2016), *Yearly report on IRPWIND and EERA JP Wind Activities*, Integrated Research Programme on Wind Energy.
- ITM POWER** (2015), “Rapid response electrolysis for power-to-gas energy storage”, <http://www.itm-power.com/news-item/rapid-response-electrolysis-for-power-to-gas-energy-storage>.
- JACOBS, D. et al.** (2016), *RE Transition – Transitioning to policy frameworks for cost-competitive renewables*, IEA Technology Collaboration Programme for Renewable Energy Technology, Utrecht, the Netherlands.
- KEMPENER, R., P. KOMOR AND A. HOKE** (2013), *Smart grids and renewables: A guide for effective deployment*, International Renewable Energy Agency, Abu Dhabi.
- KENNING, T.** (2018), “Macquarie to finance solar hybrid and ‘largest’ energy storage project in South Korea”, *PV Tech*, <https://www.pv-tech.org/news/macquarie-to-finance-solar-hybrid-and-largest-energy-storage-project-in-sou>.
- KNIGHT, S.** (2010), “Merger of German TSOs could solve electricity cost problem”, *Windpower Monthly*, <https://www.windpowermonthly.com/article/1000530/merger-german-tsos-solve-electricity-cost-problem>.
- KPMG** (2016), *EFR tender results*, KPMG, <https://home.kpmg.com/content/dam/kpmg/uk/pdf/2016/10/kpmg-efr-tender-market-briefing-updated.pdf>.
- LEW, D. et al.** (2011), *The value of wind power forecasting*, National Renewable Energy Laboratory, Golden, Colorado.
- McCONNELL, D.** (2017), “SA’s battery is massive, but it can do much more than store energy”, *Australian Broadcasting Company*, <http://www.abc.net.au/news/2017-12-05/yes-sa-battery-is-a-massive-battery-but-it-can-do-more/9227288>.
- McKINSEY** (2017), “There’s no place like (a connected) home”, McKinsey&Company, https://www.mckinsey.com/spContent/connected_homes/index.html.
- MORTON, A.** (2018), “South Australia on track to meet 75% renewables target Liberals promised to scrap”, *The Guardian*, <https://www.theguardian.com/environment/2018/jul/25/south-australia-to-hit-75-renewables-target-by-2025-liberal-energy-minister-says>.
- NADEL, S.** (2017), “Demand response programs can reduce utilities’ peak demand an average of 10%, complementing savings from energy efficiency programs”, American Council for an Energy-Efficient Economy blog, <https://aceee.org/blog/2017/02/demand-response-programs-can-reduce>.
- NATIONAL GRID** (2017), *Annual Report and Accounts 2016/2017*, National Grid, London.
- NATIONAL GRID ESO** (2018), “Commercial aggregation service providers”, https://www.nationalgrideso.com/sites/eso/files/documents/Commercial%20Aggregation%20Service%20Providers_1.xlsx.
- NBS** (2018), “In August 2018, the added value of industrial enterprises above designated size increased by 6.1%”, National Bureau of Statistics China, Beijing.
- NEUHOFF, K. AND R. BOYD** (2011), *International experiences of nodal pricing implementation*, Climate Policy Initiative, London.
- NEW YORK STATE** (2018), “REV – Demonstration projects”, <http://www3.dps.ny.gov/W/PSCWeb.nsf/All/B2D9D834B0D307C685257F3F006FF-1D9?OpenDocument>.

- NORD POOL** (2018), *Cross-border intraday: Questions & answers*, Lysaker, Norway, https://www.nordpoolspot.com/globalassets/download-center/xbid/xbid-qa_final.pdf.
- NORDREG** (2018), *Implementation of data hubs in the Nordic countries - Status report*, Nordic energy Regulators, <http://www.nordicenergyregulators.org/wp-content/uploads/2018/08/NordREG-Status-report-on-datahubs-June-2018.pdf>.
- NORTHERN POWERGRID** (2018), “Innovation Strategies launch latest chapter in GB’s energy network innovation success story”, EE Online, <https://electricenergyonline.com/article/energy/category/General/90/693663/Innovation-Strategies-Launch-Latest-Chapter-in-GB-s-Energy-Network-Innovation-Success-Story.html>.
- NPTEL** (2012), *Module 5: Locational Marginal Prices (LMPs)*, <http://nptel.ac.in/courses/108101005/27>.
- NREL** (2017), *Hydrogen energy storage: Experimental analysis and modeling*, National Renewable Energy Laboratory, Golden, Colorado.
- NREL** (2015a), “NREL and IBM improve solar forecasting with big data”, National Renewable Energy Laboratory, <https://www.nrel.gov/esif/partnerships-ibm.html>.
- NREL** (2015b), *The value of improved short-term wind power forecasting*, National Renewable Energy Laboratory, Golden, Colorado.
- NREL** (2013), *Market evolution: Wholesale electricity market design for 21st century power systems*, National Renewable Energy Laboratory, Golden, Colorado.
- NREL** (2012), *Potential for distributed and central electrolysis to provide grid support services*, National Renewable Energy Laboratory, Golden, Colorado.
- NSWPH** (2018), “Planning the future today”, North Sea Wind Power Hub, <https://northseawindpowerhub.eu/vision> (accessed 29 November 2018).
- NYISO** (2017), *Distributed energy resources roadmap for New York’s wholesale electricity markets*, New York Independent System Operator, Rensselaer, New York.
- NYSERDA** (2018), “New York State Energy Storage”, New York State Energy Research and Development Authority, <https://www.nyserda.ny.gov/All%20Programs/Programs/Energy%20Storage>.
- OFFSHOREWIND.BIZ** (2015), “Siemens hands over HelWin1 to TenneT”, <https://www.offshorewind.biz/2015/02/09/siemens-hands-over-helwin1-to-tennet/>.
- PACIFICORP** (2018), “Western grid coordination”, <https://www.pacificcorp.com/about/eim.html> (accessed 29 November 2018).
- PICKEREL, K.** (2018), “Urban Energy Solutions and SunGreen Systems will use Stem’s AI solutions in solar+storage projects”, Solar Power World, <https://www.solarpowerworldonline.com/2018/09/urban-energy-solutions-and-sungreen-systems-will-use-stems-ai-solutions-in-solar-storage-projects/>.
- POLHAMUS, M.** (2017), “Joint venture has IBM tackling renewable energy’s grid effects”, *VTDigger*, <https://vtdigger.org/2017/02/28/joint-venture-ibm-tackling-renewable-energys-grid-effects/>.
- PROMOTiON** (2018), “EU-Project PROMOTiON: Successful testing of DC circuit breaker module prototype completed”, https://www.promotion-offshore.net/news_events/news/detail/eu-project-promotion-successful-testing-of-dc-circuit-breaker-module-prototype-completed/.
- RAL** (2014), “How advanced forecasting is making it easier to integrate solar onto the grid”, Research Applications Laboratory, <https://ral.ucar.edu/solutions/how-advanced-forecasting-making-it-easier-integrate-solar-grid>.
- REN21** (2016), *Renewables 2016 global status report*, Renewable Energy Network for the 21st Century, Paris.

- RES** (2016), *PJM Frequency Regulation*, Renewable Energy Systems, http://www.res-group.com/media/2409/frequencyreg_flyer_042517.pdf.
- ROBERTS, D.** (2018), “California just adopted its boldest energy target yet: 100% clean electricity”, Vox, <https://www.vox.com/energy-and-environment/2018/8/31/17799094/california-100-percent-clean-energy-target-brown-de-leon>.
- ROBERTS, D., P. TAYLOR AND A. MICHIORRI** (2008), *Dynamic thermal rating for increasing network capacity and delaying network reinforcements*, Institution of Engineering and Technology, Frankfurt.
- SEDC** (2017), *Explicit demand response in Europe: Mapping the markets 2017*, Smart Energy Demand Coalition, Brussels.
- SEEL, J., A. D. MILLS AND R. H. WISER** (2018), *Impacts of high variable renewable energy (VRE) futures on wholesale electricity prices, and on electric-sector decision making*, Lawrence Berkeley National Laboratory, Berkeley, California.
- SEI** (2017), “Smart electric meters programme”, Smart Energy International, <https://www.metering.com/industry-sectors/smart-meters/smart-electric-meters-programme/>.
- SEI** (2016), “Global trends in smart metering”, Smart Energy International, <https://www.metering.com/magazine-article/global-trends-in-smart-metering/>.
- SEMPRA** (2017), “SoCalGas and U.S. Department of Energy’s National Renewable Energy Laboratory install nation’s first biomethanation reactor system for power-to-gas testing”, Sempra Energy, <https://www.sempra.com/newsroom/press-releases/socal-gas-and-us-department-energys-national-renewable-energy-laboratory>.
- SHELL** (2018), “Shell completes acquisition of First Utility”, Shell Petroleum Company Ltd., <https://www.shell.co.uk/media/2018-media-releases/shell-completes-acquisition-of-first-utility.html>.
- SHELL** (2017), “Shell steps up its electric vehicle charging offer”, Shell Petroleum Company Ltd., <https://www.shell.co.uk/media/2017-media-releases/electric-vehicle-charging-offer.html>.
- SIEMENS** (2018), “HVDC classic”, <https://www.energy.siemens.com/hq/en/power-transmission/hvdc/hvdc-classic.htm#content=Low%20Losses>.
- SKYES, J.** (2018), “South Australian government’s home battery scheme”, Solar Choice, <https://www.solarchoice.net.au/blog/south-australian-governments-home-battery-scheme/>.
- STATISTA** (2018), “Internet of Things (IoT) connected devices installed base worldwide from 2015 to 2025 (in billions)”, <https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/> (accessed 16 November 2018).
- STONE, M.** (2016), “Unbundled ancillary services are another energy storage opportunity in Australia”, Greentech Media, <https://www.greentechmedia.com/articles/read/unbundled-ancillary-services-are-another-energy-storage-opportunity-in-aust>.
- SURF ‘N’ TURF INITIATIVE** (2018), Surf ‘n’ Turf Initiative website, <http://www.surfnturf.org.uk/>.
- TENNET** (2018), “SylWin1”, <https://www.tennet.eu/our-grid/offshore-projects-germany/sylwin1/> (accessed 3 December 2018).
- TENNET** (2017a), “Port of Rotterdam becomes fifth partner in North Sea Wind Power Hub Consortium”, <https://www.tennet.eu/news/detail/port-of-rotterdam-becomes-fifth-partner-in-north-sea-wind-power-hub-consortium/>.
- TENNET** (2017b), “Europe’s first blockchain project to stabilize the power grid launches: TenneT and sonnen expect results in 2018”, <https://www.tennet.eu/news/detail/europes-first-blockchain-project-to-stabilize-the-power-grid-launches-tennet-and-sonnen-expect-res/>.
- TERNA** (n.d.), “Pilot storage projects”, <https://www.terna.it/en-gb/sistemaelettrico/progettipilotadiaccumulo.aspx>.

- TNO** (2016), *PowerMatcher, matching energy supply and demand to expand smart energy potential*, TNO, Amsterdam, the Netherlands.
- TOTAL** (2016), “Total takes control of Saft Groupe after the successful tender offer which will be re-opened from July 19 to August 2, 2016”, <https://www.total.com/en/media/news/press-releases/total-takes-control-saft-groupe-after-successful-tender-offer-which-will-be-re-opened-july-19-august>.
- TRACTEBEL** (2017), *Study on early business cases for H2 in energy storage and more broadly power to H2 applications*, Fuel Cells and Hydrogen Joint Undertaking, Brussels.
- TRILATIONS** (n.d.), “Is the Belgian energy market ready for residential VPP’s?” <https://www.trilations.com/is-the-belgian-energy-market-ready-for-residential-vpps/>.
- US DOE** (2018), *2017 Wind technologies market report: Summary*, US Department of Energy, Washington, D.C.
- US DOE** (2014), *Oncor’s pioneering transmission dynamic line rating (DLR) demonstration lays foundation for follow-on deployments*, US Department of Energy, Washington, D.C.
- VATTENFALL** (2017), “Vattenfall invests in innovative heat storage in Berlin”, <https://corporate.vattenfall.com/press-and-media/press-releases/2017/vattenfall-invests-in-innovative-heat-storage-in-berlin/>.
- VIKING LINK** (2018), Viking Link Interconnector website, <http://viking-link.com>.
- WALTON, R.** (2018), “FERC creates path for energy storage into RTO/ISO capacity markets”, *Electric Light & Power*, <https://www.elp.com/articles/2018/02/ferc-creates-path-for-energy-storage-into-rto-iso-capacity-markets.html>.
- WANG, W.** (2017), “Ancillary services: An introduction”, China National Renewable Energy Centre, <http://boostre.cnrec.org.cn/index.php/2017/09/14/ancillary-services-an-introduction/?lang=en>.
- WEF** (2017), *The future of electricity: New technologies transforming the grid edge*, World Economic Forum, Geneva.
- WGA** (2012), *Meeting renewable energy targets in the West at least cost: The integration challenge*, Western Governors’ Association, Denver, Colorado.
- WILLUHN, M. AND F. BROWN** (2018), “UK Power Networks to launch London’s first VPP”, *pV magazine*, <https://www.pv-magazine.com/2018/06/26/uk-power-networks-to-launch-londons-first-vpp/>.
- WOOD, J.** (2018), “These Dutch microgrid communities can supply 90% of their energy needs”, World Economic Forum, <https://www.weforum.org/agenda/2018/09/these-dutch-microgrid-communities-can-supply-90-of-their-energy-needs/>.
- WORLD BANK** (2018), “Regional power trade in West Africa offers promise of affordable, reliable electricity”, <https://www.worldbank.org/en/news/feature/2018/04/20/regional-power-trade-west-africa-offers-promise-affordable-reliable-electricity>.
- YIP, T. et al.** (2009), “Dynamic line rating protection for wind farm connections”, *2009 CIGRE/IEEE PES Joint Symposium Integration of Wide-Scale Renewable Resources Into the Power Delivery System*, 29-30 July.
- ZAMAN, A.** (2018), “100% Variable Renewable Energy Grid: Survey of Possibilities”, University of Michigan, https://deepblue.lib.umich.edu/bitstream/handle/2027.42/143152/Zaman_Ansha_Practicum.pdf
- ZHANG, L.** (2016), “China renewables curtailment: Is there light at the end of the tunnel? ”, presentation, The Lantau Group, http://www.lantaugroup.com/files/ppt_pgen16_lz.pdf.



INNOVATION LANDSCAPE FOR A RENEWABLE-POWERED FUTURE: SOLUTIONS TO INTEGRATE VARIABLE RENEWABLES

© IRENA 2019

IRENA HEADQUARTERS

P.O. Box 236, Abu Dhabi
United Arab Emirates

www.irena.org

