Solar integration in the UK and India: technical barriers and future directions

SOLAR INTEGRATION IN THE UK AND INDIA: TECHNICAL BARRIERS AND FUTURE DIRECTIONS

Report of the UK-India Joint Virtual Clean Energy Centre (JVCEC)

A collaboration of the Joint UK-India Clean Energy Centre (JUICE), the India-UK Centre for Education and Research in Clean Energy (IUCERCE) and the UK India Clean Energy Research Institute (UKICERI)

AUTHORS

Authors:
Efstratios Batzelis, Zakir Hussain Rather, John Barton, Bonu Ramesh Naidu, Billy Wu, Firdous Ul Nazir, Onyema Sunday Nduka, Wei He, Jerome Nsengiyaremye, Bandopant Pawar, Diane Palmer

Contributors:
Bikash Pal, Murray Thomson, Chandan Chakraborty, Prabodh Bajpai, Saikat Chakrabarti, Mark Dooner, Marcus King, Jihong Wang

Any inquiries should be directed to the first author:
Dr Efstratios Batzelis (**e.batzelis@soton.ac.uk**)

ACKNOWLEDGEMENTS

This report builds on research carried out within the UK-India Joint Virtual Clean Energy Centre (JVCEC), within which, the UK partners have received funding from the Engineering & Physical Sciences Research Council (EPSRC) for a project entitled "Joint UK-India Clean Energy Centre (JUICE)" with grant reference EP/P003605/1, and the India partners have received funding from the Government of India's, Department of Science and Technology (DST) for projects entitled "India-UK Centre for Education and Research in Clean Energy (IUCERCE)" and "UK India Clean Energy Research Institute (UKICERI)". Two authors also received grant funding from the Royal Academy of Engineering under the Engineering for Development Research Fellowship schemes (RF\201819\18\86, RF\201819\18\89). The views expressed in this report are those of the authors, and do not necessarily reflect the views of all JVCEC collaborators or of the funding bodies.

To follow the consortium's work and publications, please visit **http://www.juice-centre.org.uk/**, **http://www.ukiceri.com/**, **http://www.iucerce.iitb.ac.in/**.

Published: April 2021

GLOSSARY

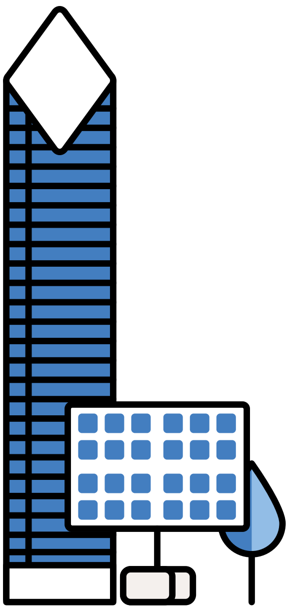
ADN	Active Distribution Network
AID	Anti-islanding detection
AS	Ancillary Services
CERC	Central Electricity Regulatory Commission, India
DER	Distributed Energy Resource
DG	Distributed Generation
DNO	Distribution Network Operator
DR	Demand Response
EVs	Electric Vehicles
FRT	Fault Ride Through
IBR	Inverter Based Resources
LCOE	Levelized Cost Of Electricity
LoM	Loss of mains
LVRT	Low Voltage Ride Through
NWP	Numerical Weather Prediction (for solar radiation forecasting)
PLL	Phase Locked Loop
PV	Photovoltaic
RES	Renewable Energy Sources
RoCoF	Rate of Change of Frequency
SCL/SCR	Short Circuit Level/Ratio
SOC	State of Charge (for batteries)
TSO	Transmission System Operator
V2G	Vehicle to Grid

PARTNER LOGOS

SPONSOR LOGOS

EXECUTIVE SUMMARY

In the past few years, the world has been mobilised in the fight against climate change, with more and more countries making ambitious commitments for a net-zero emission energy sector. Even during the COVID-19 era, major economies envision a recovery that has climate actions and energy transformation at its core. In this context, the solar photovoltaic technology has experienced remarkable boom in the past decade, in part due to falling solar photovoltaic (PV) technology prices, being today among the cheapest generation technologies worldwide.



However, global experience shows that solar installations start to level off in countries with certain integration levels. The UK saw rapid solar uptake during the first half of the previous decade which has now stalled. India has experienced lately a rapid growth in solar photovoltaic deployment with 37.5 GW installed capacity by the end of 2020, but it has a long way to go till the 100 GW solar target of 2022. The rate of solar deployments is linked to a variety of reasons such as financing, regulations and market mechanisms, but also a set of technical limitations arising from the nature of solar generation. The aim of this report is to take a deep look on the technical challenges that act as barriers to further solar integration and develop a roadmap with technology innovations and transformations that will allow a high-solar future. The UK and India are the focal points of this investigation, examining closely how the challenges and future directions relate or differ between the two countries.

This report arises out of the UK-India Joint Virtual Clean Energy Centre (JVCEC) which is a research consortium comprising the Joint UK-India Clean Energy Centre (JUICE), the India-UK Centre for Education and Research in Clean Energy (IUCERCE) and the UK India Clean Energy Research Institute (UKICERI) – a total of ten UK universities and thirteen Indian institutes. Active since 2016, the consortium aims to tackle key challenges in the development and deployment of clean energy technologies in India and the UK, with a focus on integrating solar, energy storage and network technologies. The JVCEC consortium is jointly funded by UK Newton Fund (via EPSRC) and Department of Science and Technology (DST), Government of India to a total of around £10 M over five years.

The consortium has promoted collaborative research and supported researcher visits from India to the UK and vice versa. These visits have enabled exchange of research ideas and initiated research investigations that have led to many co-authored journal papers and specialist conference presentations. The aim of the report in-hand is to build on that complementary expertise of the consortium to present the topic in a more wholistic manner, bringing together established knowledge with more novel discussion of issues arising in the progress of both India and the UK towards a solar-powered low-carbon future.

CONTENTS

Executive Summary 2

Contents 3

The Solar Picture Today 4

Solar status in the UK 5

Solar status in India 5

International experience and lessons learnt 6

- Solar PV overgeneration in California 6
- Loss of 1200 MW of solar in Southern California 6
- Experience from roof-top solar in India 7

Part A: Technical Barriers to Solar Integration 8

A.1. Balancing & flexibility challenges 9

- A.1.1. Variability of solar generation 9
- A.1.2. Uncertainty of solar generation 10
- A.1.3. Solar resource data 12

A.2. Power system stability challenges 13

- A.2.1. Common instabilities caused by solar 13
- A.2.2. Falling system inertia 14
- A.2.3. Diminishing short circuit level 16
- A.2.4. The power cut of August 2019 in the UK 17

A.3. Voltage challenges 18

- A.3.1. Voltage Rise 18
- A.3.2. Reverse Power Flows 19
- A.3.3. Voltage Flicker 20
- A.3.4. Distribution and Transmission System Interaction 20

A.4. Protection challenges 20

- A.4.1. Protection in the transmission system 20
- A.4.2. Protection in the distribution system 21
- A.4.3. Fault Ride Through 22

A.5. Anti-islanding protection 24

A.6. Power quality issues 25

- A.6.1. Harmonics 26
- A.6.2. Voltage unbalance 26

A.7. Grid codes and ancillary services 28

- A.7.1. The evolution of grid codes 28
- A.7.2. The ancillary services in India 30
- A.7.3. Limited services potential by PV systems 30

A.8. Energy storage as enabler for high solar levels 31

- A.8.1. Electrochemical energy storage technologies 32
- A.8.2. Technical barriers to integration of batteries 35

A.9. Other barriers to PV technology 36

- A.9.1. High Temperatures 36
- A.9.2. Dust and soiling 36
- A.9.3. Opportunity costs of land use 36

Part B: Roadmap to High Solar Integration 38

B.1. Rethinking the power system operation 39

- B.1.1. More flexibility and improved generation dispatch 39
- B.1.2. Better solar forecasting 40
- B.1.3. Transmission/Distribution systems coordination 41
- B.1.4. Improved voltage control in the distribution network 42
- B.1.5. Rethink the protection of distribution networks 43
- B.1.6. Improve the power quality in distribution networks 44
- B.1.7. Continuous evolution of grid codes and ancillary service products 44

B.2. Demand response 45

- B.2.1. Examples of flexible electrical loads 46
- B.2.2. Incentives and market mechanisms 48
- B.2.3. Future Challenges and Strategy 49

B.3. Energy storage 50

- B.3.1. Future prospects 50
- B.3.2. Location of energy storage 51
- B.3.3. Electric vehicles as storage devices 54

B.4. More grid-friendly solar PV systems 55

- B.4.1. Ancillary services by solar 55
- B.4.2. Fault-ride-through and Anti-islanding by solar 56
- B.4.3. Grid-forming control in PV systems 58
- B.4.4. Curtailments and power reserves in PV systems 60

Part C: Conclusions 64

References 68

Appendix A: Fault Ride Through (FRT) Operation 78

Appendix B: Islanding 81

THE SOLAR PICTURE TODAY

Renewable energy is being rapidly integrated to power systems across the world, with solar photovoltaics (PV) and wind power being the front runners. Solar PV in particular has experienced remarkable deployment worldwide in the last decade, adding in 2019 more capacity than all fossil fuel and nuclear plant additions combined and more capacity than all other renewable technologies combined (Solar Power Europe, 2020). This noteworthy increase in solar deployment is in part due to the falling price of PV technology that recently reached the landmark of 1 US cents per kWh in some parts of the world (Solar Power Europe, 2020). According to the International Renewable Energy Agency (IRENA), 40% of utility solar installed in 2019 had a levelized cost of electricity (LCOE) lower than the cheapest fossil fuel-powered generation (IRENA, 2020b). In 2021, IRENA forecasts that utility solar will be the cheapest source of electricity among all renewable energy sources (RES) and will have a LCOE less than the marginal costs of even existing fossil fuel plants, i.e. less than just the fuel and service costs ignoring the initial capital costs. In addition, in contrast to other RES, the solar PV system is probably the most modular grid-connected resource, ranging from small few-kW roof-top installations to large multi-MW open-field farms, connected to both the transmission and distribution network.

With more than 630 GW of global cumulative solar PV installed capacity (counting from 2000 to 2019), which includes around 37.5 GW in India (Dec 2020) and 13.5 GW in the UK (Jan 2021), the world is expected to exceed 1.2 TW solar capacity by 2022 (Solar Power Europe, 2020). The rapidly reducing PV technology prices and the commitments towards energy decarbonisation in the global scene have led to ambitious commitments for very high levels of solar integration into the power systems of many countries. Furthermore, massive investment in solar and other RES is seen today as a promising way for sustainable development in the post-COVID19 era, for reasons such as cheaper electricity, lucrative investment and easy financing, as well as creating many job opportunities to mitigate the jobs lost due to the COVID-19 pandemic. Notable such examples are EU's 'Next Generation EU' programme (EU Commission, 2020), as well as Malaysia's and Switzerland's economy stimulus packages (Solar Power Europe, 2020).

However, the global solar growth is now guided mainly by Asiatic countries as shown in Figure 1, while the European installations that used to lead have now slowed down. Besides all the benefits that solar PV brings, massive solar integration introduces several challenges in planning and operation of the power system, which may work as barriers to further solar deployment. The solar status in the UK and India is briefly described below, followed by lessons learnt and international experience on solar integration.

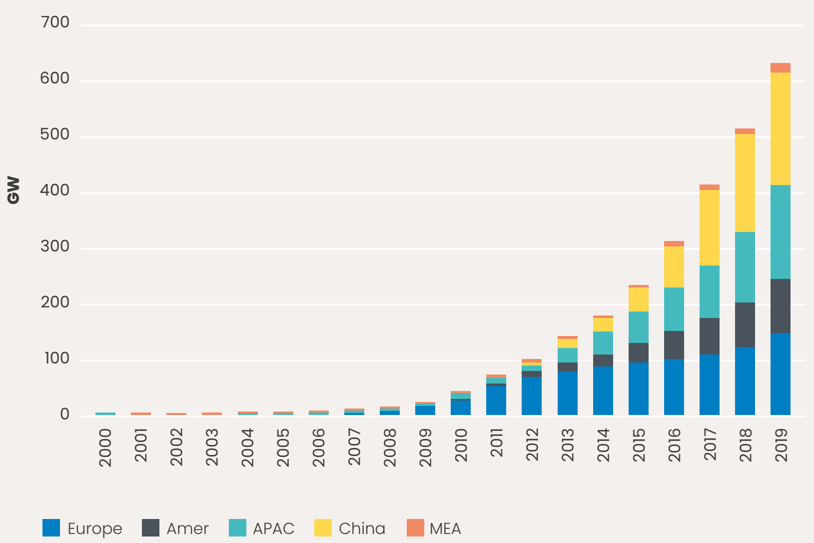


Figure 1. Global total solar PV installed capacity (Solar Power Europe, 2020).

SOLAR STATUS IN THE UK

The UK now has a solar capacity of more than 13.5 GW (Jan 2021) spread across over 1 million installations (BEIS, 2021). That is a significant part of the 78 GW total generation capacity (17% solar integration) (BEIS, 2020). It is worth noting that about half of this capacity comes from large PV plants (>5 MW), even though 93% of the number of installations are of small-scale (<4 kW) (BEIS, 2021). The share of solar energy has been steadily increasing, recently achieving a record of 30% of the total electricity produced instantly during the prolonged coal-free periods in Britain (Apr 2020) (Grundy, 2020). The electricity mix of 6 May 2020 in Britain is depicted in Figure 2, which is indicative of the sunny spring periods: solar undertakes almost 1/3 of the demand at midday, along with nuclear, gas and biomass for the rest; interestingly there is no coal online at all.

However, solar deployment has stagnated lately, mainly due to closure of the Feed-in-Tariff scheme in March 2019, and concerns are raised regarding the actions needed to allow for further solar integration in view of the recent commitments for net zero UK carbon emissions by 2050. Notably, National Grid UK– the UK transmission system operator (TSO) – estimates that solar has the potential to be one of the most significant generation technologies in the UK in the future, reaching up to 66 GW by 2050, but only if coupled with storage and other changes in the power system for increased flexibility (National Grid UK, 2018a).

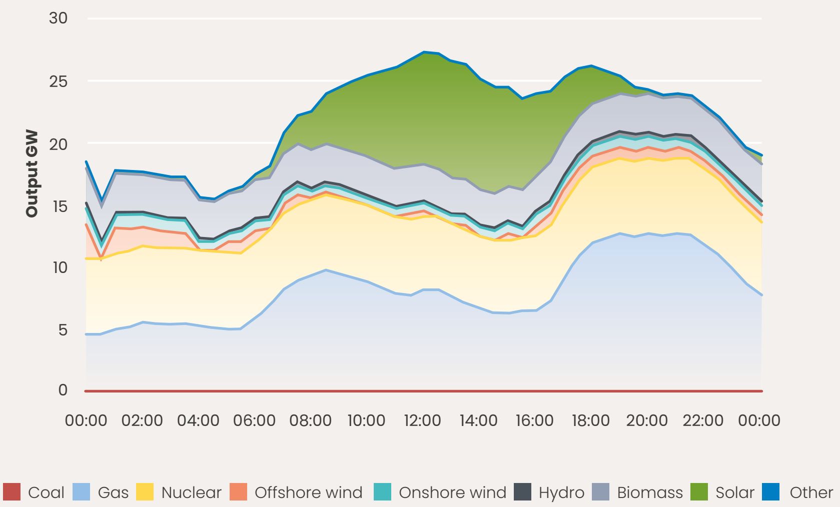


Figure 2. Daily profile of the electricity generation mix in Great Britain on 6 May 2020 (http://electricityinfo.org/fuel-mix-archive/#data)

SOLAR STATUS IN INDIA

India is a growing economy with a total generation capacity of 375 GW (Dec 2020) (Central Electricity Authority, 2020). Among the first states in India to set solar targets was Gujarat with a rooftop solar programme back in 2009 and Gandhinagar aiming to be a solar city. However, the big step towards solar integration in India was made by the government in 2010 with the Jawaharlal Nehru National Solar Mission programme (IEA, 2020). The initial target was 20 GW of solar installations by 2022, which was then revised in 2015 after the COP21 Paris agreement to a much more ambitious target of 100 GW solar power by 2022, including 60 GW of utility scale plants and 40 GW of rooftop solar systems (NITI, 2015).

Presently (Dec 2020) India has installed about 37.5 GW of solar (10% integration), which includes around 6 GW of rooftop installations (Bridge to India, 2020). The generated electricity from solar was about 13.5 TWh in 2016-17, 25.8 TWh in 2017-18, 39.2 TWh in 2018-19 and 50.1 TWh in 2019-20 (Central Electricity Authority, 2020), indicating a steady growth in solar PV integration in the country. Although these numbers come from large PV plants, rooftop PV systems are also expected to grow substantially in the coming years due to improved financing and falling PV technology prices.
It is worth mentioning that India is home to two of the largest solar PV plants in the world, Bhadla solar power park of 2245 MW capacity in Rajasthan, and Pavagada Solar Park of 2050 MW capacity in Karnataka state. Bhadla solar park

located in Bhadla village, Jodhpur district, Rajashtan is spread across more than 56.6 km^2 of land, and the park has been developed by multiple entities (Sanjay, 2019). The Pavagada Solar Park located in Karnataka's Tumakuru district has been jointly developed by the Solar Energy Corporation of India (SECI) and Karnataka Renewable Energy (KREDL); recently completed in January 2020, it spreads across a staggering 53 km^2 of drought-hit land (Ranjan, 2020). Karnataka state is the solar leader in India, having integrated 7.34 GW of solar and generating more than 60% of its electricity from renewable energy sources in August 2020 (SRLDC, 2020).

INTERNATIONAL EXPERIENCE AND LESSONS LEARNT

Solar PV overgeneration in California

California Independent System Operator (CAISO) has been experiencing high PV penetration in their system for about a decade. The well-known 'duck chart' published by CAISO in 2013 (Denholm P. *et al.*, 2015) showed how overgeneration from PV systems can lead to curtailments due to technical constraints that significantly reduce the benefits from high solar deployment. Figure 3 illustrates the net load (actual load minus solar power generation) which features a "belly" during the midday when the solar PV systems operate at full capacity. This curve becomes steeper over the years with increasing PV penetration levels, posing a risk for power curtailments and dictating more power system flexibility to cope with the high upward ramps towards the sunset. CAISO reported curtailment of 187,000 MWh of solar and wind generation in 2015, which rose to over 308,000 MWh in 2016 (CAISO, 2017). Several mitigation measures have been explored, such as effective participation of energy storage, enhancing demand-response, time-of-use rates, flexible electric vehicles (EVs) charging and exploring policies to reduce minimum operating levels for existing generators.

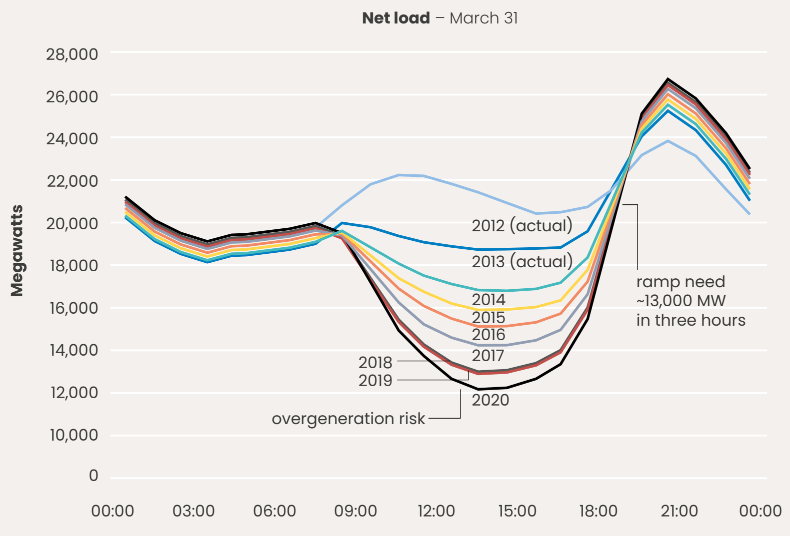


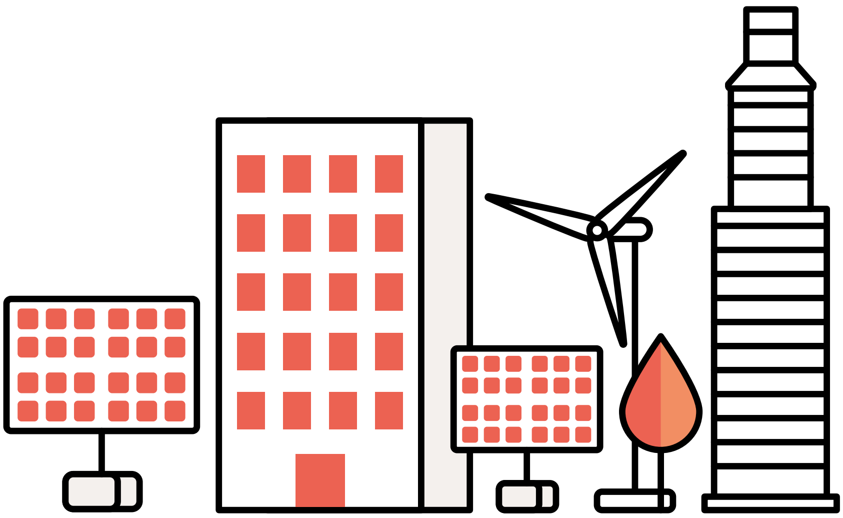
Figure 3. The CAISO duck chart (Denholm P. *et al.*, 2015)

LOSS OF 1200 MW OF SOLAR IN SOUTHERN CALIFORNIA

On 16 August 2016, the blue cut fire in Interstate 15, California resulted in thirteen 500 kV line faults and two 287 kV line faults in a single day leading to outage of generation, including tripping of a prominent 1200 MW of solar at 11:45 AM Pacific time (NERC, 2017). The investigation performed by the North American Electric Reliability Corporation (NERC) revealed that some PV inverters tripped immediately after reading erroneous grid frequency measurements that were caused by transients following the faults rather than actual frequency fluctuation. Additionally, the majority of the inverters installed at that time were configured to immediately cease operation when the terminal voltage was out of limits (0.9-1.1 per unit), which led to massive tripping during the fault-induced voltage dip with delayed recovery afterwards. This instantaneous tripping of inverters has been identified as an undesirable function and the recent guidelines advise either against it if technically possible, or require momentary cessation – immediately restoring output after the disturbance.

EXPERIENCE FROM ROOF-TOP SOLAR IN INDIA

India has set a target of 40 GW of rooftop solar installations by 2022 (NITI, 2015). A study on large-scale rooftop PV integration at the Indian distribution system concluded that the network at the rural areas with weak distribution feeders is likely to experience overvoltages at solar penetration levels of more than 40% (Gaebler, 2017). On the other hand, the investigation on urban distribution systems, considering feeders in the cities of Delhi and Bhopal, indicated higher solar hosting capacity due to feeders with shorter length. These issues can be mitigated by reactive power absorption by PV inverters, but not in highly loaded feeders that do not have the available margin for additional reactive power flow. Other mitigation measures include active power management strategies, such as limiting the PV generation to 70-75% of the inverter capacity or peak shaving using batteries, which result in improved voltage control and avoid feeder overloading.



PART A: TECHNICAL BARRIERS TO SOLAR INTEGRATION

The increasing amount of renewables, such as solar and wind, in the power system has recently started to cause concerns about the reliable operation of the electricity network. Many countries in Europe and North America that pioneered in RES integration in the past few decades, were also the first to see signs of the limitations and challenges brought by these unconventional power sources. The aim of this chapter is to take a deep and holistic look on the major technical barriers faced when deploying high levels of solar PV into the grid, drawn from the UK-India expertise of the consortium and other international experience. The primary objective is to identify the roots of these challenges and main differences between the UK and India, to provide complete understanding of the subject matter and draw a roadmap to high solar integration.

Figure 4 provides a graphical illustration of the most important technical barriers and how they relate to technology limitations and power system challenges. Probably one of the most restrictive and well-known limitation of solar technology is the variable and uncertain nature of solar generation, which makes balancing supply and demand in the system more challenging, but also poses risks for instability and voltage out of bounds in the network. But this is only a small part of the story.

Another major limitation of the solar technology is not having inherent energy storage capacity to allow adjustment and time-shifting of the plant's output when needed. Apart from the relevant balancing limitation, this also contributes to the falling system inertia which is an emerging source of stability issues in the power system.

Grid codes and regulations are often slow in embracing new concepts and ideas, and that may impede the transition of the power system. As solar PV systems have limited inherent ability to provide ancillary services, the grid codes need to strike a delicate balance between grid support requirements and investment viability and attractiveness.

Interfacing the grid via power electronic converters (inverters) allows for much faster response compared to electrical machines, but this comes with very limited overcurrent capacity. This means than an inverter-based resource (IBR) can respond very quickly to a power imbalance in the network and safeguard the frequency from fluctuating too much, but only within the limited capability of the inverter. Not being able to inject the much-needed high currents during faults contributes to a gradual lowering of the grid strength (or short circuit level), which is considered a big challenge for the stability and protection of the network. Synthetic inertia emulation by PV grid-following inverters remains inferior to a rotating machine's mechanical inertia, as it relies on actual inertia from other sources to function and is limited by the inverter's capacity. Power electronic converters also inject harmonic distortion into the grid that may cause power quality issues at high penetration.

Finally, embedding solar generation locally into the distribution network and closer to the load provides many benefits energy-wise, but it also challenges the way voltage control and protection schemes are designed and operate, requiring great efforts to accommodate more localized solar. In addition, small roof-top solar systems are often connected to a single-phase, which is a source of voltage and current unbalance in the network.

It is worth noting that many of these challenges can be alleviated or completely addressed when solar PV systems are physically or virtually coupled with energy storage, especially the balancing, stability and voltage barriers. For this reason, this document also includes a section dedicated to the key technology of energy storage and its own challenges, as an enabler to high solar integration levels.

These and many more challenges are discussed in the following pages, presenting wherever possible examples and evidence from case-studies in the UK and India.

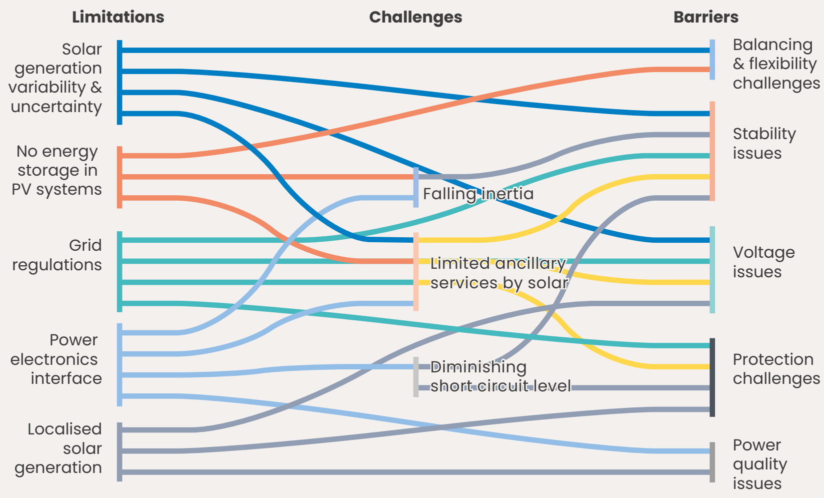


Figure 4. Technical barriers to solar integration, illustrating how technology limitations relate to different challenges and barriers.

A.1. BALANCING & FLEXIBILITY CHALLENGES

One of the most restrictive barriers towards high solar integration is the variable and uncertain nature of solar generation that poses a series of balancing and flexibility challenges to the power system. Balancing is matching supply and demand in the grid in a scheduled manner, and flexibility is the ability of the power system to resolve any mismatches that happen in real-time. Since solar generation is variable and non-dispatchable, it varies during the day and is often unavailable when needed (e.g. no power at night), which makes it an ineffective balancing source. At the same time, it is also uncertain and stochastic, meaning that the actual solar generation delivered may substantially differ from the planned value (e.g. clouds casting shadow), which in turn requires higher flexibility from the power system. These are among the main reasons why system operators maintain a limited portion of solar in the generation mix and occasionally curtail solar generation at high penetration levels. The higher the solar integration, the more the curtailments, which raises the levelized cost of electricity and essentially puts a limit on the amount of solar that can be accommodated into the power system.

A.1.1. Variability of solar generation

The power output of solar PV systems follows the solar radiation that greatly varies during the day, with no generation at night, small values at morning and evening hours, and peak output at midday. Since the electricity demand does not quite follow the same trend, this mismatch has to be met by other sources, rendering the tasks of scheduling and dispatch more challenging. In fact, National Grid UK estimates that balancing wind from Scotland, solar from England and EVs in London will become quite complex and challenging in the future (National Grid UK, 2018a).

Although there is no solar output for several hours a day, there is temporal proximity between the solar peak around noon and the peak demand usually found in the afternoon towards evening hours. To investigate this correlation, National Grid UK has forecasted the summer net power demand seen at the transmission level, affected by the embedded solar generation at the distribution network, for various solar integration scenarios in the near future (Figure 5). For more information on the four scenarios, please see (National Grid UK, 2016). Evidently, the net minimum demand is shifted from the early morning hours in 2016 to the midday in 2025 due to the solar contribution; the morning pick-up has also vanished in most scenarios in 2025 for the same reasons, but there is now much higher load ramping in the afternoon to evening hours due to retraction of solar (National Grid UK, 2016). These observations are quite similar to the duck chart and the solar overgeneration phenomenon in California discussed in the previous section.

This variability renders displacement of conventional dispatchable generation by solar more challenging. The power system has to keep online very flexible units, along with solar, with low technical minima and high ramping capabilities as discussed below, but also perform very accurate forecasting of solar generation towards credible scheduling. Although solar forecasting has seen lately much improvement through technologies like artificial intelligence and machine learning among others (Su, Batzelis and Pal, 2019), there is still room for improvement depending on the forecast horizon and time resolution; forecast errors entail balancing mechanisms and more flexibility online to resolve any supply-demand deviations.

Another critical aspect when accommodating variable power sources in the system is scheduling. Historically, most countries used to schedule at 1-hour intervals in the past, but now there is a need for more frequent dispatch to account for more up-to-date system information and for more accurate forecasts. In Britain the market operates at 30-min time slots (National Grid UK, 2016), whereas in the US many regions have moved to 5-min scheduling intervals (Denholm, Clark and O'Connell, 2016). To accommodate higher levels of solar and other variable generation, minute-level scheduling is highly recommended.

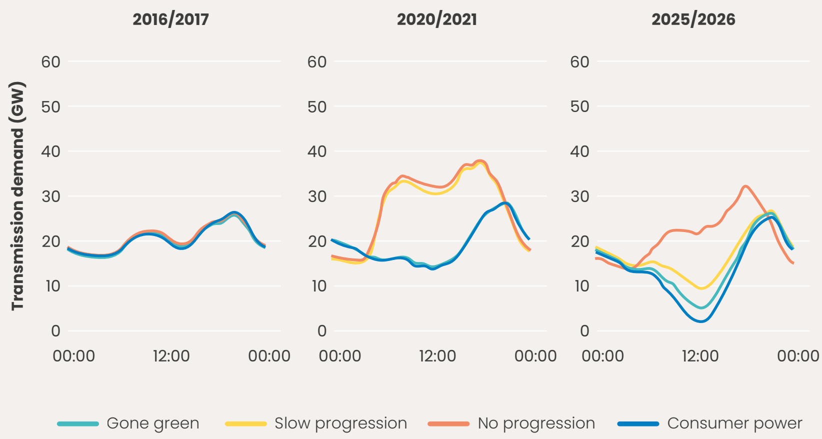


Figure 5. Electricity demand at the transmission level in Britain on a summer day with low demand for four scenarios of solar integration (National Grid UK, 2016).

A.1.2. Uncertainty of solar generation

Solar generation is also uncertain, meaning that the actual solar output may differ a lot from the forecasted value, and stochastic, meaning that it varies from minute to minute in a non-deterministic manner. The primary reason for the solar stochasticity is the volatile weather, for which the UK is renowned, with variations in incident solar irradiance due to moving clouds and in the PV modules temperature because of changes in the weather. This uncertainty not only may cause a mismatch between expected and delivered generation that has to be met by other sources, but it is also often coupled with intermittency (i.e. fast power fluctuation that can sometimes exceed 20% per second (Batzelis *et al.*, 2019)) that requires very high ramping capabilities from the balancing sources. The level of stochasticity and intermittency in solar is generally lower than onshore wind, but it still necessitates more flexibility in the system and sets a limit to the permissible amount of solar online, which in turn entails solar curtailments (Denholm, Clark and O'Connell, 2016).

More flexibility in the system means, among other things, that there are other sources online to accommodate any solar mismatch; thermal and hydro plants have been traditionally used as sources of flexibility in the past. A crucial limitation, however, is the technical minimum level of such sources (i.e. the lowest permissible output while online), which can be as high as 55% for many conventional plants in India and the UK. For example, if the operational range of such a source is 55%-100% and the scheduled level is 70% to have both upregulation (headroom) and downregulation (footroom) capability, there is limited flexibility of -15%/+30%

to support a supply/demand mismatch in the system (National Grid UK, 2016). This limitation comes into the picture mainly at the low-demand/high-solar hours at midday of the summer weekend when the net load to be undertaken by conventional plants is low (see 2025 plot in Figure 5), keeping online only a few of such units and thus having reduced flexibility.

In addition, keeping some power in reserve is not sufficient if that power cannot be deployed quickly enough to compensate for the rate of change of supply and demand. The speed by which a power plant can up- or down- regulate its output is known as ramp rate or simply ramping. Figure 6 illustrates a histogram of the residual ramp rate capability in Britain (i.e. the maximum up- or down- ramping the power system can support as a whole) for a scenario with more solar than today. Apparently, both downward and upward ramping capability is much lower in the summer than in the winter, because of the lower demand at the transmission level that entails fewer dispatchable generation units online. This happens frequently overnight and during the sunny summer days when the high embedded solar generation effectively suppresses the local load, resulting in low demand in the transmission level (National Grid UK, 2016).

Coal plants have been generally designed to act as baseload units and not to deliver flexibility, which is why they feature relatively high technical minimum levels and low ramping capabilities. These plants are seen as very expensive to retrofit and convert to more flexible sources.

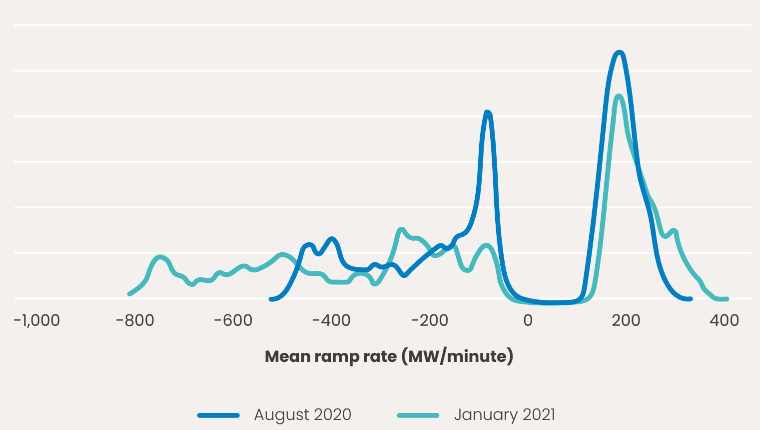


Figure 6. Distribution of forecasted residual ramp rate capability in 2020-2021 in Britain for the "Gone Green" scenario (National Grid UK, 2016).

This is among the reasons for the gradual phasing out of coal in the UK electricity mix and the recent record of several-week coal-free durations. Nuclear plants are also considered as inflexible since their output must change very slowly for safety reasons. On the other hand, gas-fired units are typically much more flexible with short start-up times and high ramping rates, and are expected to act as replacement for coal generation and provide some baseload power by 2050 in the UK (National Grid UK, 2018a). Other sources of flexibility that have yet to be fully explored are demand response and energy storage. Increasing the flexibility in the system, leveraging new technologies and extending the requirement to small generators, will be crucial to allow for more intermittent generation like solar into the grid.

A.1.3. Solar resource data

Despite its famous rain, the UK is eighth in the world in PV deployment after China, Japan, the US, Germany, India, Italy and Australia (IRENA, 2020a). India has great solar potential, rendering solar energy an excellent solution to the nation's energy needs. After the revision of its solar targets in 2015, India has quickly increased its ranking being now the fifth largest PV deployer in the world (IRENA, 2020a).

A critical component to further solar deployment is accurate knowledge of the available solar resource, which is essential during both the development and operation phases of PV projects. It is necessary for preliminary studies, site location, design, feasibility analysis, bankability, and for performance evaluation and monitoring of the established system. Financing of solar projects, in particular, can be promoted by producing reliable estimates of profits on investment based on accurate solar irradiation data. The Ministry of New and Renewable Energy of the Government of India have described reliable solar radiation data as vital for the success of solar energy installations across the country.

It is also essential to monitor and forecast the solar generation in real-time for scheduling, control, safety and efficiency purposes in the electricity network. Uncertainty in estimating solar radiation is often regarded as the largest contributor to the uncertainty of the system output for any solar PV plant. Accurate ground measurements in the form of long-term time series are required to lower the uncertainty of output predictions. Higher frequency data (i.e. hourly rather than daily or monthly) gives a better indication of weather variations and improves accuracy of energy modelling.

There are certain similarities between the UK and India on the availability of the solar resource. Solar radiation is intermittent in the two countries, while both experience peaking of solar generation at midday when most people are working away from home and the demand is low. The UK has a temperate maritime climate; it is an island, situated between the continent of Europe and the Atlantic Ocean, which leads to one of the most changeable and volatile weathers in the world. On the other hand, the Indian subcontinent has a predominantly tropical climate with both dry and humid areas; the weather in India is strongly linked to a jet stream (south-westerly summer monsoons) which follows the latitude, like in the UK. However, the weather patterns only slightly change with the latitude (Müller *et al.*, 2017), as opposed to the UK, where they strongly do so (Palmer *et al.*, 2018).

In both the UK and India, solar resource data is available from either ground-based sources or satellite derived values, usually in the form of long-term time series data of monthly averages of 10- or 20-year periods. Arguably, ground-based measurements are the most accurate, because unlike satellite values, they are measured directly and do not depend on cloud or aerosol data. On the other hand, ground sensors may be subject to missing values and require regular cleaning.

Most satellite-based solar radiation models were developed using data relating to Europe and North America (Purohit and Purohit, 2015). Data based on long-term Typical Meteorological Year (TMY) smooths out anomalies but hides trends in short-term and long-term variation. These TMY datasets were not developed for photovoltaic applications, thus functioning poorly in this context and are only used in pre-feasibility studies. TMY data is available for both countries from Meteonorm, PVGIS, NASA's Surface Meteorology and Solar Energy data set, and RETScreen.

In the UK, ground station measurements of hourly global horizontal solar irradiation are the responsibility of the UK Meteorological Office. Between 80 and 100 weather stations have been operating in recent years, with the first record in 1947. These sensors are spread unevenly throughout the country, with one station per 3,000 km^2 on average; only two stations report at one-minute intervals. In India, ground-based measurements are taken each minute by the Indian Meteorological Department and National Institute of Wind Energy at 123 irregularly distributed sites (one pyranometric station per 30,000 km^2). Measurements date since 2011. Interestingly, interpolation of hourly global horizontal irradiation values gives a similar accuracy (nRMSE 38%) (Palmer *et al.*, 2018) for both countries, despite the much higher density of weather stations in the UK. The UK's weather is changeable, and India's is relatively more stable, but its measurement stations are further apart. Therefore, both have similar errors for interpolated data.

Commercial satellite databases also are available for both countries from Solargis, 3Tier and Solcast. These are of an accuracy that matches ground data but at 15-minute intervals only. Publicly available, lower accuracy satellite values for 15- to 30-minute intervals are available from CAMS (Wald, 2016) in the UK and from SARAH (Pfeifroth *et al.*, 2017) in both India and the UK. These are produced from Meteosat instruments. India also has data from NREL (NREL, 2020) and from the Indian Space Research Organisation (ISRO), based on the Kaplana-1 satellite. This has yet to be extensively validated. When sub-hourly data is required to account for the irradiance variability, it is normally synthetically generated from hourly values using Markov-Chains, e.g. (Richardson, Thomson and Infield, 2008).

The aforementioned datasets are of varying quality, spatial and temporal resolution and standard of validation. Obtaining a proper database for a particular solar project is a challenging task. Cole *et al.* found that a 2% variation in net annual system output/net annual irradiation was possible across 10 sites in the UK, depending on which of five irradiation sources was used to model the output (Cole *et al.*, 2018). Aggregation of hourly irradiation values to yearly sum results in substantial error smoothing. Similarly, in India, significant variation in PV yield estimation calculated using different global horizontal irradiation databases was noted for 23 representative locations (Purohit and Purohit, 2015). To this day, accuracy and availability of solar resource data at various time frames remains an open issue.

A.2. POWER SYSTEM STABILITY CHALLENGES

Replacing synchronous generation (e.g. thermal plants) with intermittent solar generation interfacing the grid via power electronic converters gives rise to a series of operational challenges in the power system. A main challenge is the uncertain nature of solar power – not guaranteed – especially in cloudy days, which generally dictates more operating reserves often provided by conventional sources (e.g. thermal and hydro). Other increasingly prevalent challenges come from the solar plants not having inertia – absence of rotating masses – and the power converters' low overcurrent capacity – their ability to withstand currents only slightly over the rating. These limitations, apparent to some extent to other renewables as well (e.g. wind), contribute to the reduction of the power system inertia and short circuit level (SCL) and pose risks of instability in the power system. Furthermore, solar plants cannot provide the same ancillary services traditionally offered by conventional power plants, such as frequency operating reserves to contain power imbalances in the network (e.g. loss of generation). New ancillary services will be needed to handle high PV penetration, such as fast upward and downward power ramping, grid flexibility, fast frequency support, etc. Tackling, or at least mitigating, these challenges is crucial to permit universal replacement of the conventional power plants by solar systems and achieve high solar integration levels.

A.2.1. Common instabilities caused by solar

High penetration of solar energy has the potential to substantially affect the dynamic behaviour of the power system due to a variety of reasons related to the highly different electrical and dynamic characteristics of solar compared to synchronous generation. Some of the most common stability issues are (i) transient stability, (ii) small signal stability, (iii) frequency stability and (iv) voltage stability. While transient stability (large disturbances) is mainly affected by the dynamic response and protection settings of PV inverters, small-signal stability (small disturbances) is primarily influenced by the PV inverter controller parameters. Frequency stability, on the other hand, is dictated by the total system inertia and the ability of PV systems to withstand and support frequency disturbances. Finally, dynamic voltage stability is negatively affected by the insufficient reactive power injection and current contribution during faults due to the PV inverters overcurrent limitations. The risk of each instability heavily depends on the structure of the power system, i.e. its size, the network strength, and the generation mix. As expected, these parameters vary during the day, which renders time as another critical risk-related factor; for example, the risk is higher at high-PV/low-demand periods, such as at midday on a sunny day, or during evening periods when the solar generation declines steeply and the demand increases rapidly.

The negative impact of high solar penetration on the frequency stability of the power system has arisen lately as a topic of concern for the system operators. Although it is a challenge of the future rather than of today, replacing more and more conventional power plants with solar PV systems will lead to lower system inertia and reduced capacity to absorb large power imbalances in the system. This aspect is discussed in more detail in the following section. In addition, solar plants are less reliable sources under severe disturbances compared to conventional generation, which entails higher level of power reserves to compensate for sudden loss of solar. For example, Southern California witnessed an aggregated loss of 900 MW of solar power on 9 October 2017 due to a voltage dip triggered by two transmission line faults caused by the Canyon 2 Fire.

Voltage instability comes primarily from reactive power imbalance. Although the synchronous machines can support the voltage during faults by injecting additional current up to 6-8 times the nominal, the PV inverters are limited to an overcurrent capacity of 1.2-1.6 times the nominal value. Therefore, replacing synchronous generation with inverter-based solar results in lower short circuit strength and dynamic reactive power resources in the network. A more thorough analysis in this topic follows. Other reasons for solar-induced voltage instability are undesirable tripping of PV systems at voltage dips and controller interactions among neighbouring generators.

A.2.2. Falling system inertia

The system inertia is the total energy stored in the rotating masses of machines in the power system (generators and motors) and is the first line of defence during power imbalance and fluctuation of the grid frequency. When inertia is high, there is a lot of stored energy to feed a sudden generation loss or load tripping, thus limiting how fast the grid frequency changes; under low inertia conditions, a small power imbalance can lead to high frequency excursion with cascaded implications (e.g. generators tripping, load shedding or even system collapse).

Figure 7 shows how the frequency typically changes when a generator is lost: the initial period of decline is the most critical, which determines the rate of change of frequency (ROCOF) and the minimum frequency value (nadir), both directly related to the total inertia of the power system. If the frequency falls below a certain level, some load is automatically cut off (under-frequency load shedding – UFLS) to protect the system from collapse; also, when the frequency changes too fast (high ROCOF) some generation may trip due to protection settings, which may trigger further frequency drop and eventually load shedding.

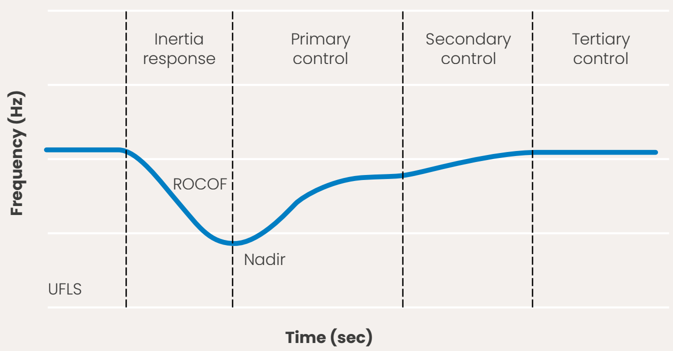


Figure 7. Typical system frequency response at loss of generation.

Another illustration that shows how different levels of inertia affect the frequency is given in Figure 8 (simulations of the IEEE 9-bus testbench in DIgSILENT PowerFactory). The same disturbance results in widely different ROCOF and frequency nadir values: the more inertia, the better. This is why replacing synchronous generation by solar risks frequency instability if not accompanied by proper countermeasures.

In the UK, the major inertial contribution comes from conventional power plants and to a much lesser extent from smaller synchronous generators, synchronous demand and induction motors (National Grid UK, 2016). Technologies that do not have rotating mass, such as solar PV plants, do not inherently contribute to system inertia. National Grid UK has been recently paying significant attention to the falling system inertia of the Great Britain power system due to the uptake of renewables, including solar, which is estimated to decrease inertia from 220 GVAs to about 100 GVAs on average in a few years (Figure 9). Notably, the cost for managing the maximum rate of change of frequency (ROCOF) to prevent undesirable tripping of loads and generators in the system has more than doubled lately, from £60 million in 2017/18 to £150 million in 2018/19 (National Grid UK, 2019b). For this reason, National Grid UK is currently exploring advanced methods to monitor the system inertia in real-time via various projects, which was simply estimated in the past (National Grid UK, 2019b). In order to achieve high solar integration levels, new sources of inertia should be explored, e.g. from demand response or synthetic inertia provision by solar plants. Presently there is no similar concern in India, where the power system has sufficient synchronous generation. However, by achieving the envisioned RES targets it is not unlikely to start seeing such problems in the Indian network as well in the future.

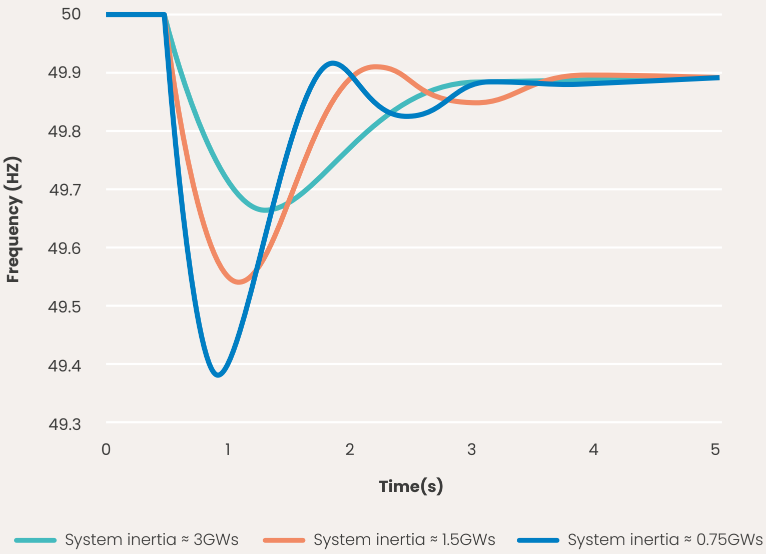


Figure 8. IEEE 9 bus system frequency under a disturbance for different system inertia values.

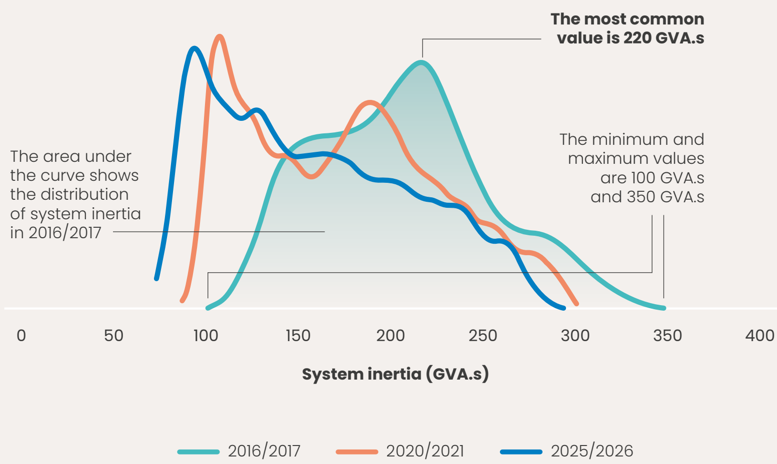


Figure 9. Distribution curves of system inertia in the UK (National Grid UK, 2016)

A.2.3. Diminishing short circuit level

Short circuit level (SCL) or ratio (SCR) or simply grid strength, at a particular node of the network is the ratio of short circuit current over the rated current of a generator to be connected. SCL is a measure of the grid strength at a node of interest: high SCL means "strong" grid that can withstand line faults with limited oscillations in the voltage; low SCL implies a "weak" grid that will experience significant voltage oscillations during faults and poses a risk for voltage instability (see illustration in Figure 10). SCL is primarily influenced by synchronous generation, due to the inherent ability of such machines to withstand as high as 6-8 times the nominal currents for short durations. In contrast, the power converters of solar plants (and other inverter-based resources – IBRs) have very limited short term overcurrent capacity (typically up to 120-160% of the nominal current), which leads to reduced contribution to a fault and the SCL of the neighbouring network.

Along with the inertia, SCL is considered a critical stability indicator, expected to continue falling rapidly in the UK in the coming years (Figure 11). Low SCL implies risk of control instability, stringent fault-ride-through (i.e. staying connected to the grid during faults) and more challenging anti-islanding (i.e. tripping when the network is islanded) in IBRs (IEEE/NERC, 2018). In fact, SCL is usually lower in remote regions where solar and wind parks are often installed, which is why National Grid UK anticipates phase-locked-loop (PLL) instabilities in parks connected to North Scotland by 2030 (National Grid UK, 2018b). Other problems arising from a low SCL and weak grid are control interactions among neighbouring systems (e.g. fighting for voltage control on the same nodes, reactive power oscillations between a solar park and HVDC or STACOM) and difficulties in energizing large transformers by IBRs (IEEE/NERC, 2018). For these reasons, India introduced in 2019 a requirement for at least SCR = 5 at the point of interconnection of new DGs as a precautionary measure (Central Electricity Authority, 2019). Since SCL is a "regional/local" metric, in contrast to the "global" inertia, it is imperative to explore how solar plants can more actively contribute to the strength of the local grid.

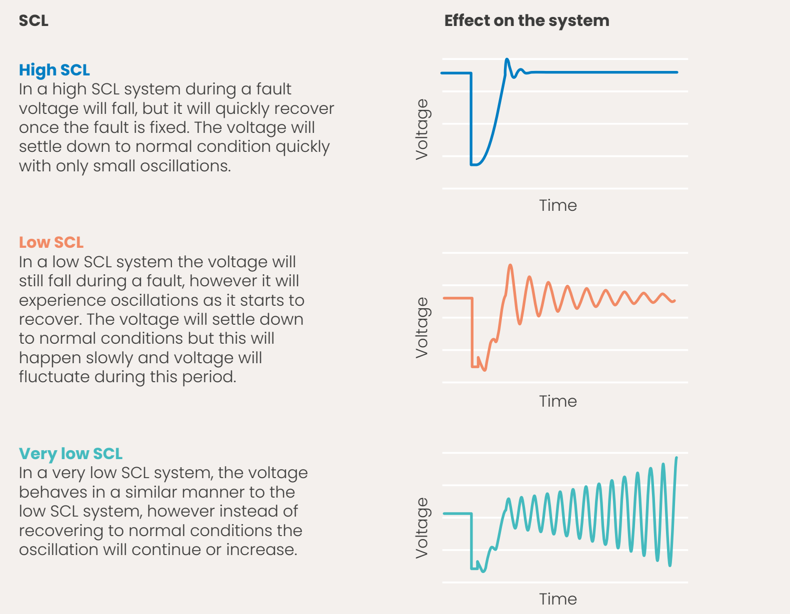


Figure 10. Impact of SCL on voltage stability during faults (National Grid UK, 2018b)

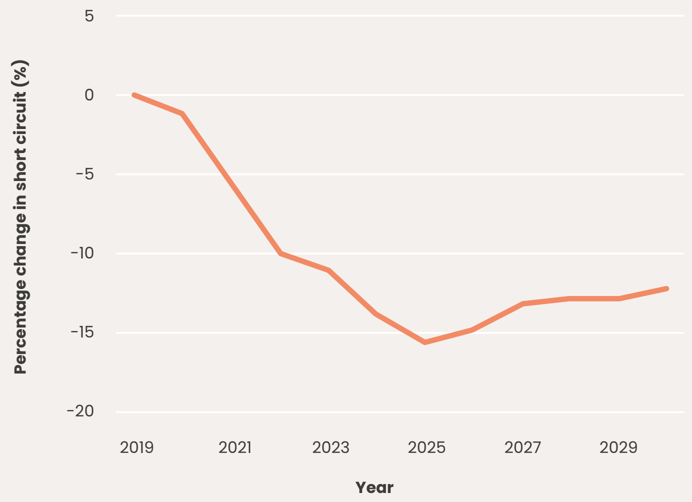


Figure 11. Estimated change in SCL in the UK (National Grid UK, 2018b)

A.2.4. The power cut of August 2019 in the UK

On the 9th of August 2019, a series of events resulted in a large power cut in the UK that caused major disruption to about 1.1 million customers: a rare event that has not happened in over a decade (National Grid UK, 2019c). A lighting strike on a transmission circuit and a technical fault in a steam turbine led to more than 1.1 GW generation loss from the Hornsea offshore wind farm and the Little Barford gas power station; this consequently led to almost 500 MW embedded generation tripping and eventually significant load shedding upon subsequent faults in the Little Barford plant (Figure 12).

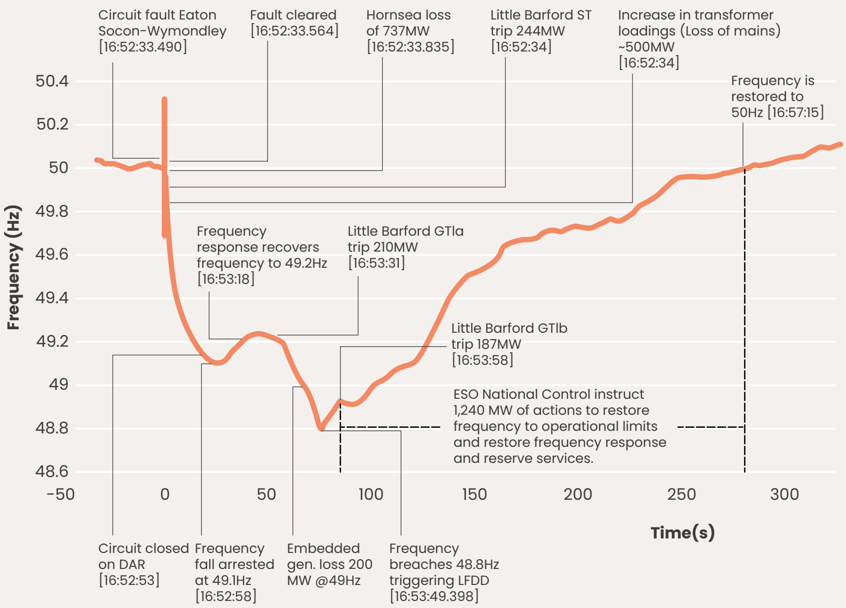


Figure 12. Frequency variation during the power cut of 9th August 2019 in the UK (National Grid UK, 2019c).

The Hornsea wind farm deloading by 737 MW was caused by oscillations in the grid voltage that resulted from the fault in the transmission circuit; critical factors were the controller's settings and the weak grid that emerged by clearing the fault (National Grid UK, 2019c). This highlights the control instability and low-SCL risks that come with IBRs, such as wind or solar farms, and raises the need to consider more seriously these new IBR-related challenges.

Furthermore, the 500 MW embedded generation that tripped due to vector shift or high ROCOF was unnecessary for some sources, especially the power-electronics-based IBRs like solar: the IBRs do not have synchronised rotating masses and technically are capable of withstanding severe grid voltage and frequency distortions. There is a need to fully explore the decoupled potential of solar and other IBRs to come up with better interconnection standards.

This incident highlights the new type of challenges the UK power system faces with the massive uptake of distributed generation. Another two frequency dips below 49.6Hz were apparent in May and July 2019 (without any load shedding), which have sparked a debate on the reliability of the power system in the UK while heading towards the net-zero carbon future of 2050.

A.3. VOLTAGE CHALLENGES

High PV penetration in the distribution network renders controlling the voltage of the network – keeping the voltage within limits at all nodes – more challenging. New loading patterns, the variable nature of solar power and interaction of PV inverters with conventional voltage regulating devices (e.g. on-load tap changers (OLTCs), step voltage regulators, switched shunt capacitors) have rendered today's voltage control a concern to distribution system operators (Borghetti, 2013; Jabr, 2019).

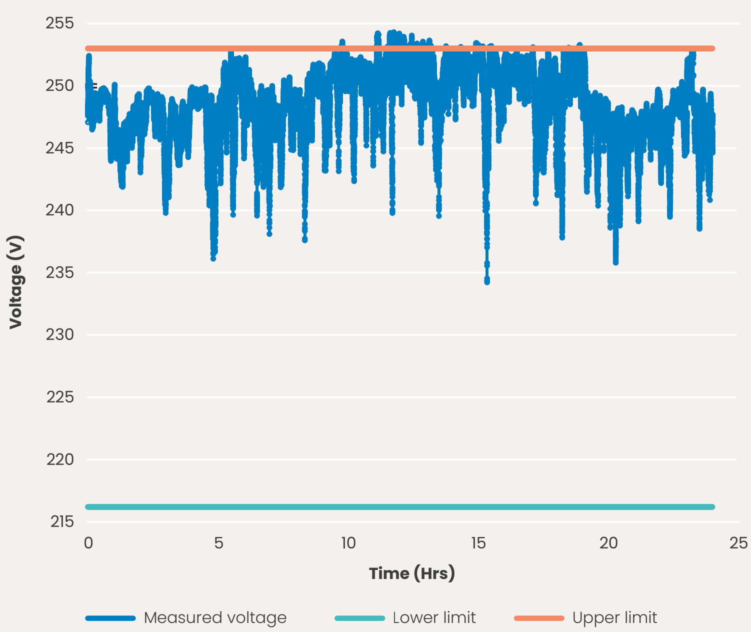


Figure 13. Voltage rise in the low voltage network in the UK.

A.3.1. Voltage Rise

One major impact of distributed solar generation on the network is voltage rise – having voltage exceeding the limit at certain nodes. This undesirable phenomenon is more severe at higher solar penetration levels and during the low demand times (Masters, 2002). It is a well-known challenge to distribution network operators (DNOs); the UK Power Networks reported a voltage rise of more than 2% in some feeders in 2015 due to residential PV installations (UKPN, 2015b), while similar voltage rise issues were found in the Peterborough Central grid in the UK (UKPN, 2015a). An example of voltage rise in the low-voltage network in the UK is shown in the daily profile of Figure 13: there are several times at midday when the PV generation peaks and the customer demand is low, resulting in voltage higher than the upper limit of 253 V (230 V +10%). Voltage rise is made worse by the voltage set point of distribution transformers, that is often set close to the upper limit. As described in the next section, this is done on the assumption that power only flows from the higher voltage levels to the lower voltage levels, and from the transmission grid to the distribution grid.

These issues are more prominent in the distribution network, whose lines are typically more resistive than inductive (high R/X ratio) in contrast to the transmission network. This entails that the active power flows in the distribution network affect the voltage to a great extent, unlike in the transmission system. Figure 14 shows the operating principle via a simple Thevenin equivalent circuit; if the substation voltage V_0 is close to nominal ($1\angle 0°$ per unit), the voltage magnitude at the PV node would be (Strbac *et al.*, 2002):

$$|V_{PV}| \cong V_0 + (P_{PV} - P_l)R + (\pm Q_{PV} - Q_l)X$$

When the voltage approaches the limit, the standard approach is to use voltage regulating devices, such as on-load tap changers and shunt capacitors, to reduce the voltage back to an acceptable range. An additional tool towards the same goal is to leverage the reactive power capability of the PV inverters (inductive mode) which can also reduce the voltage at the PV nodes depending on the inductive value of the line.

However, these options have important limitations too. The voltage regulating devices are meant to operate occasionally only a few times a day, which does not fit well with the intermittent solar generation, especially during partially cloudy days, that may require minute-level voltage regulation. More frequent than normal switching of these devices results in additional stress and deterioration of their life expectancy. Additionally, the reactive power consumption by the PV inverter may not be that effective in the distribution lines where the inductive part is usually lower (or much lower) than the resistive part. These challenges are expected to be more severe in rural grids with weaker and lengthier feeders, such as in rural India. To this day, optimal coordination of all these actions towards efficient and voltage-secure network operation remains an open challenge for DNOs and the scientific community.

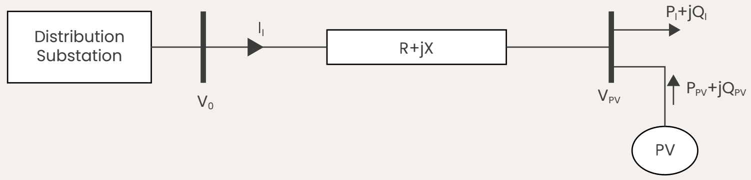


Figure 14. **Thevenin equivalent looking from the PV node.**

A.3.2. Reverse Power Flows

Conventionally, the power has been flowing in one direction from the main grid towards the load connected across the distribution feeder. This is why the distribution system has been traditionally treated as a passive load and the voltage control has been designed considering unidirectional power flows only (Sun *et al.*, 2019). For example, the voltage control of distribution systems has been historically carried out based on the concept of line drop compensation, which assumes that voltage decreases with distance as we move away from the substation along the feeder. Based on this principle, the tap changers traditionally adjust their settings using local current measurements to estimate the voltage drop across the feeder.

However, embedded solar generation into the distribution system does not only result in reverse power flows, but also multidirectional variable flows: power may flow in opposite directions in different subsections of the feeder, a condition that is not static but also varies from minute to minute. This complicated situation interferes with how tap changers function, resulting at times in worsening of the voltage rise, rather than alleviating it, during reverse power flows. In addition, some tap changers and voltage regulators may have a lower than the nominal power rating at reverse power flow, which complicates their operation even further.

In the UK, we have started seeing these issues in the network. A technical report on the changing nature of the transmission and distribution boundaries carried out by the Scottish Power Network (SP Energy Networks, 2017) describes the case of the Dunbar grid supply point that exhibits high levels of reverse power flow. The case study of 2015 showed peak demand of only 30 MVA while having installed about 110 MW of distributed generation, resulting in exporting power to the transmission grid for 63% of the time. Similar concerns arise for India, where the 40 GW rooftop PV installations target by 2022 is expected to lead to similar issues for several distribution feeders in solar-rich states.

A.3.3. Voltage Flicker

Another voltage regulation challenge for the DNOs related to high solar penetration is power-line flicker. Flicker is the condition when the voltage varies periodically, resulting in visually noticeable changes in brightness of light and power quality deterioration that interferes with the electronic devices on the network. It may be caused by fast variation of the PV generation due to movement of clouds (Barker and De Mello, 2000).

A.3.4. Distribution and Transmission System Interaction

Another emerging issue at high solar integration levels is the interaction between the transmission and distribution network when controlling the voltage and exchanging reactive power. Autonomous voltage control by PV inverters may compete with other regulation equipment and it may also affect the dynamic interactions of reactive power between the two layers of the power system. A more holistic voltage control framework will be necessary to coordinate all devices in the transmission and distribution network simultaneously, while taking into account the different ways in which the reactive power and active power affect the voltage in the two layers.

A.4. PROTECTION CHALLENGES

With the increase of solar PV integration in the UK power network at different voltage levels, it has become more challenging for the traditional protection schemes to function properly and protect the network from faults (National Grid UK, 2016). These newly brought challenges are mainly related to how solar PV systems respond during faults. In contrast to synchronous generators, solar plants have very limited overcurrent capacity (like other IBRs) and their current contribution during faults is little and slow in response (IEEE, 2019). These may have a negative impact on the post-fault grid voltage recovery, as well as on the current measurement of protective relays and their effectiveness in detecting and isolating faults (ENTSO-E, 2016; H. Urdal *et al.*, 2016; Li *et al.*, 2016). In addition, in order to support a fault, the PV system has to have fault ride through (FRT) capability – to stay connected to the grid despite the disturbance – which is not a trivial task for an IBR. Furthermore, embedded solar plants still face challenges in the anti-islanding protection, occasionally tripping when they should not or failing to trip when they should during major disturbances and islanding events in the network. With the anticipated high solar integration levels in the UK and India, operators are increasingly expected to face a series of challenges in the protection of transmission and distribution systems.

A.4.1. Protection in the transmission system

The protection scheme of the UK transmission system incorporates overcurrent, distance and differential protection mechanisms (National Grid UK, 2016). The grading and setting of these protection settings is based on an assumed range of short circuit level (SCL). High levels of solar in the network will negatively impact the SCL, which in turn may impair the effectiveness of these protection mechanisms, as briefly explained in Table 1.

Furthermore, with low SCL in the system, it may be difficult to discriminate between actual faults and normal events of high inrush current caused for example when starting-up motors (without soft starter) that may require up to 6-10 times their rated current for a short time (National Grid UK, 2016). To address these challenges, some technical reports (H. Urdal *et al.*, 2016; Tuladhar and Banerjee, 2019) recommend to give more weight to differential protections over the alternative schemes. This approach, however, may malfunction as well at low SCL when the fault currents are lower (National Grid UK, 2016). It remains a challenging task to keep the protection scheme of the transmission system up to date with the increasing IBRs, implying that fundamentally different approaches and a complete restructuring may be required for the inverter-intensive power system of the future.

PROTECTION SCHEME	OPERATING PRINCIPLE	IMPACT OF LOW SCL
Differential Protection	Compares the current infeed and output from the equipment; if the difference between the two is greater than the bias current, the relay is set to trip.	If the difference between the currents is very small, it may not be detected by the relay. The bias may need to be set comparatively high at times of low SCL to avoid maloperation.
Distance Protection	Calculates the impedance at the relay point and compares it with the reach impedance; if the measured impedance is lower than the reach impedance, the relay is set to trip.	Not affected if the ratio of voltage to current decreases following the short circuit. This ratio however will be affected by the significantly different volumes of synchronous generation at peak and minimum demand and may drive additional settings.
Overcurrent Protection	The operating time of the relay is inversely proportional to the magnitude of the short circuit current.	This type of protection is the most likely to be affected by low SCL. However, these schemes are mainly used for back-up protection and therefore the consequences may not be severe, provided that main protection schemes are not compromised.

Table 1. Operating principle and impact of low SCL on UK transmission protection schemes (National Grid UK, 2016)

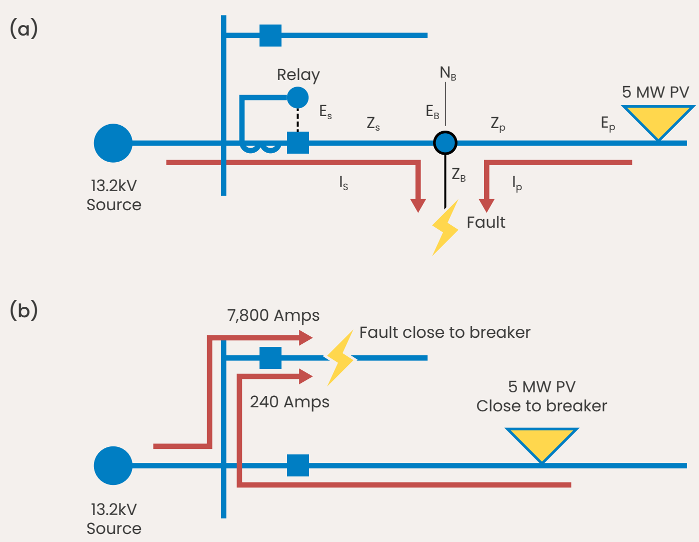


Figure 15. Examples of (a) lower and (b) higher fault current flows due to embedded solar in the distribution network (Bryan Palmintier *et al.*, 2016)

A.4.2. Protection in the distribution system

Installing solar generation at the end nodes of the distribution system provides transmission-like features to the otherwise radial unidirectional network, with bidirectional power flows that are usually found in meshed grids. Along with the low fault current of PV systems, these pose a real risk to the traditional protection of distribution networks (overcurrent relays and fuses), whose operation heavily depends on the magnitude of the fault current. An example is shown in Figure 15: the current flowing through a relay or breaker during a fault may be either lower or higher due to a nearby solar plant, potentially leading to relay desensitization or equipment damage (Bryan Palmintier *et al.*, 2016). Of course these challenges refer mainly to three-phase solar plants connected at the medium voltage level, since the impact of single-phase low-voltage PV systems is quite limited, even negligible for faults not close to the solar plant (Bhagavathy *et al.*, 2019).

Unfortunately, these challenges are not simply overcome by applying the transmission protection schemes to the distribution network (Hooshyar and Iravani, 2017). The limited fault current contribution by solar is comparable to a heavy load condition, thus rendering the overcurrent protection scheme ineffective. This fault current is also configured to be symmetrical even at unbalanced faults, which may seriously challenge directional relays that are based on negative/zero voltage sequence or on voltage polarising (IEEE, 2019). The latter may also affect the distance relays that are based on voltage and current measurements which depend on the fault type and impedance (Hooshyar and Iravani, 2017).

It is worth noting that massive deployment of solar in the distribution network not only affects the distribution system protections, but may also compromise protection mechanisms in the transmission level and the operation of other network equipment such as circuit breakers, lines, and transformers in similar ways (H. Urdal *et al.*, 2016).

Furthermore, it is likely that many distribution feeders will evolve into microgrids in the future, supporting both grid-connected and islanded mode of operation, towards increased reliability and resilience. This will further challenge the protection schemes, as faults are much harder to detect in islanded operation (National Grid UK, 2019a). For microgrids in particular, the current practice is to design protection schemes on a per case basis, entirely tailored to that particular network (Shiles *et al.*, 2018), which indicates that there may be no place for "generic" and "universal" protection schemes in the distribution network of the future.

Another source of concerns relates to unnecessary tripping of solar generation during disturbances, which has been seen to take place in quite a few power cuts in the UK and elsewhere (Roscoe *et al.*, 2017; National Grid UK, 2019c; E3C, 2020). For example, the 2016 fire incident in California led to disconnection of 400 MW of solar due to ROCOF and vector shift protections even though there was no islanding (Roscoe *et al.*, 2017). Since then, the protection settings have been revised several times, now having banned the vector shift protection and relaxed the ROCOF cut-off limits from 0.125 Hz/s to 1 Hz/s with a delay of 0.5 s for all DGs in the recent Engineering Recommendation G99. Similarly, the recent power cut of August 2019 in the UK had about 500 MW of embedded generation trip, either due to high ROCOF or vector shift, which was to some extent unnecessary (National Grid UK, 2019c). Erroneous high ROCOF readings may also be recorded due to noise, off-nominal frequencies and interharmonics (EURAMET, 2018). All these recent examples clearly show that misconception of islanding and unintentional generation tripping is expected to remain a challenge for DGs well into the future (Roscoe *et al.*, 2017; EURAMET, 2018).

A.4.3. Fault Ride Through

The duration of faults is usually very short (in the range of tens to hundreds of milliseconds), either because they are of temporary nature or because the network isolates them through the protection equipment discussed previously. The risk for solar plants and other DGs is to trip at such short-term disturbances, either intentionally or unintentionally, triggering cascaded implications that extend to a much larger time scale. The desirable capability of a power plant to withstand these faults and remain connected to the network during faults is denoted as fault ride through (FRT). Voltage FRT and frequency FRT are nowadays common requirements for large DGs by most standards and grid codes. Nevertheless, the track record of fault incidents that led to disconnection of significant distributed generation in the past few years in India, the UK and the US (Table 2) indicates that there is more to be done.

DATE	DETAILS OF INCIDENT	LOSS OF GENERATION (MW)
July 2014	Delayed clearance of fault in 230 kV Kayathar-Tuticorin TPS line, Tamilnadu, India	920 - wind
August 2016	Blue cut fire incident led to a normally cleared fault on 500 kV line, Southern California, US	1200 - solar
October 2017	Canyon 2 fire incident caused two transmission faults (220 kV and 500 kV), Los Angeles, US	900 - solar
August 2019	Lightning strike on transmission lines (400kV) and power plant faults, Great Britain, UK	1691 – various DG

Table 2. Trip events of wind and Solar PV generating units due to network faults.

Another relevant incident with two consecutive transmission faults at the Northern part of India in June 2016 is shown in Figure 16 (CERC, 2014). The voltage in Figure 16(a) features a dip for about 1.88 seconds until the protections cleared the fault, but it also exhibits delayed voltage recovery up to 5 seconds after the fault. This phenomenon, referred to as 'fault-induced delayed voltage recovery', may last up to 30 seconds post-fault (G. Lammert, 2019) and can lead to fault-induced load loss. Such a load loss was the aftermath of the 2016 incident in India, which in turn led to a frequency overshoot in the system that lasted for almost 10 minutes (Figure 16 (b)).

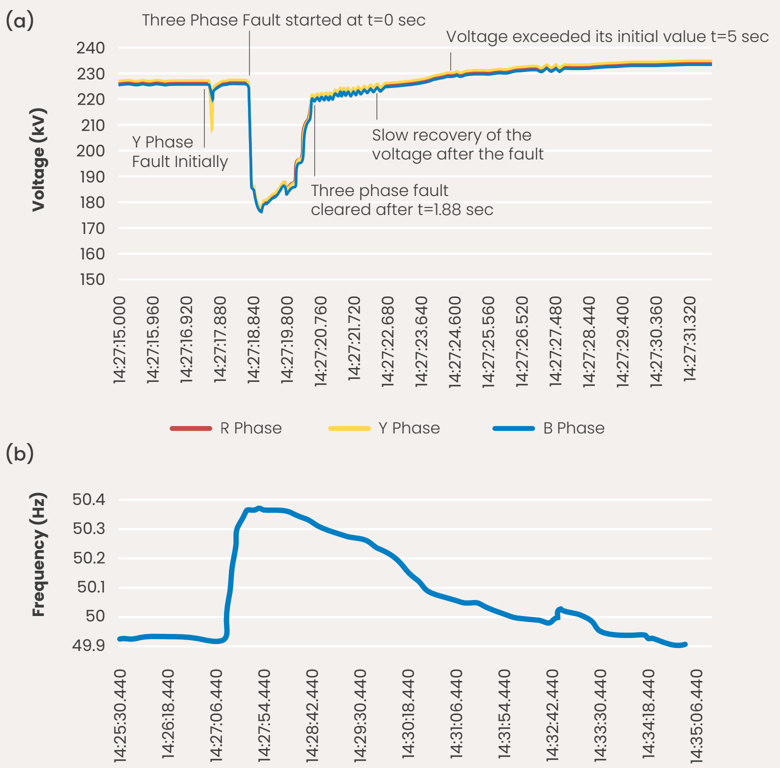


Figure 16. Fault response in the Indian electricity grid during the event of June 2016. (a) Voltage at Dadri station, (b) System frequency (Shukla *et al.*, 2017)

The Blue cut fire in California in 2016 is indicative of how simultaneous tripping of many solar plants can lead to other types of frequency distortions. The faults at the 500 kV transmission lines caused disconnection of about 1,200 MW of solar, which was reflected in a frequency dip of 130 mHz shown in Figure 17(a). Figure 17(b) depicts the post-fault solar power output: about 450 MW of solar recovered in a ramp-like manner within two minutes (Zone-I); another 350 MW that tripped due to PLL inaccuracy reconnected after five minutes (Zone-II); the remaining 400 MW deliberately remained offline for safety reasons and resumed the next day.

This experience clearly shows that reliable FRT function in PV systems is critical to allow large-scale solar deployment. There is a need to develop new means and methods so that solar plants and other DGs can withstand a wider range of voltage and frequency disturbances.

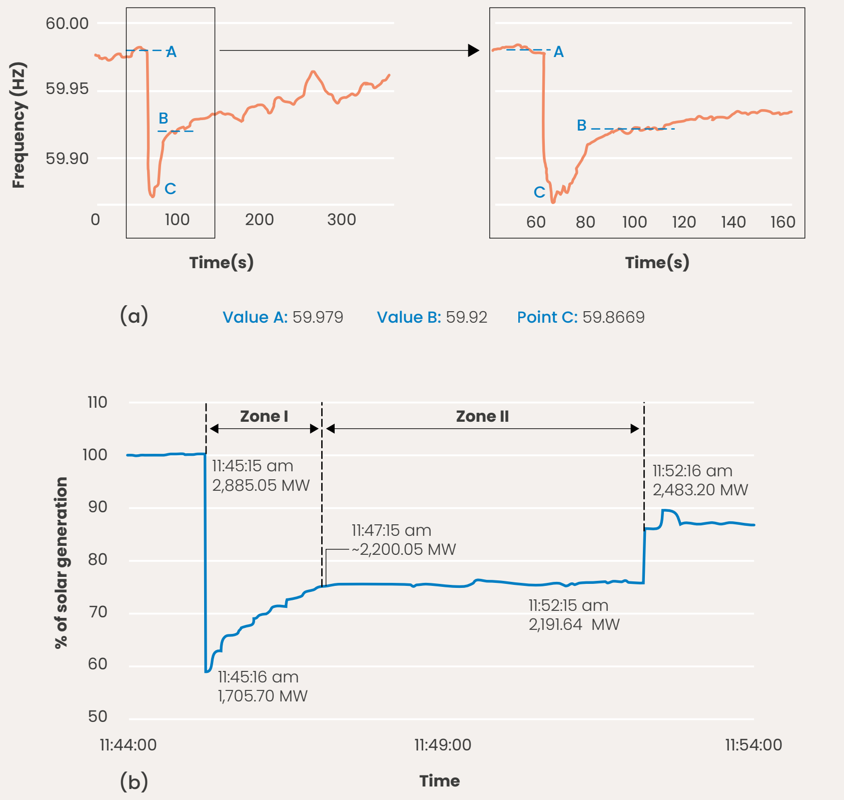


Figure 17. Blue cut fire incident in California 2016 leading to disconnection of 1,200 MW of solar generation. (a) Frequency dip (b) solar generation profile.

A.5. ANTI-ISLANDING PROTECTION

When a part of the network that does not have conventional generation is cut off from the main grid due to a fault (islanding), then the islanded network experiences a loss of mains (LoM). During LoM events, it is essential that any embedded DG ceases operation for the safety of equipment and people in the distribution network. Anti-islanding detection (AID) is the software and hardware in a DG dedicated to detecting such islanding events. However, this is not a trivial task and faces two main conflicting challenges (Weitzl and Varjasi, 2010; Dietmannsberger and Schulz, 2016; Ropp *et al.*, 2016; Li and Reinmuller, 2018).

Failure in detecting LoM

During a LoM event, the anti-islanding protection of a DG may fail to act and cease operation, especially when the embedded generation and load in the islanded network happen to balance out. This poses a series of hazards: electricity distribution workers safety is at risk; power quality may be compromised in the islanded part of the system; instantaneous reclosing can result in out-of-phase reclosing of embedded DGs, resulting in excessive currents and torque loads (Mahat, Chen and Bak-Jensen, 2008). The set of conditions under which AID fails to detect LoM is referred to as the non-detection zone.

Because of the conservative approach of most operators, there have been recorded only a few incidents of accidental islanding. An incident of undesirable reclosure of a wind farm in Canada resulted in large inrush currents (Li and Reinmuller, 2018). There have also been failures of anti-islanding systems in solar photovoltaic plants in an Iberdrola grid (Pazos *et al.*, 2013) and a risk assessment of potential islanding of solar PV in India (Joshi and Pindoriya, 2013).

False tripping

In order to avoid any undetected islanding, the anti-islanding schemes are occasionally found to erroneously trip when they should not. With reduced inertia and grid strength in the power system, large changes in grid voltage, phase angle or ROCOF may give the impression of a false LoM resulting in DG disconnection. This in turn may cause cascaded implications, disturbing further the frequency and voltage in the network, leading to further DG disconnections in a domino-like manner and possibly to power cuts.

The Blue cut fire in California in 2016 and the power cut in the UK on 9th August 2019 are such examples of false tripping. In both cases, embedded generation including solar disconnected due to high ROCOF and vector shift protections triggered by faults, even though there was no LoM. Afterwards, the operators relaxed the protection settings to avoid such phenomena in the future, but this is not really the solution: by relaxing the settings too much, an actual islanding event may go unnoticed. Other examples of temporary disconnection of DGs are described in (Li and Reinmuller, 2018). Another event of false tripping has occurred in the UK due to vector shift LoM protection on 22nd May 2016 (National Grid, 2017). These instances show that anti-islanding protection remains to this day an open issue.

A.6. POWER QUALITY ISSUES

We have power quality issues when the waveforms of the current and voltage in the network deviate from what they should be; common such problems are harmonics, voltage unbalance, flicker and voltage rise. These issues are more prominent in the low-voltage level of the distribution network, where PV systems are more common as compared to other RES (Nduka, Kunjumuhammed, *et al.*, 2020).

Any distortion in the current and voltage waveforms (due to the presence of other frequency contents) that differentiate them from the ideal sinusoidal signals is referred to as harmonics or inter-/sub-/supra-harmonics depending on the frequency components of the distortion (Smith *et al.*, 2017). These harmonics may come from PV inverters or other power electronic devices, whose produced voltage and current usually contain other frequency components apart from the fundamental grid frequency (50 Hz in UK and India).

The voltage unbalance is another problematic condition, under which the voltage magnitude in the three phases is not equal, resulting in asymmetrical voltage and current flows in the network. Historically, such unbalance was caused by uneven loading among the three phases when connecting single-phase consumers. However, a similar situation arises in the case of connecting single-phase PV systems to the three-phase network (e.g. in kW-scale rooftop solar systems), which may lead to uneven current flows and voltage in the three phases. Voltage or current unbalance in the network is detrimental to utility assets, with more significant impact in three-phase systems with grounded neutral (Karthikeyan *et al.*, 2009; Smith *et al.*, 2017).

The intensity of these issues depends on a range of factors, such as the network conditions prior to PV connection, the technology of the PV inverters and the standards they comply with, and of course the amount and location of solar generation. The type of network, i.e. urban, semi-urban or rural, is of particular importance due to widely different electrical and physical characteristics (Smith *et al.*, 2017; Nduka, Kunjumuhammed, *et al.*, 2020). When comparing India to the UK, these challenges are greater in the former case that has been already experiencing high levels of voltage/current distortion and voltage unbalance (Karthikeyan *et al.*, 2009; Rajesh *et al.*, 2016); integrating lots of solar into networks that already exhibit such issues may be tricky and risks further worsening of these conditions. On the other hand, the UK generally uses underground cabling within its cities in contrast to India's overhead lines. The capacitance of the underground cables can theoretically interact with impedances in the network (e.g. transformer or grid-side filter of PV inverter) and lead to resonance phenomena and undesirable voltage or current excursions (Nduka and Pal, 2017). This may result in deterioration of the cables' insulation and burnout of fuses, thus accelerated ageing of the utility assets and sometimes maloperation of customers' sensitive loads, e.g. plasma TVs, laser devices etc.

In the following, we discuss the power quality challenges that have been observed in typical UK distribution systems with customer-owned PV units and draw parallels with the Indian electricity networks. The findings presented are based on field measurements conducted on PV systems that were certified to comply with regulatory standards in the UK.

A.6.1. Harmonics

Field data on the harmonic emissions of PV inverters obtained from household measurements in the UK are shown in Figure 18. This plot depicts the total harmonic distortion in the current (ratio of harmonic components over the current at the fundamental frequency (e.g. 50 Hz) - THDi) for seven days. Not unsurprisingly, THDi as a ratio takes very high values at times, even reaching 45%, when the solar power output is low and the harmonic currents are comparable to the reduced fundamental current.

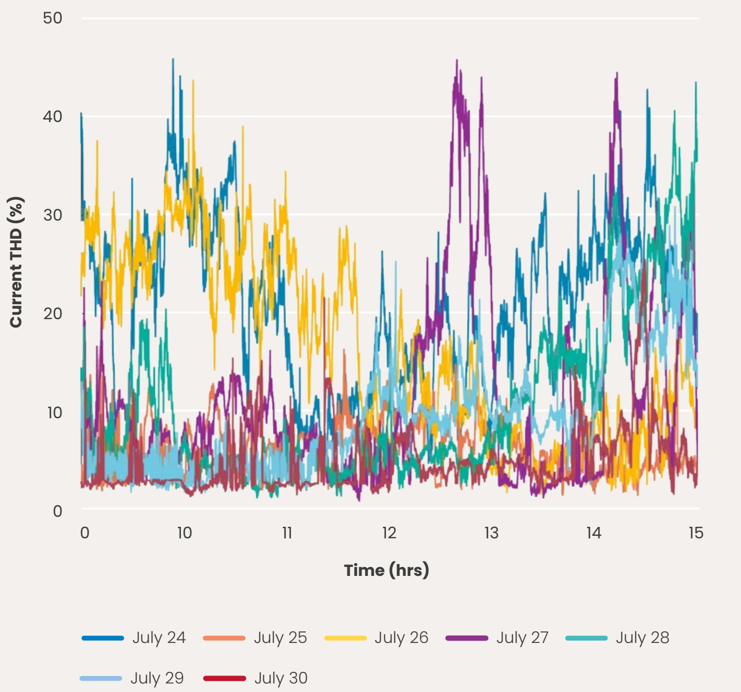


Figure 18. Total harmonic distortion (percentage) in the current for a UK household at seven days.

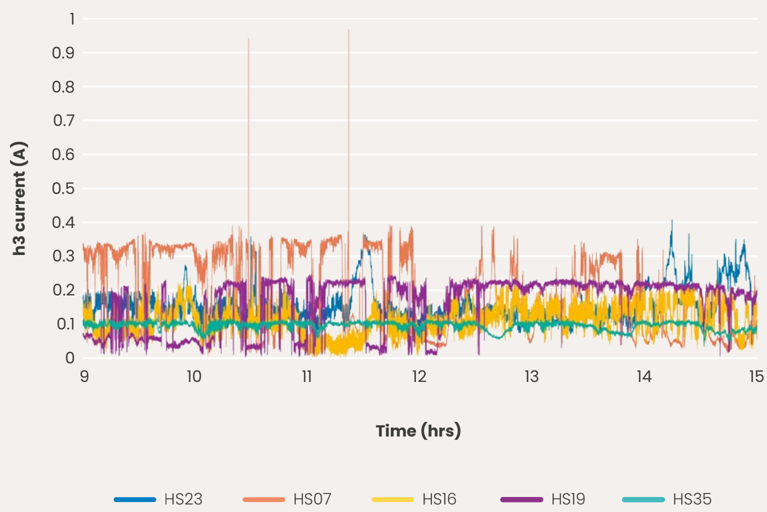


Figure 19. Magnitude of the third harmonic current (absolute value) for five different inverters

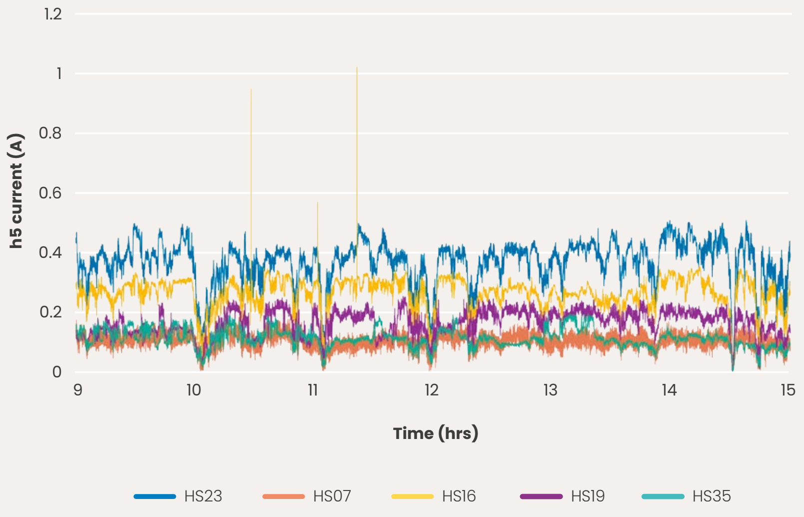


Figure 20. Magnitude of the fifth harmonic current (absolute value) for five different inverters.

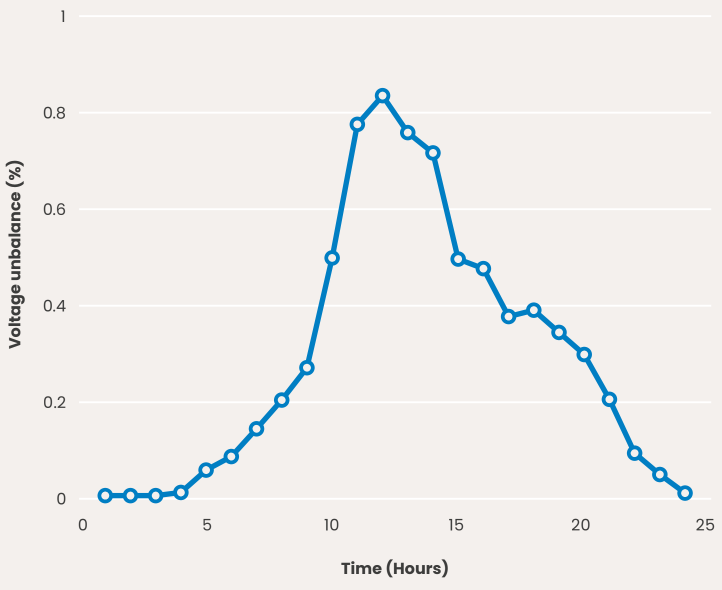


Figure 21. Assessing voltage unbalance due to PV uptake

For more detail, Figure 19 and Figure 20 show the third and fifth harmonic components in absolute values (Amperes) of five PV inverters for one day (July the 30th), which are fully acceptable. Interestingly, there is widely different emissions level among the five certified inverters, some units injecting more than double the harmonic current than others. This demonstrates how the inverter and the connection point affect the harmonic emission. Although the absolute current values are low for each individual household, interaction of neighbouring units with the same harmonic behaviour may lead to aggregation of the harmonic currents and undesirable effects to the utility assets, especially at low-voltage transformers and cables.

While the harmonic emission by PV systems at household level is sufficiently low in the UK, it is difficult to draw parallels with the Indian networks due to the cheaper power electronic converters used in developing nations including India. Moreover, given the existing power quality issues in Indian distribution networks – particularly phase voltage unbalance and existing harmonic levels, it is expected to face more such challenges with the rapid uptake of rooftop solar in the Indian low-voltage networks.

A.6.2. Voltage unbalance

The statutory voltage unbalance limit stipulated by International Electrotechnical Commission (IEC) is 2% (Karthikeyan *et al.*, 2009). Figure 21 depicts simulation result of the voltage unbalance at the point of connection of a single-phase PV system integrated into the UK distribution network. The computational tool developed by the authors and published with the IEEE (Nduka, Yu, *et al.*, 2020) has been used for the simulation. As expected, the level of unbalance varies over the day, peaking at midday when the solar generation is maximum, but not exceeding the 2% limit. On the contrary, measurements conducted in India indicate that voltage unbalance is already an issue in the regional networks (Karthikeyan *et al.*, 2009; Rajesh *et al.*, 2016), which highlights the need for careful integration of single-phase rooftop PV systems that could further worsen this condition.

A.7. GRID CODES AND ANCILLARY SERVICES

The main purpose of grid code regulations is to discipline the grid, and thus ensure secure and stable operation of the power system under the increasing levels of RES integration. Grid code regulations – or simply grid codes – can be broadly classified as shown in Figure 22. The planning code primarily covers planning aspects, such as demand forecasting, system reserves, transmission line planning, generation planning, grid connection requirements, related licensing etc. On the other hand, the operation code refers to the actual operation of the power system, such as the generators' response to

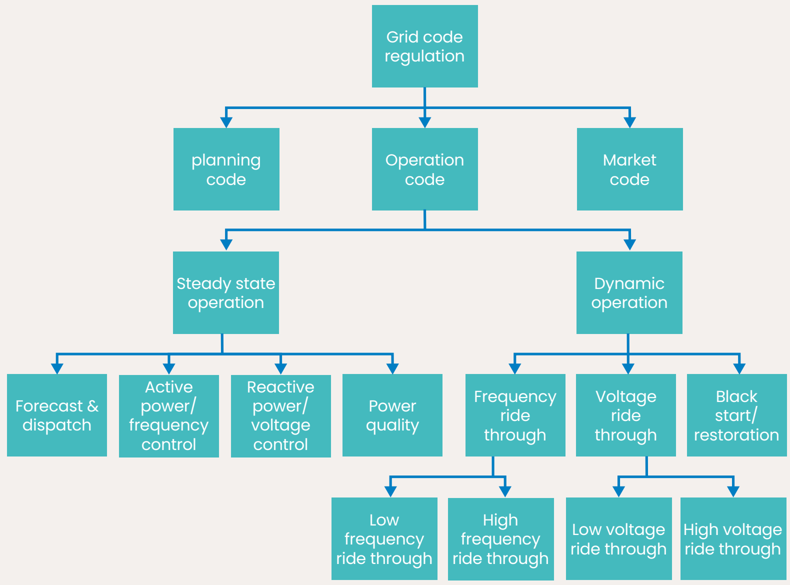


Figure 22. Broad classification of grid code regulations

the operator commands, response to grid disturbances and power quality standards. This code can be further split into the steady state and dynamic operation codes, the former focusing on the power plants behaviour during steady state operation and the latter covering the response of the power system components to grid dynamics. Market regulation guides the market for trading electricity between generators and consumers.

One of the most critical requirements when it comes to solar PV systems and other DGs is the fault ride through (FRT) function, and especially the Low Voltage Ride Through (LVRT) requirement. The LVRT function not only requires that the power plant stays connected to the grid during a dip in the grid voltage, but it also supports the grid at that time by supplying reactive and active power. This requirement greatly varies among countries as shown in Figure 23, with some countries demanding even zero-voltage ride through. The shape of these curves depends on a series of factors, such as the grid strength (SCL) and power system size, the generation mix and RES penetration level, the dynamics of the system load, the reactive power capacity of the system and any HVDC links.

A.7.1. The evolution of grid codes

The need for comprehensive grid codes emerged with the massive uptake of renewables in the past few decades, as they introduced a series of technical challenges to the power system due to their intermittent and non-synchronous nature. At first, solar and other renewables were treated on a "must-take" basis and were permitted to operate in an "ON/OFF" fashion, i.e. to disconnect freely during disturbances at the network. Under low renewable

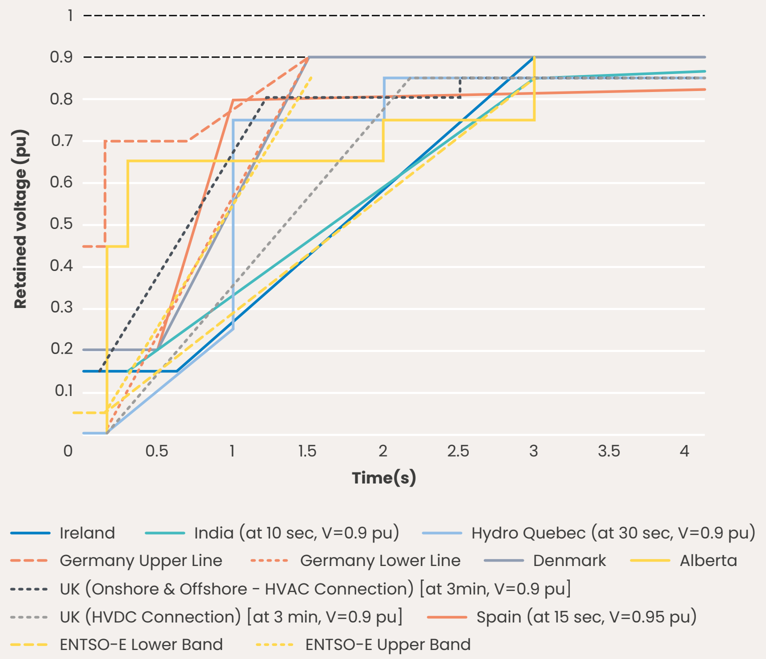


Figure 23. LVRT curves in different countries

integration levels, this simple regime is effective and beneficial for both the power system and the RES plants. However, as the proportion of such power plants in the generation mix increases, there is a need for these sources to behave in a more structured manner and share the burden of keeping the power system up and running. Permitting a simple "ON/OFF" operation for RES has led in the past to massive tripping under severe grid disturbances, which in turn can have cascaded implications in the power system even resulting in a black out.

Historically, the first countries to note these challenges and introduce grid code regulations for RES were Denmark and Germany in the 1990s. Since then, almost every country in the world with renewables has its own grid codes, which are regularly updated and become more and more stringent. The Indian electricity grid code (IEGC) was first issued by the Central Electricity Regulatory Commission (CERC) back in 2010; while at first it was largely based on relevant regulations from other countries, it has been gradually adapted and aligned to the specific characteristics and challenges of the Indian power system. Since 2010, the Indian code has been amended six times (2012; 2014; 2015; 2016; 2017; 2019). Currently, it is undergoing another round of review with a particular focus on the smooth implementation of the ambitious RES targets in the coming years. This review is being undertaken by an expert committee formed in May 2019, whose recommendations were recently published by CERC in January 2020 after a series of consultations with stakeholders in July and August 2019. Major changes in the draft IEGC 2020 report are the introduction of three new codes: i) Protection, Testing and Commissioning Code, ii) Cyber Security, and iii) Monitoring and Compliance Oversight code. Additionally, the planning code was reformed significantly, and the allowable frequency range was reduced from 49.9-50.05 Hz to 49.95-50.05 Hz. Other modifications include mandatory field testing of machines every five years to keep the models used by the system operator up to date, and classification of hydro plants (in case of excess water leading to spillage) in the category of must-run power plants like wind and solar.

The UK has relatively more stringent and advanced grid code regulations, mainly due to its nonsynchronous cross border interconnection and the relatively smaller synchronous control area. For example, RES plants in the UK are required to remain online for voltage greater than 0.15 p.u. for up to 140 ms duration.

It is worth highlighting that the successful grid code strikes a balance among the interests of all stakeholders. While more stringent regulations aim at secure and reliable operation for the power system, at the same time they disincentivise further deployment of renewables by making them less attractive investments, thus defeating their very purpose. Valuable tools towards this goal are the effective integration of the electricity market into the grid operation, as well as new ancillary service products such as fast frequency response, ramping products, dynamic reactive power support and other services.

Furthermore, the high level of differentiation of the grid codes among countries requires costly redesign and customization of products in the solar power industry. Harmonizing these regulations is expected to strengthen the solar PV/Wind power industry and foster further deployment of renewables.

	PRIMARY	SECONDARY	TERTIARY SLOW	TERTIARY FAST
Reserves amount	4000 MW	3623 MW	5218 MW	Pilot level
Response time	Few sec to 5 min	30 sec to 15 min	15 min to 60 min	5 min to 30 min
Manual / Automatic	Automatic	Automatic	Manual	Manual
Paid / Mandated	Mandated	Paid	Paid	Paid

Table 3. Earmarked power reserves by CERC for frequency response services (CERC, 2018)

A.7.2. The ancillary services in India

India has recently experienced a rapid increase in integration of renewables, mainly solar PV, which led to an update of the ancillary services regulations in 2015 by CERC. At the moment, the frequency support services in India are classified into (i) primary, (ii) secondary, (iii) fast tertiary, and (iv) slow tertiary services. The required power reserves for each service are given in Table 3 (CERC, 2018).

Primary frequency response is provided by all central power plants, called Inter-State Generating Stations (ISGS) in India. The secondary frequency control – or Automatic Generation Control (AGC) – is applied independently to the five regional grids of India and it has not been implemented to the entire Indian system as a whole yet. The 3623 MW secondary reserves include 1000 MW in the Southern region, 800 MW in the Western region, 800 MW in the Northern region, 660 MW in Eastern region, and 363 MW in North-Eastern region. Tertiary slow reserves – or Reserves Regulation Ancillary Services (RRAS) – are required by all generators that are regional entities and their tariff for full capacity is determined by CERC; they get compensated by the system operator. All the participating generators must share information on their technical minimum and ramp rates (up and down) along with unit-wise installed capacity, start-up time (hot and cold), and eventual module constraints. Finally, tertiary fast services have been tested only at a pilot level.

While the existing ancillary services framework has been beneficial to the Indian system, it also faces certain design and operational challenges. One such issue is the availability of the tertiary reserves (RRAS) for deployment during hours of high demand. While all eligible generators' unscheduled capacity is considered available, only the running machines can really deploy them in short notice in contrast to machines that are offline. The non-dispatched margin can be also very small at high demand and unnecessarily large at low demand hours. Furthermore, the ancillary services procurement mechanism is not yet technology-neutral in India, as opposed to most developed electricity markets, this being a barrier towards fair competition and unlocking their true potential. CERC has recognised these limitations and is currently working to this end.

A.7.3. Limited services potential by PV systems

It is now generally accepted that high levels of renewables into the power system implies more advanced ancillary services. However, the solar PV system as a generator has very limited capacity for the provision of such services and has to overcome lots of technical hurdles to impact the grid to a similar extent as the synchronous generators. Some of the most prominent such limitations are briefly outlined below, using the European ENTSO-E 2013 (ENTSO-E, 2013) classification of ancillary services into (a) voltage regulation, (b) frequency regulation, and (c) robustness/restoration services:

(A) VOLTAGE REGULATION SERVICES

- Provision of reactive power based on commands issued by the grid operator may be very slow due to inadequate communication infrastructure (IEEE/NERC, 2018).
- The dynamic voltage support during faults is restricted by the inverters' low overcurrent capacity, which may lead to low SCL and weak grid, as well as relays failing in detecting and isolating the fault (IEEE/NERC, 2018).

(B) FREQUENCY REGULATION SERVICES

- Frequency response by non-standard sources, including solar, was found to suffer from high latency in communication in the UK (National Grid UK's EFCC project) (National Grid UK, 2019d).
- Provision of under-frequency and inertial response implies up-regulation of the output power, which is not possible in solar systems if they already harness the maximum available power; the solar plant has to be either coupled with energy storage (e.g. batteries) or curtail some power to keep reserves (power headroom). This service is still optional in the latest standard IEEE 1547-2018 (IEEE, 2018).

(C) ROBUSTNESS/RESTORATION SERVICES

- Although the fault-ride-through (FRT) requirements are regularly revised, about 500 MW of embedded generation, including solar, tripped in the recent power cut of August 2019 in the UK due to vector shift or high RoCoF (National Grid UK, 2019c). This was unnecessary to some extent, especially for IBRs like solar, which is why National Grid UK is currently changing the protection settings of installed DERs to avoid unnecessary tripping in the future.
- Solar PV parks conventionally cannot establish voltage and frequency in the system (grid-following sources), thus not being able to support islanded networks and must trip. Islanded operation capability (grid-forming) would increase the resilience of the system.
- Black start function (i.e. the capacity to restore the network in the event of a blackout) is not required by solar PV systems and other DERs, thus having to maintain lots of conventional generation in case of a blackout (IEEE/NERC, 2018). A National Grid UK's project concluded that black start from wind and solar is technically possible, but it will be weather-dependent and should come from an aggregation of various sources (National Grid UK, 2019a).

A.8. ENERGY STORAGE AS ENABLER FOR HIGH SOLAR LEVELS

Many of the technical challenges brought by solar can be mitigated or completely addressed by leveraging the transformative technology of energy storage. When coupled with a PV system either physically or virtually, energy storage can effectively convert the variable solar energy source to a fully dispatchable power station (Nikolaidis *et al.*, 2016). Based on the form of energy stored in the system, energy storage can be categorised into (Luo *et al.*, 2015): mechanical (pumped hydroelectric storage (PHS), compressed air energy storage (CAES), and flywheels), electrochemical (conventional rechargeable batteries and flow batteries, hydrogen storage with fuel cells), electrical (capacitors, supercapacitors, and superconducting magnetic energy storage), thermochemical (solar fuels), and thermal energy storage. Figure 24 provides a graphical illustration of each technology capabilities in terms of power rating, energy capacity and discharge rate.

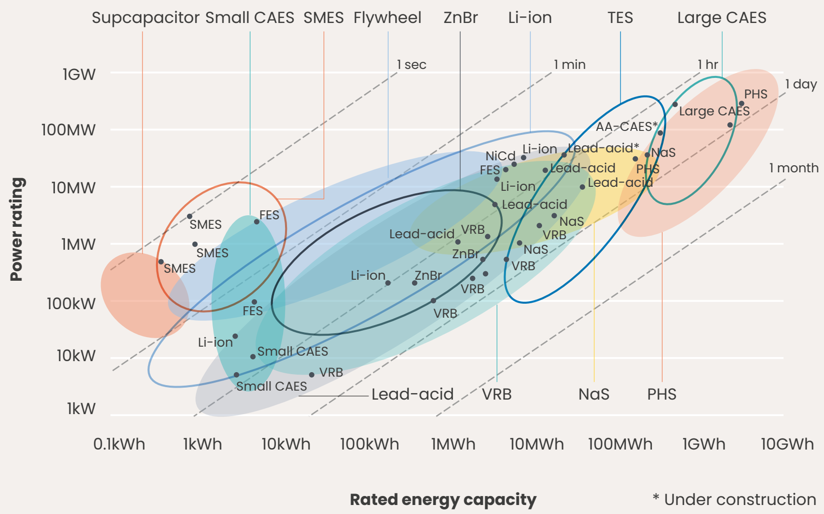


Figure 24. A list of energy storage technologies compared in terms of power rating, energy capacity and discharge time at nominal power (Luo *et al.*, 2015)

When coupling these technologies with solar, figures of merit often considered include: the capital cost, lifetime and round trip efficiency, with Table 4 providing typical values for some of the most commercialized technologies (the capital cost of fuel cells technology is only indicative, as energy and power are fully decoupled). The pumped hydro and compressed air technologies are quite lucrative options in terms of both capital cost and cost per cycle, but they are mostly applicable to large-scale applications and come with a series of geographical constraints. Pumped hydro has the longest history and largest energy capacity among all technologies, constituting about 180 GW or 95% of the global energy storage in Feb 2020 according to US DOE Global Energy Storage Database (US DOE, 2020). The compressed air technology has also shown great potential, with two large plants, the Huntorf plant (290MW, build in 1978) and the McIntosh plant (110MW, built in 1991), delivering consistent good performance with 91.2–99.5% starting and running reliability for several decades (He and Wang, 2018). However, when it comes to solar PV systems, electrochemical energy storage technologies have been almost exclusively used instead, mainly due to their scalability, efficiency, and appropriateness for small-scale applications.

A.8.1. Electrochemical energy storage technologies

Within the family of electrochemical energy storage methods, four key technologies have been applied to stationary grid applications: lead acid batteries, lithium-ion batteries, redox flow batteries and electrolyser/fuel cells. The most mature of these technologies is the lead acid battery, which is commonly used for ancillary services in automotive applications. This early adoption for engine start-up systems drove the economies of scales and cost reduction that rendered this technology a leader in stationary applications. However, whilst the capital cost of the system is low, the low round-trip efficiency and poor lifetime have been motivating the industry to find alternative solutions.

More recently, there have been increasing numbers of solar integration projects utilising lithium-ion batteries. This has mostly been driven by their rapidly decreasing cost and improving lifetime due to their widespread use in consumer electronics and electric vehicles. Within the sub-category of lithium-ion batteries, there is also a variety of different types characterised by the materials used in their construction. The most critical components of a battery are the anode and cathode materials. In the vast majority of cases the anode is made of graphite, whereas the cathode can differ greatly in terms of composition. For grid-scale storage, the most commonly considered types are the lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC) and lithium nickel aluminium cobalt oxide (NCA) (Hesse *et al.*, 2017). Other chemistries which have been used for consumer electronics and early electric vehicles, such as the lithium cobalt oxide (LCO) and lithium manganese oxide (LMO), have not received much commercial attention in grid-scale storage due to high costs and limited lifetime, respectively (Schledde *et*

TECHNOLOGY	PUMPED HYDRO	COMPRESSED AIR	LEAD ACID BATTERY	LITHIUM-ION BATTERY	ELECTROLYSER/ FUEL CELL	REDOX FLOW BATTERY
Capital cost ($/kWh)	10-100s	10-100s	10-100s	100s	1000s	100s
Cost (c/kWh/ cycle)	<1-10	<1-10	10s-100s	10s-100s	100s-1000s	10s
Round trip efficiency (%)	70-85	50-75	65-85	80-90	<40	65-85

Table 4. Comparison of different energy storage technologies for the grid. Adapted from Few *et al.* (Few *et al.*, 2016)

al., 2018). LFP in particular is seen as an attractive option for grid applications due to the low cost of the materials, long lifetime due to the very limited volume change during operation, and improved safety of the chemistry. However, LFP exhibits a strong voltage hysteresis during cycling which makes state-of-charge (SOC) estimation quite challenging for control applications (Xing *et al.*, 2014; Crawford *et al.*, 2018). Furthermore, the anode-side graphite is often found to be the electrode with the most severe degradation, which has motivated the use of alternative anode materials such as lithium titanate (LTO) that is much more stable albeit at additional cost (Zhao *et al.*, 2015; Reniers, Mulder and Howey, 2019).

Despite the prevalence of lithium-ion battery technology, various studies have shown that as the scale and storage capacity of the storage system increases, the cost of a lithium-ion battery-based system becomes less attractive due to intrinsic material costs. Thus, efforts are being made to develop alternative technologies such as redox flow batteries and electrolyser/fuel cell systems, which are potentially more favourable for longer duration storage.

Redox flow batteries are seen as a potential solution for storage systems requiring about 4-10 hours' worth of storage due to their ability to decouple power and energy. In a lithium-ion battery, the power and energy are often coupled, which implies overrating power in long-duration applications. In contrast, a redox flow battery commonly stores energy through changing the oxidation state of liquid electrolyte stored in external tanks. These electrolytes are then pumped through a flow battery stack where they can be charged or discharged. Therefore, if more energy is required, the tanks can be made larger, whereas if more power is required then a larger battery stack can be used. There are a number of different flow battery chemistries emerging, however the two technologies that have attracted commercial uptake are the all vanadium flow and zinc-bromine flow batteries (Skyllas-Kazacos *et al.*, 2011). Several kWh-scale zinc-bromine systems have been demonstrated, but a reconditioning cycle is often required every few days when the battery is fully discharged to prevent formation of zinc dendrites and failure of the battery (Weber *et al.*, 2011; Wang *et al.*, 2013). This reconditioning cycle is thus a real challenge for applications in solar PV systems, which is why the all-vanadium alternative has received more focus with several systems already deployed at the scales of multi-kWh and multi-MWh (Alotto, Guarnieri and Moro, 2014; Cunha *et al.*, 2015). In theory, these flow battery systems can have a lower cost and longer lifetime than lithium-ion batteries, however they have not received as much research and development as the latter. Furthermore, these benefits are only achieved once a certain system size is achieved, which means that system cost remains a major challenge.
Despite the advantages of the lead acid, lithium-ion and redox flow batteries, these technologies are not appropriate for inter-day storage and beyond. For longer storage capacity, an electrolyser/fuel cell system is a better alternative. An electrolyser can convert excess electricity into chemical fuels, such as hydrogen, which are then converted back to electricity at a

later time by passing through a fuel cell; however, the conversion efficiency of these systems results in a roundtrip efficiency of less than 40%. Alternatively, the hydrogen can be used in a power-to-gas system, where the chemical fuel is injected into a natural gas system for combustion. For electrolysis, three main technologies are used: the alkaline, proton exchange membrane and solid oxide electrolysis cell. Here, the main barrier is the capital cost which is forecasted to vary within 700-1400 €/kW, 800-2200 €/kW and 2500-8000 €/kW respectively for the three types (Schmidt, Gambhir, *et al.*, 2017). These numbers are predicted to fall in 2030 to 700-1000 €/kW, 700-1980 €/kW and 750-6800 €/kW, although with economies of scale they can be reduced even further. Fuel cells have similar cost challenges to electrolysers, which combined with the hydrogen storage costs currently limit wider industrial uptake of this energy storage technology.

While the cost of these technologies do vary significantly, Schmidt *et al.* used experience curves to show that regardless of technology, costs are on a trajectory towards 340 $/kWh for an installed system and 175 $/kWh at the (battery) pack level, once 1 TWh of installed capacity is reached (Schmidt, Hawkes, *et al.*, 2017). However, the capital cost should be considered along with the device lifetime, with Schmidt *et al.* later evaluating the levelized cost of electricity (LCOE) for various storage technologies (Schmidt *et al.*, 2019). They show therein that lithium-ion batteries are most likely to be the most cost-effective solution for nearly all stationary applications by 2030. However, beyond that time frame and as technology innovations carry on, this may well change, and different storage technologies may find niches within various application areas. Table 5 shows six different commonly considered grid applications and the characteristics of the required energy storage system.

	FREQUENCY REGULATION	DEMAND CHARGES	DEMAND RESPONSE
Power/energy ratio	4:1 to 2:1	1:1 to 1:3	1:2 to 1:4
System size	100 kW to 40 MW	20 kW to 1 MW	100 kW to 10 MW
Response time	<20 ms	1 to 5s	<10 mins
Grid domain*	T, D, BtM	C&I, BtM	C&I, BtM
	DOMESTIC SOLAR INTEGRATION	**TIME-OF-USE SHIFTING**	**ENERGY ARBITRAGE**
Power/energy ratio	1:1 to 1:3	1:2 to 1:4	1:3 to 1:10
System size	5 kWh to 30 kWh	5 kWh to 1 MWh	1 MW to 100 MW
Response time	<1 min	<5 mins	<5 mins
Grid domain*	BtM	C&I	D, T

**T: Transmission, D: Distribution, BtM: Behind the meter, C&I: Commercial and industrial*

Table 5. Comparison for figures of merit for different stationary energy storage applications. Adapted from (Lux research Frankel, Laslau and Torbey, 2016)

A.8.2. Technical barriers to integration of batteries

With lithium-ion batteries forecasted to be the most likely technology to enable solar integration, there are still a number of issues to be resolved, of which lifetime is one of the largest. This is mostly due to the highly usage-dependent and non-linear degradation of lithium-ion batteries, as illustrated in Figure 25.

Operating regimes that accelerate degradation include high temperatures; low temperatures with high charging currents; and high SOC, which implies that the charge/discharge control of the battery system is a critical factor for the longevity of the battery. Model-based control is seen as a promising way forward. For instance, Patsios *et al.* developed an integrated framework for the analysis and control of grid-connected energy storage systems, whereby a physics-based model of a lithium-ion battery was combined with models of the power electronics and a grid (Patsios *et al.*, 2016). At high SOCs, the available energy is maximised and the resistance of the battery is minimised, which increases the round-trip efficiency. However, prolonged operation at high SOCs leads to accelerated degradation through the formation of a solid-electrolyte interphase layer on the anode that leads to power and capacity fade, an effect intensified at higher temperatures. Conversely, if the batteries are charged at low temperatures, this can lead to formation of lithium dendrites which can also accelerate degradation or cause catastrophic failure. The complexity of these constraints on battery operation thus highlights the need to consider the battery control strategy alongside the objectives of the PV system (e.g. extraction of the maximum power) (Reniers, Mulder and Howey, 2019).

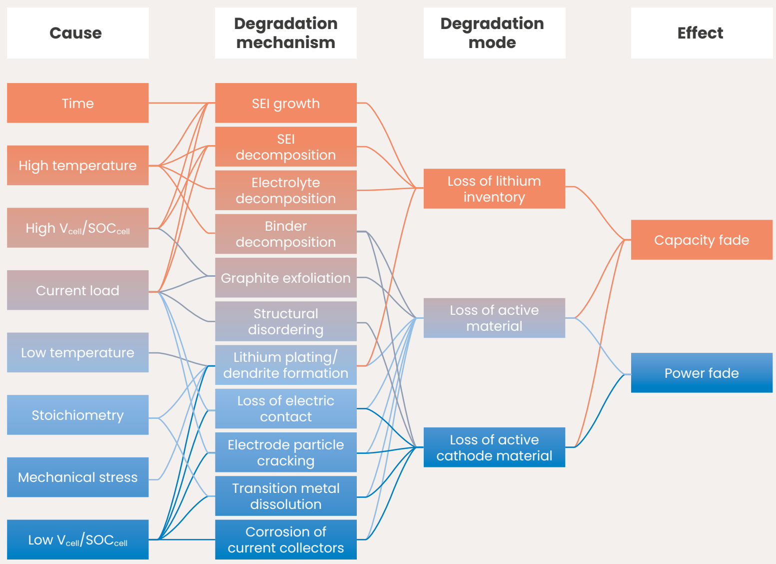


Figure 25. Cause and effect of degradation mechanisms and associate degradation modes in lithium-ion batteries (Birkl *et al.*, 2017)

Another challenge in integrating batteries to solar systems is the alignment of component lifetimes. The widely adopted polycrystalline and monocrystalline PV panels exhibit lifetimes in excess of decades, whereas lithium-ion batteries struggle to achieve such durations in a cost-effective manner. Given the importance of levelized cost of electricity, maximising the lifetime of these MWh-scale batteries often requires thermal management. The correlation between lifetime and operating temperature typically follows an exponential decay relationship, which makes temperature control even more critical in hot environments. Typical thermal management systems can range from active air cooling to liquid cooling, but in both cases, these incur additional cost and parasitic load that reduces the round-trip efficiency.

In addition, from the power electronics perspective, the voltage of a lithium-ion battery varies as a function of its SOC. The magnitude of this variation depends on the specific chemistry but is commonly between 4.2–2.7 V for an NMC/graphite cell. When translated into a large-scale system, assuming for example 200 cells in series, this results in an 840–540 V fluctuation, which poses an input voltage challenge for the power electronics.

Relevant to the previous challenge is the cell balancing in a large battery stack. A lithium-ion battery system of kWh and MWh scale consists of several thousands of cells connected in series and in parallel; slight differences among the individual cells during manufacturing may result in uneven charging/discharging and deterioration of the cells, which directly impacts the entire battery pack that is as strong as its weakest cell. To address this, battery packs often include a battery management system that monitors the voltage of the individual cells and seeks to balance them out. Two main cell balancing regimes exist: the passive and active method; passive balancing involves resistors that slowly discharge overcharged cells in a passive manner, which is a simple and the most widely adopted method to this day; active balancing transfers charge from one cell to another in a selective and optimal fashion through power electronics, resulting in higher roundtrip efficiency albeit at additional cost and complexity.

A.9. OTHER BARRIERS TO PV TECHNOLOGY

A.9.1. High Temperatures

The performance of solar PV panels is certified under standard test conditions (STC), but those conditions are never encountered in the real world. Standard test conditions include a temperature of 25 °C, an irradiance of 1000 W/m^2 and a light spectrum equivalent to 1.5 air mass (Muñoz-García *et al.*, 2012; Ndiaye *et al.*, 2014). While the power output of the PV panel increases with high irradiance, it decreases at high temperatures. A typical temperature coefficient of power output is 0.41% drop for each °C, such that the real PV module efficiency can drop from 15% at 25°C to 12.85% at 60°C for the same irradiance value (Skoplaki and Palyvos, 2009).

In practice, high levels of irradiance usually accompany high ambient temperatures. In addition, the solar irradiance causes surface heating in the solar panels such that module temperatures can be as much as 25 °C higher than the ambient temperature (Faiman, 2008; Muzathik, 2014). They can easily reach and exceed 60 °C on the hottest days in India. Another temperature-driven effect of more permanent nature is degradation due to high temperatures and humidity. Module degradation rates can be widely variable, with observed rates from 0.22% to almost 3% per year (Ndiaye *et al.*, 2014). Therefore, for India, it is important to use PV modules with good resistance to tropical climate and to monitor their performance over time with regular replacement of deteriorated and damaged modules.

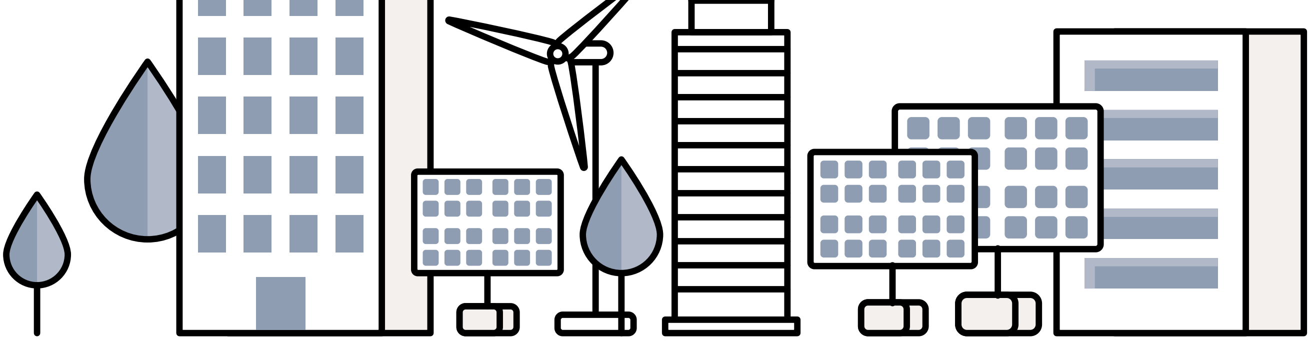
A.9.2. Dust and soiling

Dust accumulation heavily depends on rainfall and atmospheric levels of dust. In the UK context, it is rare for PV power output to be significantly reduced by dust, but in hot dry climates, power output can be reduced by as much at 34% (H. Qasem, 2013). In Kuwait, the optimum PV cleaning frequency was calculated as about once every 8 days. Similar weather conditions occur in some parts of India during the summer. Most PV cleaning schemes use water to wash modules, and while the relevant energy cost is not significant compared to the energy output of the PV, the logistical difficulty of obtaining water and the labour costs are important barriers to cleaning PV (H. Qasem, 2013). Automatic PV cleaning systems are being developed and commercialised to make cleaning easier (Mondal and Bansal, 2015; Jaradat *et al.*, 2016), while hydrophobic coatings in the PV modules may be a good option in the future to reduce dust accumulation (Quan and Zhang, 2017; Womack *et al.*, 2019).

A.9.3. Opportunity costs of land use

A solar installation occupies space, and in so doing, it precludes other land uses to a great extent; if solar is the only use of an area of land, then the value of energy must be higher than the value of alternative uses for that land. Loss of agricultural land is sometimes cited as a reason for opposition to solar PV (Stronberg, 2019). Only low-value land, such as poor grazing land, brown-field sites and desert land, is unquestionably suitable for such exclusive use by PV farms. When such sites are separated from centres of population by long distances, they incur high network expansion and electricity transmission costs. It is worth noting, however, that there are great examples of low-value land close to centres of population, such as brown-field land in cities, poor moorland close to Sheffield and Manchester in the UK (Natural England, 2010) and a non-rice growing area close to Jaipur in India (Xiao *et al.*, 2006). While installing rooftop solar in towns and cities is now well established (Wiginton, Nguyen and Pearce, 2010), it can only provide a small portion of the local energy use on its own, especially in densely populated cities (Peng and Lu, 2013).

It is generally preferred to combine an open-field solar installation with other land uses. Agriculture is a good such option, also known as agrivoltaics. Grazing under PV arrays is very common, but systems of arable cropping under PV arrays have also been established (Dupraz *et al.*, 2011; Dinesh and Pearce, 2016; Lane *et al.*, 2017; Santra *et al.*, 2017; Aroca-Delgado *et al.*, 2018), mostly in experimental settings and greenhouses.



PART B: ROADMAP TO HIGH SOLAR INTEGRATION

Higher solar integration into the grid entails mitigating the challenges it brings in terms of balancing, stability, voltage and protection in the power system. There is no golden rule on how much solar can be accommodated to a network without interventions, and there are examples in several countries that have experienced very high solar and other RES penetration for short times. However, a future power system with solar generation levels that exceed other sources on a regular basis has to seriously consider the challenges of the previous section or risk the reliability and security of the grid.

This chapter discusses a wide range of actions and interventions in the power system that assist in overcoming the main barriers of solar integration, organized into four directions as shown in Figure 26. The major direction in this roadmap is the ongoing transformation and rethinking of the power system towards higher flexibility and more RES-receptiveness. These actions involve: more flexible generation with higher ramping rates; more frequent security-constrained economic dispatch (e.g. as often as every 5 minutes); redesigning the electricity market and updating grid codes to account for new and more relevant ancillary service products; more credible forecasting of solar generation; cooperation between the TSO and DSOs in managing the embedded solar; improved voltage control and redesigning the protection schemes in the distribution network.

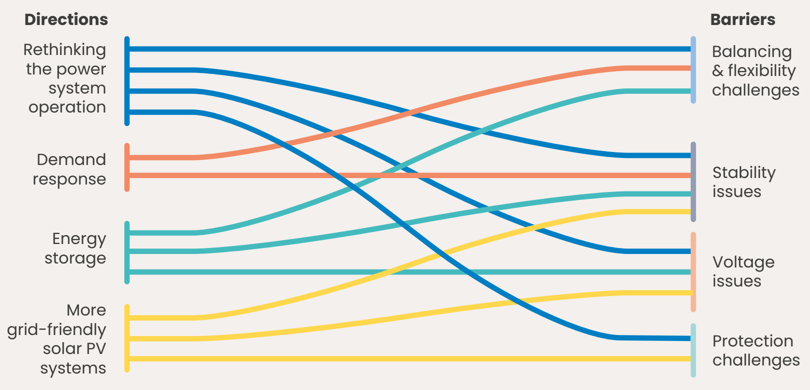


Figure 26. Roadmap to high solar integration, showing how each direction addresses individual barriers

There are also two key technologies in this regard that are worth mentioning separately: demand response and energy storage. Demand response has great potential in tackling flexibility and balancing challenges by better aligning supply and demand over the day, and also in mitigating stability issues that may arise with generation intermittency. Similarly, energy storage may substantially assist in balancing the system and in voltage regulation of the network; if collocated with the solar plant, these benefits are maximized by converting the plant to a dispatchable power station with additional ancillary services that makes a tangible contribution to the power system stability.

Furthermore, apart from what the power system can do to allow more solar, there is also what solar can do for itself by becoming more grid-friendly. This entails a wider range of services to the grid, especially fault ride through (FRT), and operating in grid-forming mode to assist in challenges related to stability, voltage and protection. To unlock this full potential, the future solar plants should be able to maintain some power in reserve, by collocating energy storage or curtailing power or both.

B.1. RETHINKING THE POWER SYSTEM OPERATION

A limited amount of solar can be readily integrated into the power system with minimal interventions. With increasing levels of solar penetration, however, come higher needs for flexibility and more advanced operation regimes. Most importantly, there is a need for more flexible generation with lower technical minimum limits and higher ramping rates to support the variable and intermittent solar generation. Promising options include gas-fired plants in place of coal, more hydro and interconnections where possible, and fully deploying the new technologies of demand response and energy storage. This more versatile electricity mix should be coupled with more frequent generation dispatch and more reliable solar forecasting to minimise the flexibility requirements. Relevant to solar forecasting, although further improvement in accuracy is expected with recent advances in machine learning, attention should be paid also to the balancing mechanism for the deviations between forecasts and actual generation.

In addition, it has become important that the TSO and DSOs start to effectively coordinate their actions to exploit ancillary services by embedded solar and support upward power flows to the transmission network. More effort should be put into the voltage control of distribution networks, leveraging new optimization techniques and fully exploring the reactive and active power capabilities of solar and other DERs. The protection regime of the distribution network may also require a restructuring, deploying new types of relays and telecom infrastructure, much like in microgrids. Furthermore, to avoid deterioration of the power quality in low and medium voltage networks, harmonic emissions of PV inverters should be regulated even at low generation. Finally, the grid codes and regulations need to be constantly updated to account for changes in the system and technology advances, always maintaining a balance between grid security and incentives for solar deployment.

B.1.1. More flexibility and improved generation dispatch

Increasing the flexibility of the power system is one of the major requirements to allow for more variable and intermittent generation like solar into the grid. An essential step towards this goal is tapping the flexibility potential of existing energy sources by lowering their technical limits and boosting their ramping rates. This is a challenge for most thermal stations that have been traditionally designed as less-flexible base-load units, although there are relevant successful examples in the global scene, such as technical minimum of 10% in Kauai, Hawaii. In India, the technical minimum requirement for central power plants is currently 55%, but it is expected to be reduced in view of the ambitious RES targets by 2022; the net load ramp-up rate is also forecasted to reach 32 GW/hour. Converting coal-based units to meet these new flexibility needs will probably incur prohibitive costs, although there a few pilot projects ongoing that explore faster ramp rates and lower technical minimums from coal plants (GTG-RISE, 2020). Going for gas-fired plants instead seems a better alternative for thermal power stations, as they enjoy very low technical limits, short start-up and shutdown times, and high ramping rates; this is one of the reasons that the UK's strategic plan involves mainly gas and no coal at all as thermal energy sources into the electricity mix from 2025 and onwards (National Grid UK, 2018a).

Hydro power plants are also a very good source of flexibility and already play a dominant role in the Indian energy mix, although the relevant geographical constraints do not render hydro a universal solution for every power system. In the UK, interconnections with neighbouring countries will continue to be a very important source of flexibility, supporting ramp rates of more than 50 MW/s and being able to alleviate many ROCOF and downward regulation constraints (National Grid UK, 2016). It is also expected to increase the available flexibility by extending these services to smaller generators and DERs via aggregators. Furthermore, apart from the aforementioned conventional options, the new technologies of demand response and energy storage are very promising sources of flexibility, discussed in more detail in the following sections.

Another tool towards decarbonization of the energy sector that has attracted a lot of interest lately is sector coupling across several energy vectors, such as electricity, heating, cooling, transportation and gas. Historically, there has only been limited coupling of electricity and heat in combined heat and power (CHP) plants in some countries, but a universal cross-sector multi-energy coordination is yet to be implemented on a national basis. This approach usually involves substantial electrification of the energy sector and allows for self-reliance on a local level, forming energy islands. For example, massive electrification of the transportation would bring an additional source of flexibility to the system, in terms of balancing, reserves and frequency services, as well as reducing the carbon emissions of the transportation sector. Multi-energy sector coupling is seen today as one of the most promising ways forward to increase flexibility and renewables penetration in the power system.

In terms of system balancing, there is also a need for more frequent and effective generation scheduling. Unit commitment and economic dispatch that used to be performed with an hourly or half-hourly time step in most countries, should be carried out more often, every few minutes, to account for changes in both supply and demand. For example, ERCOT moved from a 15-min zonal market to 5-min nodal market in 2010, which led to higher integration of renewables in the ERCOT system (Adib, Zarnikau and Baldick, 2013). An essential component of more effective dispatch is accurate short-term forecasting of the solar generation, as discussed in a separate section below. Such enhanced power scheduling should be followed by a flexibility market framework that will incentivise sources of flexibility to support the solar generation at times of high penetration.

Last but not least, to actively include the solar PV systems in the power dispatch, the visibility and telecommunication access to these systems have to be upgraded. An improved monitoring and communication framework would be beneficial to allow the operator to have minute-resolution visibility of the power output and to communicate power commands to both large and small PV plants in real-time (e.g. reactive power commands for voltage regulation). Regardless of this control regime being centralised or decentralised, having some kind of bidirectional communication between the PV plants and the operator is seen as a credible way to facilitate coordination of the various components within the network.

B.1.2. Better solar forecasting

The impact of the solar generation uncertainty on the power system can be mitigated to some extent by a good forecast; knowing with confidence what the solar profile will be in the next few minutes to hours permits effective generation scheduling and balancing in the system, successful voltage control in the distribution network, and keeping the right amount of reserves and flexibility online towards secure but also economical system operation (Brancucci Martinez-Anido *et al.*, 2016). An accurate and reliable solar forecasting tool essentially removes the uncertainty and stochasticity features from the solar generation, converting it into a semi-deterministic, albeit variable, energy source with higher capacity credit.

Two major families of solar forecasting methods exist today: the physical methods and the statistical methods (Sobri, Koohi-Kamali and Rahim, 2018). The physical methods employ meteorological measurements and models to infer the expected operating conditions of the PV system. They are further divided into Numerical Weather Prediction (NWP), Sky Imagery and Satellite-Imaging models. NWP usually adopts meteorological models and involves radiative transfer equations of the solar flux and atmospheric dynamics; it is a well-established approach that produces its best results for periods from 6 hours to two weeks and is almost exclusively used by the US and European weather services. The Sky Imagery method requires a ground-based digital camera that captures a hemispheric image of the sky to extract cloud presence, speed and direction by generating cloud motion vectors from consecutive images; this is quite useful for sub-hourly predictions. Satellite Imagery also captures cloud patterns, but from above, employing cloud motion vectors as well. This method is very good for forecasting horizons between 15 minutes and 6 hours.

The statistical or data-driven methods, on the other hand, depend on past data of meteorological parameters and solar generation and aim to extract the relation between the two. Regression and autoregressive and moving average functions (ARMA or ARIMA) models are such examples. Spatio-temporal kriging allows predictions to be made at one or more locations between and beyond observation times. Another group of time-series functions are the Artificial Intelligence (AI) methods which are learning approaches. Popular representatives are: (i) k Nearest Neighbour (kNN), a classification and voting technique; (ii) Support Vector Machine (SVM), another classification method; (iii) Artificial Neural Network (ANN), a computer network which mimics human learning; (iv) Genetic Algorithms (GA), which carry out selection based on fitness, i.e. forecasting accuracy; and (v) hybrids of the above methods. These statistical methods need several months of data collection prior to deployment. They deliver accurate results when used for sub-hourly forecasting but also for time horizons of a few hours or more. Each method has its strong points and weaknesses, so the latest research combines techniques from different families to achieve robust estimation at different horizons (Diagne *et al.*, 2013; Su, Batzelis and Pal, 2019).

An important aspect in solar forecasting is the spatial diversity of the solar resource and the inherent smoothing out of the local intermittency at the transmission system layer. Forecast errors from individual plants or small regions caused by local weather phenomena are somewhat filtered out in the transmission level, having little effect on tasks like balancing. On the other hand, voltage regulation is a local optimization in the distribution network and the regional solar intermittency needs to be accounted for. Therefore, the various control operations in the power system have different solar forecasting needs in terms of accuracy, forecasting horizon, temporal and spatial resolution. Deviations between forecasted and delivered solar generation lead to a balancing gap that is currently addressed in different ways worldwide. Some countries penalise the variable generator for deviations above a certain limit, which implies an additional financial burden for the investors. In other countries, the generator operator is required to fill the gap from the balancing market, which again introduces important financial constraints and risks at times of high irradiance uncertainty. Co-locating solar and energy storage (e.g. batteries) is seen as a solution that resolves short-term forecasting errors, albeit with additional installation and service costs. The take-home message here is that accurate solar forecasting has become vital for many stakeholders in the power system, from the solar plant owner to the DNO and TSO.

B.1.3. Transmission/Distribution systems coordination

The constantly increasing penetration of DERs in the distribution level, including solar, has rendered the cooperation between the two layers of the power system an emerging need. The traditional distribution networks have evolved into Active Distribution Networks (ADNs) that may utilise the embedded generation for more economic, reliable and secure operation of the entire power system beyond the distribution level. Locally installed DERs have the potential for a wide range of system-wide ancillary services (AS) that extend to the transmission layer, such as frequency and voltage support, congestion management and balancing, flexibility and black-start services.

To fully unlock this potential, however, an appropriate layer of real-time communication and coordination between the TSO and the DSOs has to be in place, in order to align requirements and resolve potential conflicts. Harmonizing the way these operators work is not a trivial task. A recently completed European project has concluded in five different potential cooperation schemes given in Table 6, exploring various market mechanisms and alternatives for the level of responsibility among the TSO and DSOs (SmartNet project, 2019). Given the current regulations in the UK and India, the centralized AS market seems to fit better to these needs, having the TSO undertaking and leading the role in this coordination.

TSO/DSO COORDINATION MODEL	MECHANISM
Centralized ancillary services (AS) market	The TSO manages the AS market for both distribution and transmission sources with minimal DSO involvement
Local AS market	The DSO first addresses the local constraints and then offers the remaining services to the TSO
Shared balancing responsibility	The TSO and DSO agree on a common schedule
Common TSO-DSO AS market	Both operators aim at reducing AS costs either via a common market operated jointly or by effective integration of TSO and DSO local markets
Integrated flexibility market	A common market for both regulated and deregulated players run by an independent market operator

Table 6. TSO/DSO coordination models proposed in the SmartNet project (SmartNet project, 2019).

In the UK 'Power Potential project', National Grid UK (TSO) and UKPN (DSO) explored the potential for reactive power/voltage support and active power support from the DSO through a model similar to the local AS market, aiming mainly at resolving voltage and thermal constraints at the transmission level (National Grid UK, 2020b). The distribution system is considered by the TSO as a virtual power plant with the capacity to provide dynamic reactive and active power support to the transmission level. For this purpose, a digital platform facilitates the power exchange between the two layers of the power system, exploring three scenarios of support services: (a) reactive power consumption by the distribution system during overvoltage at the transmission network (e.g. during light loading of the transmission lines), (b) reactive power injection during voltage dips at the transmission level (e.g. due to a fault), and (c) active power support for managing congestion at the transmission system.

Another reason for TSO/DSO coordination when focusing on solar generation and other variable renewables, is the spatial diversity of the resource that provides an inherent smoothing mechanism to an otherwise intermittent generation. From the TSO's perspective, treating all solar PV systems in the network as an aggregated less-intermittent power plant will lower the balancing and flexibility requirements. Although it is commonly accepted that the TSO/DSO cooperation is a key technology to high RES integration, there are still many operational and market challenges to be overcome to fully deploy this concept.

B.1.4. Improved voltage control in the distribution network

Maintaining the voltage within limits has become increasingly challenging in the distribution network due to the integration of solar and other variable generation. The intermittent and fast-changing generation makes it difficult for conventional regulation devices, such as on-load tap changers (OLTCs), step voltage regulators and switched shunt capacitors, to control the voltage throughout the network.

A new tool explored lately to this end is the PV inverters to provide voltage support services by injecting or consuming reactive power. This function can mitigate to some extent the voltage fluctuations induced by the PV system itself, but it is also an excellent local source of reactive power for loads in the vicinity, which reduces the reactive power flows from the substation and the relevant power losses. It is indicative that the IEEE 1547 standard initially expected a unity power factor from PV plants (IEEE, 2003), but it now requires participation of the solar systems to voltage regulation by reactive or active power injection (IEEE, 2018). The 'Power Potential project' in the UK also explored this concept in the south-east part of England (National Grid UK, 2020b). There are many ways that this voltage support is implemented in a PV system, most of them employing droop characteristics of voltage-reactive power, active power-reactive power, voltage-active power, or more simply constant power factor or constant reactive power value (IEEE, 2018). The challenge that arises is how to coordinate all the regulation equipment of the network (OLTCs etc.) along with the PV systems in an efficient and optimal manner. There are basically three big families of improved voltage control which are currently under investigation and development, detailed in Table 7.

METHOD	FUNDAMENTALS
Centralised Methods	These methods rely on extensive communication and employ a single central controller that coordinates all devices in the network. They employ mathematical models of the network and real-time measurements to form an optimization problem that is solved centrally (Ul Nazir, Pal and Jabr, 2019). Advanced versions of these techniques consider the dispatch of PV inverters along with conventional devices (Dall'Anese, Dhople and Giannakis, 2014) and the uncertainty of solar generation (Kekatos *et al.*, 2015).
Distributed Methods	These methods distribute the optimization effort over various controllers, each controller being responsible for a separate zone of the network (Dall'Anese *et al.*, 2014). Allowing proper coordination among these controllers facilitates the optimality of the final solution. In addition, these distributed solvers also resolve communication bottlenecks, permitting parallelization of the solver and limited information exchange, and increase the resiliency against cybersecurity threats.
Decentralized Methods	Under these methods, each device regulates the voltage autonomously following its own control rule. This rule may differ among the devices and is either fixed (hard-wired in the local controller) or transmitted and updated regularly by a central controller (Jabr, 2018).

Table 7. The different philosophies of voltage control in the distribution network

B.1.5. Rethink the protection of distribution networks

The protection challenges experienced recently in the distribution networks were found first in isolated microgrids. Bidirectional power flows, meshed grid and limited overcurrent capacity by the inverters are no strangers to a microgrid, which is why the relevant research and experience is a source of inspiration in restructuring the protection of distribution networks. A summary of major directions in microgrid protection is given in Table 8, all mandating additional sensors or telecom infrastructure.

It is worth noting that most of these schemes are tailored and derived for a particular microgrid, i.e. certain topology, generation mix, location, size and operating conditions (Hooshyar and Iravani, 2017; IEEE, 2019), and do not necessarily remain appropriate and effective if the system changes substantially. This is a major limitation when translating these approaches to the distribution network, which is much more volatile and evolving.

One of the popular methods is to use directional overcurrent relays and adapt their settings according to the microgrid state or topology (Mahat *et al.*, 2011; Laaksonen, Ishchenko and Oudalov, 2014; Coffele, Booth and Dyśko, 2015; Tummasit, Premrudeepreechacharn and Tantichayakorn, 2016). This continuous adaptation is implemented through local measurements or a central unit. The main challenge in these protection schemes is a need for prior knowledge of all possible network configurations and heavy computational execution time whenever the network changes. That might be an issue when extending this approach to the distribution network.

Distance protection schemes inspired by the transmission system employ admittance or impedance relays (Dewadasa *et al.*, 2009). They can be applied to both medium and low voltage levels but are not very effective in detecting phase to phase and earth faults or high-impedance faults, and they are susceptible to admittance measurement errors, harmonics and transients. There is also another alternative based on voltage measurements and Park transformation (Loix, Wijnhoven and Deconinck, 2009), but this again struggles at short lines, has a strong dependence on the network topology and has high computational complexity.

One of the most promising directions is the differential protection-based techniques (Sortomme, Venkata and Mitra, 2010; Dewadasa, Ghosh and Ledwich, 2011; Sortomme, Ren and Venkata, 2013; Xu *et al.*, 2016; Kar, Samantaray and Zadeh, 2017). These methods are very accurate in detecting any type of faults, as they are not affected by bidirectional flows, current levels, the number of DERs, weak infeed or the microgrid operating mode. They also remain effective in meshed microgrids and fully support the LVRT function of solar or other DGs. The main weak point is the communication infrastructure required, which entails significant additional costs especially when appropriate redundancy is considered for safety reasons.

PROTECTION SCHEME	ADVANTAGES	DISADVANTAGES
Adaptive Protection	Dynamic change features in settings between relays • Communication improves the speed of operation • Can be effective in grid-connected and islanded mode of operation	Expensive due to communication infrastructure Complex, involves heavy computational simulations and can compromise real-time operation • Communication dependant which can impact reliability
Directional Overcurrent Protection	Effective in bidirectional current flows Good selectivity • Can allow local or central implementation	Expensive, as it requires voltage and current measurement devices • Prior knowledge of all possible system configurations
Distance Protection	Can provide fast operation • Can be suitable for both grid-connected and islanded mode of operation	Expensive, as it requires voltage and current measurement devices • They may not be effective for short line and DG-intensive systems due to high sensitivity to DG fault contribution • Inability to detect high impedance faults • Susceptible to harmonics and transients
Voltage measurements	Effective fault detection	Coordination issues for short lines • Requirement of voltage measurement devices • Network structure dependence • May not detect high impedance faults
Differential Protection-based techniques	High fault detection accuracy • Immune to bidirectional power flow, changing current levels, number of DGs, system topology and operation mode	Expensive communication system • Communication dependent • Requirements for synchronised measurements for long lines • Traditional differential protection may fail in islanded mode of operation

Table 8. Summary of protection schemes proposed for microgrids

B.1.6. Improve the power quality in distribution networks

The power quality issues brought by type-tested (certified) embedded solar PV systems to the distribution networks are not significant at the moment, but there are concerns for the near future especially related to the 40 GW rooftop solar target in India. These issues are mainly solar-induced harmonic distortion and voltage unbalance, but also voltage rise/swells and flicker.

Although there are regulations on the total harmonic distortion of PV inverters, these usually refer to power levels close to the nominal power rating, i.e. when solar generation is high, and the proportion of harmonic distortion is relatively low. However, at lower generation conditions, usually in the morning or on a cloudy day, the solar-induced harmonics are much higher as a percentage, which poses a risk for high distortion levels in the network at times. In addition, these requirements are more relaxed for small kW-scale PV systems and are not quite followed in some developing countries. There is a need for universally more stringent requirements on the harmonic emissions from PV inverters across the entire power range. There is today mature technology on multi-level converters and advanced filter design that can meet these targets and thus these should be encouraged in the solar system design and installation industry.

Voltage unbalance is already an issue in rural India and there are concerns that it may be further amplified with the rapid uptake of small-scale rooftop solar connected in a single-phase fashion. There should be a plan from the network operator and a coordination with the PV installers to evenly distribute these systems across the three phases in the same area, aiming at balanced power flows throughout the year. Going for three-phase connections in smaller PV systems is also an effective measure to this goal.

B.1.7. Continuous evolution of grid codes and ancillary service products

The grid code is a key factor for the integration level of renewables into the power system. The successful grid code takes the concerns of all stakeholders into consideration, while maintaining grid security and stability as the primary objective. While lenient regulations may potentially compromise grid security and place extraordinary burden on the system operator, stringent codes may disincentivise further solar deployment thus defeating their very purpose. It is worth noting that for many renewables the cost of technology is closely linked to the grid codes compliance, this being a critical factor for the pace and extent of a particular renewable penetration in a market. The grid codes should follow a technology-neutral and realistic approach that strikes a balance among the diverging interests of all involved stakeholders.

Furthermore, these regulations should be regularly revised and updated to account for changes in key factors in the network, such as the grid strength (SCL), the generation mix and RES penetration levels. For example, a large share of old-type wind generators with induction machines indicates a weak grid and slow post-fault voltage recovery, thus necessitating stringent LVRT requirements to ensure grid stability after a severe fault. However, these old and directly coupled wind turbines will be replaced with newer variable-speed ones in the future, resulting in stronger grid that permits relative easing of the LVRT requirements.

In addition, new ancillary service products will be needed to account for the new generation mix with lower synchronous generation, reduced system inertia and grid strength. For example, fast frequency response over the first few seconds of a disturbance in the power balance will be key in a low-inertia power system. Introducing new ramping products of various rates by both conventional and new generation is also expected to assist with the variability of solar and other renewables. It is indicative that EirGrid in Ireland and National Grid UK in the UK have already introduced fast frequency services in their respective control areas. In EirGrid in particular, seven new system services were implemented in 2018, with the market value around € 235 million per year, as opposed to € 50 million the year before.

It is important to also monitor technology developments in the field and new challenges brought. For example, the smart grid technology has created cybersecurity risks, while the grid-forming technology has the potential for increased grid support by solar and other IBRs; these advances should be taken into account in the new grid codes to guide easing or tightening parts of the regulations accordingly. Moreover, the ancillary services market and the grid codes need to be reviewed simultaneously and in a coordinated fashion to avoid inconsistencies or conflicts between the incentives for voluntary involvement driven by the former and the mandated requirements set out by the latter.

B.2. DEMAND RESPONSE

In the traditional electricity system, the energy demand has been treated as inelastic except for stability reasons, thus putting all the burden to match supply and demand on the generation side. This may not be an option anymore with the massive uptake of renewables like solar, which are to a great extent variable and intermittent power sources. The concept of demand response (DR), i.e. modifying the load consumption according to the power system needs, is not entirely new, but it has been applied so far only in selected industries and it has yet to be fully deployed to system-wide commercial and household loads.

The DR technology has great potential in mitigating the balancing and flexibility challenges brought by solar. Time-shifting part of the demand to coincide with solar generation (e.g. at midday) makes scheduling easier and more economic, while cutting off some load in the same way that solar generation changes (e.g. solar retraction towards evening) reduces the ramping requirements by other sources and the flexibility needs. DR can be also found useful in power system stability issues brought by solar and other intermittent sources. Committing part of the demand to be adjustable and interruptible may effectively absorb unforeseen fluctuations of solar generation (e.g. due to clouds), thus limiting their impact to the transient stability and frequency stability of the power system. This technology along with energy storage has a great potential in tackling some of the most fundamental barriers to solar integration.

Electricity is not an isolated form of energy but must be seen as part of an integrated low-carbon energy system, as depicted in Figure 27. DR can be given by a multitude of electrical loads that provide some service or commodity that can be either interrupted with minimal impact on users or stored for later use. A discussion on such loads follows. Other terms associated with DR and used interchangeably or with overlap in meaning include:

- Demand-Side Management (DSM) or Demand Management (DM) which can also mean demand reduction and reduction in peak demand
- Demand-Side Response (DSR)
- Demand-Side Participation (DSP)
- Flexible Demand (FD)

B.2.1. Examples of flexible electrical loads

The following are a few examples of common flexible loads from a very wide range of energy use sectors that can be used for DR (Gils, 2014). This list is indicative and not exhaustive by any means.

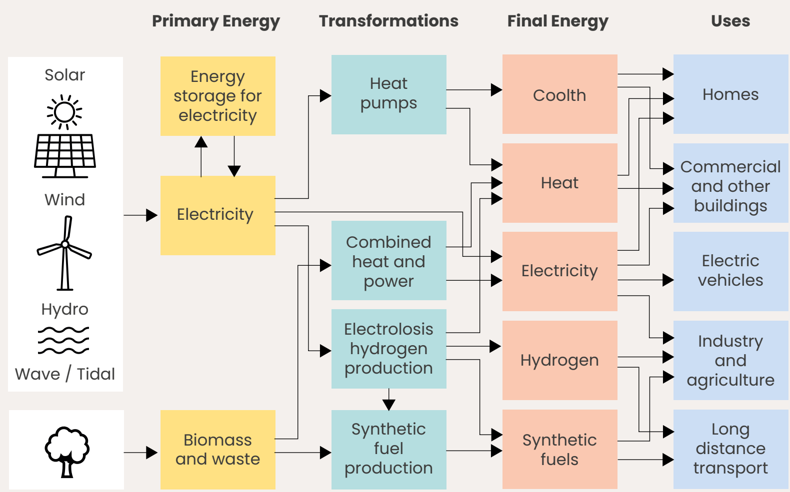


Figure 27. Energy flows in an integrated low-carbon energy system.

Water pumping. Water pumping can be done at any time of the day because water can be stored in water tanks. Stand-alone solar PV-powered water pumping is becoming increasingly economically viable for irrigation and drinking water in rural locations (Odeh, Yohanis and Norton, 2006; Chandel, Nagaraju Naik and Chandel, 2015; Engelkemier *et al.*, 2019), but grid-connected water pumps can also provide DR services (Ma *et al.*, 2013; Menke *et al.*, 2016).

Refrigeration and air conditioning. Cooling delivers lower temperatures to a space and materials within that space. There is usually a range of acceptable temperature and a substantial thermal mass of material that allows flexibility of the timing of the cooling process (Wai *et al.*, 2015). Refrigeration and air conditioning are large and growing sectors of electricity demand and can provide significant amounts of DR. Domestic and small commercial fridges can easily provide a 25% reduction in demand for a few minutes, perhaps for over 1 hour (Short, Infield and Freris, 2007; Lakshmanan *et al.*, 2016), without noticeable impact in their performance. Freezers can provide DR for several hours, even running on solar PV power alone (González *et al.*, 2018). Air conditioning of indoor spaces can provide DR with a duration of about an hour (Zhang *et al.*, 2013), but disruption of any longer duration affects the thermal comfort of building occupants, so it is appropriate for short-term interruptions. A promising enhancement is air conditioning with ice storage, with already a few products available (Kosi *et al.*, 2016), but the uptake has been slow.

Water heating. Water has a very high specific heat capacity, is easily stored, and hot water is widely used, both domestically and industrially. Resistive water heating is very cheap to install and can make use of solar PV power at high power levels when surplus electricity is available. Heat pumps are more expensive and require a low-grade heat source, and although more efficient than resistive heating (COP>1), their higher cost and lower heat delivery temperature make them less popular for water heating.

Space heating. Heat pumps are the leading technology to replace fossil fuelled space heating and can be readily converted to a flexible load. However, like air conditioning, the opportunity for modulating the heat input only lasts for up to about 1 hour. Although buildings have significant thermal mass, the occupants' tolerance on air temperature for thermal comfort is quite narrow, so space heating has great potential for minutes-duration interruptions (like air conditioning) that can be used to absorb solar intermittency due to passing clouds.

Electric vehicle charging. The transport sector must also decarbonise, and the leading technology to replace fossil fuels in surface transport over short distances is electric vehicles (EVs). This is expected to create a very large increase in demand for electricity generated from low-carbon sources, but also an opportunity for flexible electricity use. The batteries onboard EVs are a form of energy storage that allow separation of EV charging from EV use. The flow of energy is mostly from the electric grid to the vehicle, but new EVs have also the capacity to provide ancillary services and inject some power back to the grid through the so-called vehicle-to-grid (V2G) mode. In this regard, EVs can be treated as mobile energy storage units that have great potential for time-shifting DR and acting as flexible generators in the network.

Energy intensive industries. Some industrial output can be ramped up or down, interrupted or shifted to times of the day when solar power is more abundant. Energy intensive industries that could make large contribution to demand flexibility include aluminium, chlorine, paper production and recycling, steel and cement (Gils, 2014).

Most of these industries currently operate 24 hours a day and any variation in output has a knock-on effect on capital cost. For a given total output per day, the plant capacity is inversely proportional to the full-power hours of operation per day as shown in Figure 28, i.e. the plant capacity should increase to afford less-than-maximum production at times. Assuming a required average industrial output of 100 units per hour in this example, three different approaches are shown:

- 'Flat Output' does not provide any DR and requires a production capacity of 100 units per hour
- 'Peak Lopped' ramps up and down production according to solar generation and entails a 33% capacity increase to 133 units per hour
- 'Solar Powered' strictly follows the solar generation profile and necessitates an increase over 300% in capacity to 412 units per hour

Therefore, there is a trade-off between electricity cost and capital cost of the plant: whether to invest in manufacturing capacity, invest in onsite electricity storage, or to buy in somebody else's demand response.

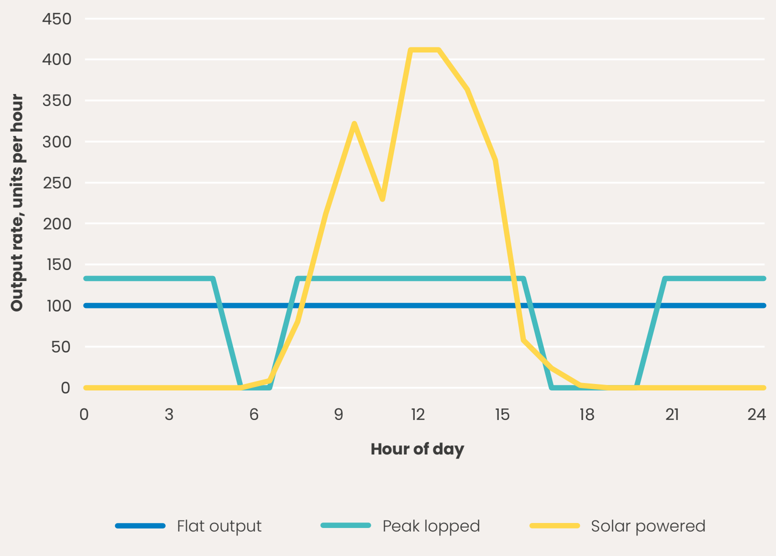


Figure 28. Manufacturing output rate for three flexibility scenarios. Peak capacity increases as operating hours reduce. Solar irradiance time series generated by the CREST demand model (Barton *et al.*, 2017; Barton, 2018).

Water desalination. Water scarcity is forcing many countries to use desalination to provide enough drinking water for their population. The leading technology for new desalination plant is reverse osmosis (RO), which is electrically driven. The RO desalination installation is expensive, but the electrical energy used to run the plant is also quite large at typically 5 kWh/m^3 of water. RO desalination is therefore a particularly important example of an energy-intensive industry, which has potential for time-shifting and DR with proper oversizing and water storage facilities.

Hydrogen and synthetic fuel production. In order to decarbonise all sectors of the economy, low carbon alternatives must be found for all uses of energy outside of the electricity sector, including, for example long-distance transport fuels, fertiliser production and iron smelting. These sectors cannot be directly electrified and must use a fuel, which may be synthesised. Synthetic fuels also provide a means of long-term or inter-seasonal energy storage. Examples of synthetic fuel include hydrogen, ammonia, methane (synthetic natural gas), methanol and synthetic long-chain hydrocarbons to substitute for petrol, aviation fuel and diesel.

The industrial route to all the above synthetic fuels is via hydrogen. While low-carbon hydrogen can be produced from fossil fuels with carbon capture and storage (CCS), such hydrogen will never be completely carbon neutral due to fugitive emissions of methane and incomplete CO_2 separation and storage. In a truly sustainable energy system, hydrogen is made from sustainable feedstocks and energy sources. Unless there are big technological breakthroughs in areas such as direct photochemical water splitting, electrolysis will be the principle source of hydrogen and an excellent flexible load. In a zero-carbon economy, given the large amounts of fuel required by industry and long-distance transport, the renewable energy generation will be much larger than the purely electrical demand, so as to support hydrogen production intended for other energy uses. A great opportunity in this approach is that hydrogen production can be directed to absorb the solar variability as shown in Figure 29, thus serving as an excellent source of flexibility and balancing to the power system.

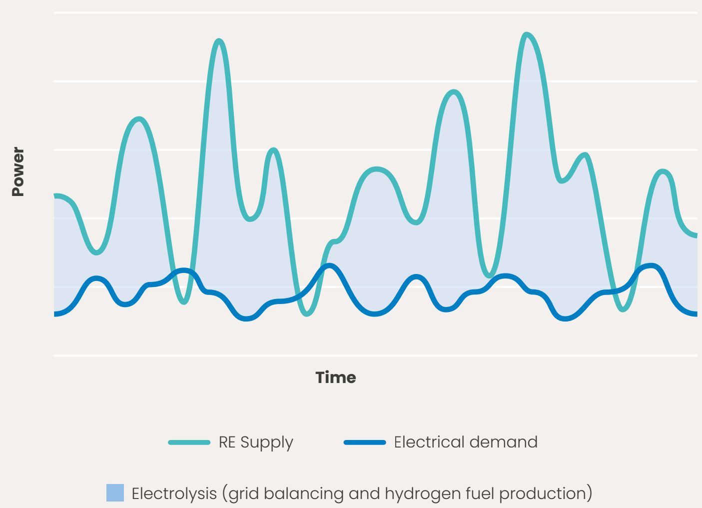


Figure 29. Hydrogen fuel production becomes a load management technique for a zero-carbon electricity grid (Gammon, 2007).

B.2.2. Incentives and market mechanisms

United Kingdom
In the UK, the existing market mechanisms for demand response consist of reduced unit prices for interruptible electricity supply, high charges for consumption at times of peak demand (triad charges), charges based on peak monthly demand, and half-hourly metering. The details of these schemes are specific to the contracts between consumers and their electricity supply companies but they are bundled together and sold to National Grid UK (TSO) as ancillary services. National Grid UK buy the following services (National Grid UK, 2020a) specifically related to DR of active power (so excluding reactive power for voltage support and black start etc.):

- Demand side response (DSR)
- Demand turn up (DTU)
- Enhanced frequency response (EFR)
- Fast reserve
- Firm frequency response (FFR)
- Mandatory response services
- Short term operating reserve (STOR)

National Grid UK currently contracts with just 19 companies as aggregators of balancing services, and some of these aggregators have contracts with smaller providers of DR. The market is changing, and new trading platforms are being created for DNOs and aggregators to buy and sell flexibility services, for example

'TraDER' and 'Piclo Flex' (Schittekatte and Meeus, 2020).

Until recently, such market mechanisms have been available only to large commercial and industrial consumers. Domestic customers could have simple Time-Of-Use tariffs (TOU) tariffs. However, DR pricing is now available to all smaller consumers through a Dynamic Time-Of-Use (dTOU) tariff offered by one electricity supplier in the UK (Octopus Energy, 2020), and to some EV owners through a specific supplier (Honda, 2020). Various dynamic electricity pricing tariffs have been created in other countries and research trials carried out (Schofield, 2015; IRENA, 2019; Hussain and Torres, 2020).

India

India has an ambitious target of installing a total renewable energy generating capacity of 175GW by 2022 (CERC, 2018; Tongia, Harish and Walawalkar, 2018), but India's ancillary services market is more limited and traditional than in the UK, with almost all services provided by gas-fired, coal-fired and large hydro power plants (Priolkar, 2015; Kumar *et al.*, 2018; Singhvi, 2019). Ancillary services are used for both grid balancing and overcoming network constraints. Balancing services, called 'Reserves Regulation Ancillary Services' (RRAS) are despatched by the Regional Load Despatch Centres (RLDC) for each of the five grid regions. RRAS are provided by just 67 large power plants spread across India (CERC, 2018). Ancillary services are provided at sizes of 1000MW or more. Inertia, primary response and secondary response (response times up to 15 minutes) are provided automatically. Tertiary response and generation scheduling are despatched manually on longer timescales.

India's states effectively buy and sell electricity from each other at a price based linearly on system frequency (CERC, 2017b), but this mechanism does not extend to suppliers or customers. India's electricity system regulator, the Central Electricity Regulatory Commission (CERC) recognises that the market for ancillary services needs to expand and develop and therefore published a discussion paper in 2018 (CERC, 2018). The provision of ancillary services depends on dispatched generators operating at less than rated power and therefore able to quickly ramp-up power output. The transmission system operator, known as Power System Operation Corporation Limited (POSOCO), recognises that this surplus capacity is in short supply at times of high demand. CERC propose a transparent market in ancillary services in which 'all technologies and services should be able to compete for Ancillary Services on a 'level playing field' and 'regardless of size or type' (CERC, 2018).

B.2.3. Future Challenges and Strategy

For DR to achieve its full potential, the markets for ancillary services in both India and the UK need to continue to reform to enable all available technologies to participate at all physical scales. There are many challenges in the contractual complexity, communication and aggregation of DR providers at all scales (Rajabi *et al.*, 2017), namely:

- The need to prove compliance with turn-up and turn-down signals
- Aggregation into dispatch units that are large enough to sell services into the ancillary services market (Lipari *et al.*, 2018)
- The acceptability of more volatile electricity prices, including much higher prices at times of peak demand and low supply (Octopus Energy, 2020)
- Implementation of local and variable pricing mechanisms (Albadi and El-Saadany, 2008)
- Issues of trust and buy-in (Albadi and El-Saadany, 2008)
- Market stability and price-finding (Nguyen, Negnevitsky and De Groot, 2012)
- Investment in smart appliances
- Weather dependence and unpredictability affecting business planning

Schemes for implementing DR fall into two types: direct control and real-time pricing. Direct control methods (Nguyen, Negnevitsky and De Groot, 2012; Lipari *et al.*, 2018) use a system of offers and bids by market participants in bilateral contracts, often to control individual flexible loads, with immediately verified change in demand. In contrast, real-time pricing strategies (Lu and Nguyen, 2005; Dutta and Mitra, 2017) employ a broadcast price signal, or use properties of the network itself (voltage and frequency) to this end. Real-time pricing appears to be simpler and easier to implement and requires much less communication between parties. Real-time pricing relies on an aggregated average response but is more appropriate to smaller consumers and smaller flexible loads.

B.3. ENERGY STORAGE

Energy storage is undoubtedly a key technology for the integration of solar and other variable renewables, exhibiting lately great potential with the advances in battery technologies. Coupling solar with energy storage essentially converts the variable solar source to a fully dispatchable power station that has grid-support capacity similar to conventional plants. This pairing can alleviate most of the balancing and flexibility challenges brought by the variable solar radiation, while it paves the way for a full range of ancillary services and contributes to system inertia, thus tackling several stability issues in the power system. The dispatchable operation is also useful in the voltage regulation of the distribution network, allowing to adjust the power flows in the network to address voltage rise phenomena caused by intermittent solar generation.

This coupling can be made either physically with collocation in the same site, or virtually by pairing the solar generation with energy storage installed elsewhere in the network.

Many technologies exist for large-scale energy storage, but smaller kW-scale systems employ mainly batteries. The battery technologies are more appropriate for collocation within the solar plant and have also recently enabled a mobile version of energy storage in the form of EVs. The following sections discuss the future and placement of energy storage in regard to solar, as well as the role of EVs as mobile energy storage devices.

B.3.1. Future prospects

National Grid UK considers energy storage as a key factor for all future scenarios of a high-RES UK power system, identifying mainly four technologies: pumped hydro, compressed/liquid air, batteries and hydrogen (National Grid UK, 2018a). Pumped hydro and compressed air are large-scale technologies with great peak-shaving and time-shifting capabilities that complement nicely the daily variation of solar generation. These systems have also storage potential for more prolonged periods of many days or even months, storing solar power when it is abundant and cannot be accommodated into the grid (e.g. summer days) to be deployed at other times of the year (Hunt, de Freitas and Junior, 2017). Typical round-trip efficiencies are 70-85% for pumped hydro (Ibrahim, Ilinca and Perron, 2008) and 45-70% for compressed air (Budt *et al.*, 2016), (Zavattoni *et al.*, 2017). In the UK, pumped hydro currently dominates the energy storage sector with a total capacity of about 26.7 GWh and provision of about 3 TWh in 2018 (Table 9). There is also some potential in converting dam hydro into pumped hydro plans (Scottish Renewables, 2016). However, this technology has important geographical, size and scale constraints, and cannot be collocated with PV systems, which puts a limit on how useful it can be in supporting further solar deployment into the grid.

Although the UK does not have operational compressed air plants at the moment, there are good geological resources underground for air storage. Using saline aquifers, this technology could be used as inter-seasonal storage (e.g. 77-96 TWh, about 160% of the national electricity consumption for January

NAME	STORAGE CAPACITY [GWH]	DISCHARGING POWER CAPACITY [MW]	YEAR OF COMMISSION
Ffestiniog	1.3	360	1963
Cruachan	10.0	440	1965
Foyers	6.3	300	1974
Dinorwig	9.1	1728	1984

Table 9. Pumped hydro energy storage plants in the UK (Scottish Renewables, 2016; BEIS, 2020)

and February) with a relatively low cost ($0.42-4.71/kWh) (Mouli-Castillo *et al*., 2019). In addition to saline aquifers, salt-mine deposits can be also used to store compressed air. Currently several gas facilities (more than 66 million cubic meters) have been built and used for natural gas storage, which could be potentially used for compressed air storage as well (Parkes *et al*., 2018). Such a 268 MW plant was scheduled to be built in Larne, Northern Ireland to use the underground caverns created within geological salt deposits on the Islandmagee peninsula, but recently the planning application has been unexpectedly withdrawn despite funding having been secured by a £77 million EU grant.

In India, integration of energy storage into the grid is low at the moment, but it is expected to increase rapidly with the massive electrification of isolated rural communities and the ambitious targets for 30% EVs by 2030 (World Energy Council, 2019). At present, Lithium-ion batteries are the most commercially viable technology in India due to their competitive price and improving performance parameters (India Smart Grid Forum, 2019). Pumped hydro compares quite favourably as well, with about 5,757 MW capacity (operational and under construction) (Buckley, 2019; IEEFA Australasia, 2019). The compressed air technology has more limited potential though, due to low availability of suitable geological formations for underground storage caverns (Aghahosseini and Breyer, 2018).

When small-scale distributed energy storage is considered, batteries dominate the field. There is a perfect match between batteries and PV systems for collocation in the same site, a coupling that reduces installation costs, treats solar intermittency at its very source, and supports local energy systems. Batteries in a solar plant can assist in voltage regulation of the network and increase the local consumption of solar energy (Von Appen *et al*., 2014); can smooth out fluctuations in solar generation (Li, Hui and Lai, 2013); can defer upgrades in the distribution network to host more solar capacity (Tant *et al*., 2012); and can provide a wide range of other technical and financial benefits (Ekren and Ekren, 2010; Sahraei *et al*., 2018; He *et al*., 2020). Currently, the UK has about 700 MW of energy storage apart from pumped hydro, most of which being lithium-ion batteries installed in the last few years.

Overall, lithium-ion batteries are expected to be the most likely technology to facilitate solar integration in the coming years, due to the versatile and effective nature of the battery storage system and the falling prices. Lead acid batteries, whilst cheap, suffer from poor lifetime and roundtrip efficiencies. All-vanadium redox flow batteries have the potential for a lower capital cost and LCOE at scale, but they have yet to achieve economies of scale. Electrolyser/fuel cell systems have potential for intra-day and longer timescales of energy storage, albeit at a prohibiting cost at the moment. Among the various lithium-ion battery chemistries, NMC/graphite and LFP/graphite cells are the most commonly applied, benefitting from their uptake in automotive systems. LFP/graphite has the potential for lower cost and higher safety over NMC/graphite systems, but challenges related to strong voltage hysteresis renders SOC estimation a more laborious task (Xing *et al*., 2014; Crawford *et al*., 2018).

Degradation of batteries strongly depends on how they are operated (SOC, depth of discharge, currents magnitude) and on the cell temperature. These points should be seriously considered when designing the control and operational framework of the batteries' energy storage system. Beyond the cells themselves, the thermal and battery management systems also add significant costs, but with intelligent control and engineering optimisation there is a potential for substantial cost reduction. Battery packs currently cost about 340 $/kWh with the ancillary components making up half of the system costs.

B.3.2. Location of energy storage

The size and location of an energy storage system is an important factor to the associated costs and value to the network. Although in technologies like pumped hydro and compressed air these parameters are pretty much determined by the geographical constraints and there is little room for manoeuvre, battery energy storage can be placed almost anywhere in the network and at any size required. The following dialogue aims to inform the optimal location for energy storage.

Should storage be placed close to solar generation or close to centres of demand?
The cost of grid reinforcement dictates that energy storage is more valuable when placed close to the greatest source of variability. Solar PV generation is more variable than demand during the day, and so energy storage should be placed closer to the PV plant rather than the centre of demand. This is illustrated with an example solar farm and a town in Figure 30, the town having the same average electricity demand as the solar farm's output.

Plotting the output of the solar farm over a 24-hour period (Barton *et al.*, 2017; Barton, 2018), and a typical aggregated demand profile on the Indian electricity system (Gaur *et al.*, 2017), Figure 31 shows that the solar farm generation is much more variable than the electricity demand. Therefore, if the energy storage is placed adjacent to the town, the required power rating of the transmission line should be 41 MW. However, if the energy storage is placed next to the solar farm, the required power rating of the transmission line will be only 11 MW, i.e. a 73% saving.

Ground-mounted solar farms have been built in the UK with energy storage since 2014 to enhance the value of electricity supplied and to overcome network capacity constraints without paying for grid reinforcement (Anesco Limited, 2014). They are now being built without subsidy (Stoker, 2019).

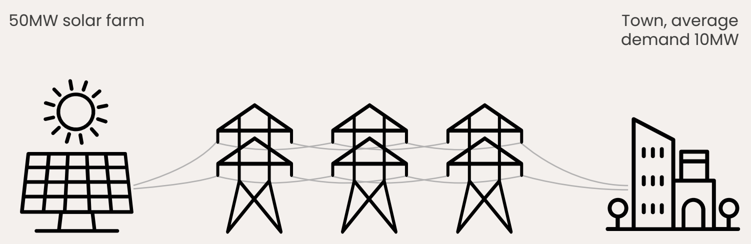


Figure 30. Illustrative solar farm and town connected by a transmission line.

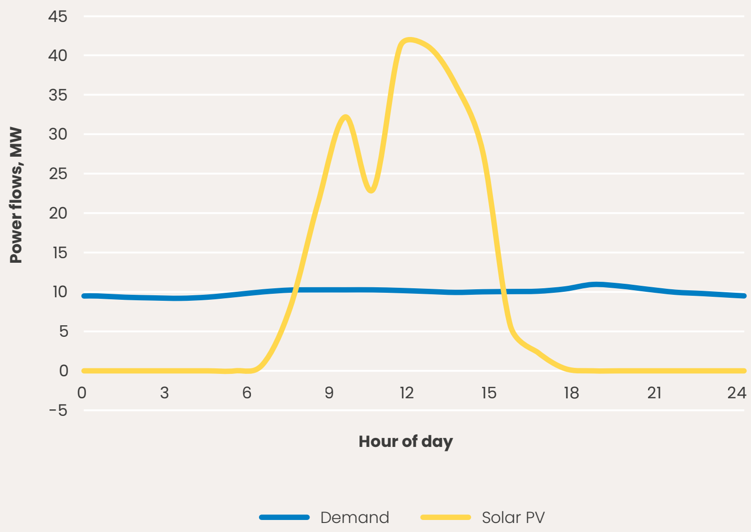


Figure 31. Solar PV generation and power demand for the example of Figure 30.

Are there economies of scale in a larger energy storage system?
For most conventional battery chemistries, e.g. lead acid or lithium ion, the time constant (energy/power ratio) is only about 1 hour, and energy is stored in the plates of the battery at room temperature. Theoretically there are no physical constraints governing the size of the battery, although practically there are economies of scale relating to manufacturing processes and industry learning rates.

When considering diurnal energy storage, however, a longer energy/power ratio is required, typically 6 hours. Other battery types have lower cost per kWh and are therefore more suitable for these longer-term storage applications. No clear winner has yet emerged, but the candidate battery types fall into two broad categories:

1. Hot batteries such as sodium-nickel-chloride (Benato *et al.*, 2015) or sodium-sulphur (Sudworth, 1984; Kamaludeen *et al.*, 1991). The high temperatures enable a very reactive metal (sodium) to be stored in liquid form.
2. Flow batteries (Weber *et al.*, 2011; Shibata *et al.*, 2013; Wang *et al.*, 2013; Alotto, Guarnieri and Moro, 2014; Cunha *et al.*, 2015) such as vanadium redox flow battery, vanadium bromide, zinc bromide, iron chloride, zinc-cerium, lead–acid (methanesulfonate), manganese-hydrogen and others. Energy is stored in separate tanks that enable the energy capacity to be arbitrarily large and independent of the power rating.

These long time-constant batteries do exhibit economies of scale. In the example of Figure 31, energy storage capable of supplying all the demand using PV alone would require a charging power capacity of 31 MW, a discharging power of 11 MW and an energy capacity of 152 MWh. The hot batteries have larger volume/area ratios at larger scale and hence slower heat loss rates. The flow batteries have the same complexity of pumps, valves and control systems regardless of storage capacity, and this fixed overhead cost is relatively smaller at larger scale. For these reasons, diurnal energy storage is better placed in a larger industrial setting than in a domestic setting. Again, this suggests that solar farms are good locations for energy storage.

Can the cost of inverters be minimised by prudent location of energy storage?
Solar PV electricity is first generated as direct current (DC) and it is then converted to alternating current (AC) to be exported to the grid via the inverters. By placing energy storage within the solar farm and upstream of the inverter, the inverter capacity can be minimized due to the smoother exporting profile (lower peak) similarly to the transmission line capacity reduction.

Maximum Power-Point Tracking (MPPT) is still required on the output of PV arrays, but a simpler and cheaper DC-DC converter can be placed between each PV string and the energy storage. The location of storage upstream of the inverter also achieves some of the advantages of Generation Integrated Energy Storage (Garvey *et al.*, 2015).

Can energy storage provide ancillary services to the electricity network?
Energy storage provides flexibility to active power flows and can thereby participate in the provision of ancillary services, such as fast frequency response and short-term operating reserve (Renewable Energy Association, 2015; National Grid UK, 2020a). Again, by placing energy storage upstream of the solar inverters, the inverters can provide these ancillary services, increasing the value for the solar farm operator.

Is the local electricity network reliable?
In many countries like India, rural distribution networks suffer more lost customer minutes per year than urban networks (Chowdhury and Koval, 2000; Yu, Jamasb and Pollitt, 2009; Harish, Morgan and Subrahmanian, 2014). For this reason, local energy storage is more useful to rural consumers than urban ones. If the consumer is also a generator of electricity (a prosumer), then the ownership of energy storage can enhance the value of that generation, maximising the value of exports and minimising the cost of imports.

Is there a large, local, intermittent electricity demand for which energy storage might reduce the cost of grid reinforcement?
Rapid EV charging points (40kW or more) will be required in very large numbers to enable EVs to be adopted as the principle technology for road transport. Their installation is sometimes limited by electricity network constraints. For those locations, energy storage would enable new charging points without

grid reinforcement. Considering the times and locations of rapid EV charging, it is most required during long, inter-city journeys. This suggests that there may be another synergy with large solar PV farms in the countryside and thus another income stream for solar PV farm operators.

Conclusion

In an electricity system dominated by solar PV generation, the best location of most bulk grid-connected energy storage is upstream of inverters, inside ground-mounted solar PV farms where it provides the following benefits and services:

- Defers some grid reinforcement
- Provides ancillary services to the grid
- Enhances the rural network reliability
- Minimises the cost of diurnal energy storage
- Minimises the capacity and cost of inverters
- Enables highway EV rapid charging

Some residential and other small consumers in rural locations may also benefit from battery-backup energy storage. This conclusion is confirmed by National Grid UK which forecasts that embedded generation, including solar, will exceed Britain's demand quite often in the future and that collocation of storage with PV plants will play an important role in time-shifting the excess generation (National Grid UK, 2018a).

B.3.3. Electric vehicles as storage devices

Electric vehicles (EVs) are one of the key transformative technologies in greening the transportation sector. The number of electric vehicles on both British and India roads is expected to increase rapidly in the coming years. In the UK, the target is set to 50%-70% of new car sales being EVs by 2030, with sales of pure petrol and diesel cars being banned from 2030 (HM Government, 2020). National Grid UK estimate the EV numbers between 2.7-10.5 million by 2030 and up to 36 million by 2040 (Hirst, 2020). India aims at a 30% EVs by 2030 as well (World Energy Council, 2019).

To accelerate this uptake and become the norm in place of cheaper fossil-fuelled vehicles, the EVs should deliver an additional advantage. Their use as storage units for clean energy during periods of peak demand could be this advantage, having the potential to reduce the Total Cost of Ownership of EVs via utility incentives.

There is a range of services that EVs can deliver to the network operators in terms of balancing, frequency, voltage and congestion management much like other types of energy storage. Exploring such financial incentives is particularly important for India, as batteries generally degrade faster and exhibit poor charging performance in hot climates. In that case, it may be more beneficial to use more expensive and temperature-tolerant batteries (e.g. LFP over NMC) for longer life, while offsetting the cost overhead with such grid-support services.

The unique feature of EV battery storage as opposed to other batteries, is its mobility: vehicles charge in one location and transport the stored energy to another. For example, 86% of EV owners in the UK currently charge at home overnight. When stationary and partly or fully charged, the vehicle's battery may also provide supply at times of peak demand, e.g. when the owner has returned home in the evening from work. Nissan and Renault are currently undertaking European trials to enable EV owners to obtain payment for sharing energy from their vehicles when they are not in use, without compromising mobility needs or causing deterioration of vehicle components.

However, despite the potential opportunities of vehicle-to-grid (V2G) applications, there are concerns around the potential reduction in lifetime of the automotive battery if used in this way. In general, increasing energy throughput in a battery can result in accelerated degradation due to the volume expansion/contraction in the battery active material. However, if controlled in the right way V2G has the potential to extend the lifetime of an automotive battery as shown by Uddin *et al.* (Uddin *et al.*, 2017). This is due to other degradation modes, such as operation at high SOCs, which, if avoided through intelligent control during the idle phase of vehicle use, can maximise the battery lifetime whilst providing grid services at the same time.

B.4. MORE GRID-FRIENDLY SOLAR PV SYSTEMS

The previous sections of this report explore how the power system has to change as a whole to accommodate more solar generation; the remaining part of this roadmap focuses on what solar generation can do for itself towards the same goal. To facilitate solar integration, a PV system should evolve to be a more friendly and compatible power station to the electrical network, i.e. become more 'grid-friendly'. This entails relieving some of the burden solar places upon the power system in terms of balancing, stability, voltage control and protection, as well as providing additional flexibility and services to the network during disturbances. High levels of solar integration most certainly require co-evolution of the power system and PV systems together.

A grid-friendly solar plant should have the capacity to provide a wide range of ancillary services to tackle stability and voltage issues in the network. A particularly critical service is fault ride through (FRT) that avoids unintended disconnection of solar and relevant stability implications, while it also contributes to the grid strength (SCL). In addition, a new transformative technology in IBRs is 'grid-forming control', which paves the way for 100% IBR network, encourages local energy islands, and allows for services otherwise not possible, such as black-start and islanded operation. To gain these additional functions, a solar plant has to keep some power in reserve to deploy when providing these services and at grid-forming operation, a feature gained by either installing energy storage or operating below capacity and curtailing power. The details of this roadmap to unlock the full grid-friendly potential of solar plants follow.

B.4.1. Ancillary services by solar

The Indian target for 175 GW of renewables by 2022 is expected to result in very high instantaneous penetration to the electricity mix, momentarily reaching 88% in the southern and 75% in the western region (USAID and Government of India, 2017). At such high integration levels, issues in stability, voltage control and protection of the power system brought by solar power are likely to pose risks for the security of the electrical network, which may work as a potential barrier to further solar deployment.

A very promising way to mitigate these challenges is to equip the solar PV power stations with ancillary services support capability for secure and stable grid operation. These services may include frequency and voltage support functions, as well as robustness and restoration services much like the synchronous machines of conventional plants. Some of these services aim to counterbalance an inherent limitation of the PV system, such as synthetic inertial response to make up for the missing physical inertia, or fault ride through (FRT) to curb severe disturbances and maintain the grid strength (SCL) within limits. Other services, however, extend to the network beyond the solar plant and may provide an additive value to the system, such as injecting reactive power to assist in local voltage regulation or fast frequency response to support the network at generation loss. It is important that the future PV systems provide the widest possible range of ancillary services and that this flexibility is extended also to plants of smaller size beyond the MW-scale solar parks.

Types of services

The grid codes and standards worldwide require now a wide range of ancillary or grid-support services by DERs that somewhat mimic the way that synchronous generators support the power system during disturbances. These standards greatly differ from country to country and among the various types of DERs and their power rating. Some of the most common and fundamental services required are shown in Table 10, classified into three main categories according to the European code ENTSO-E (ENTSO-E, 2013):

At the moment, only a minimal number of these services are mandatory for solar PV plants mainly due to the variability of the solar resource (non-dispatchable), and when they do apply, they usually refer to large plants of MW scale. Among the three categories in Table 10, the voltage stability services are generally the easier to facilitate in a PV system by injecting/consuming reactive power, which is a straightforward task for the power converter of an IBR. This is why most standards require these functions for a wide range of PV installations, quite often alongside appropriate inverter oversizing of the order of 5% to minimise bottlenecks between active and reactive power.

VOLTAGE STABILITY SERVICES	FREQUENCY STABILITY SERVICES	ROBUSTNESS AND RESTORATION SERVICES
Reactive power injection/ consumption Dynamic reactive current injection Oscillations damping	Dispatchable operation Primary frequency response (Synthetic) inertial response	Fault-Ride-Through (voltage and frequency) Black start capability Islanded operation

Table 10. Common ancillary services requirements by DERs (ENTSO-E, 2013)

On the other hand, the frequency stability services require both up- and down- regulation of the active power, which entails a need for a power headroom to allow increase of the output in the former case (e.g. to support under-frequency events). This is not straightforward in solar PV systems that have been traditionally operating at their maximum power point and generally do not have the provision of dispatchable primary resource or energy storage. The only way a solar PV plant could provide a full range of frequency services is to maintain some power in reserve, either by means of energy storage or by operating in a deloaded manner to establish a power headroom (National Grid UK, 2019d). With the falling of system inertia due to the increasing number of IBRs in the network, this kind of service is expected to be key in the future of solar integration.

Among the robustness and restoration services, FRT is commonly required by most grid codes albeit with significant differences on the tolerance limits and time duration. That may be the most critical service stability-wise and is discussed in more detail in the following section. The capability for black start (i.e. to restore the power system in case of blackout) and islanded off-grid operation (i.e. isolated with no grid connection) implies that the PV system works in grid-forming mode (i.e. acts as a voltage source and can establish voltage and frequency in the network), which again is not the case for today's PV systems. Most solar systems run at grid-following (or feeding) mode, which aligns better with the uncertainty of solar irradiance but cannot establish and support the grid in the same way.

To allow for a wide range of ancillary services by solar power plants, there are two key technologies to be explored that will unlock the full grid-friendly potential of PV systems: keeping power reserves, either through energy storage or power curtailment, and operating in grid-forming mode. The specifics and potential of these emerging technologies are discussed later in this section.

B.4.2. Fault-ride-through and Anti-islanding by solar

Fault Ride Through (FRT) capability of a PV system, i.e. to remain connected to the grid during major disturbances and faults, is usually a mandatory grid code requirement; it guarantees there will be no domino-like disconnections due to faults and it is an essential requirement to allow a massive solar fleet into the network. This service is strongly related to the anti-islanding protection, i.e. to detect an islanding and LoM event and cease operation. Staying connected to the grid during a fault entails that the PV system supports the network with much needed fault current that limits the voltage and frequency distortion, as well as it sustains the grid strength (SCL) and helps the protection scheme of the network to function properly.

Grid regulations on FRT

The FRT service includes the voltage FRT function, i.e. withstanding sags or swells in the voltage magnitude, and frequency FRT that refers to fluctuations in the grid frequency. In the former case the PV plant can further support the grid voltage by injecting additional reactive current (dynamic reactive current injection service), while in the latter it may be possible to adjust its active power output to support the system frequency (frequency response service). More technical details on these mechanisms may be found in Appendix A.

The FRT service was the first requirement for DGs introduced in the grid codes. It is indicative that the Indian grid code introduced a voltage FRT requirement for the first time in 2014, referring to the 66 kV level to account for high wind integration in the southern states of Tamil Nadu and Andhra Pradesh. It was then extended to 33 KV recently in 2019 to include utility-scale solar PV stations. The voltage FRT characteristic of the Indian grid code is depicted in Figure 32: as long as the terminal voltage of the PV system lies within the two lines it has to remain connected, otherwise it is permitted (but not obliged) to disconnect. These clearing times and limits vary with the voltage level of the network.

During that time, the DG should supply reactive power as a high priority, meaning that it may curtail some active power to make room for the reactive power, but in that case the output has to be restored to 90% of the pre-fault level within 1 second of the voltage restoration (Central Electricity Authority, 2019). This dynamic reactive power service is crucial in sustaining the voltage until the fault is cleared and supports the SCL of the local grid.

As for the frequency FRT function, the Indian code requires the generator to stay connected within a frequency range of 47.5 Hz to 52 Hz and feed in the nominal active power within 49.5 Hz and 50.5 Hz. There are also requirements for dispatchable operation, droop frequency control and ramping limits for generators of 10 MW capacity or more connected at 33 kV and above (Central Electricity Authority, 2019).

It is important that these functions are tested and certified for all relevant DGs to make sure that they comply with the regulations. In India, there are some industries that provide testing facilities to validate the compliance of wind plants to

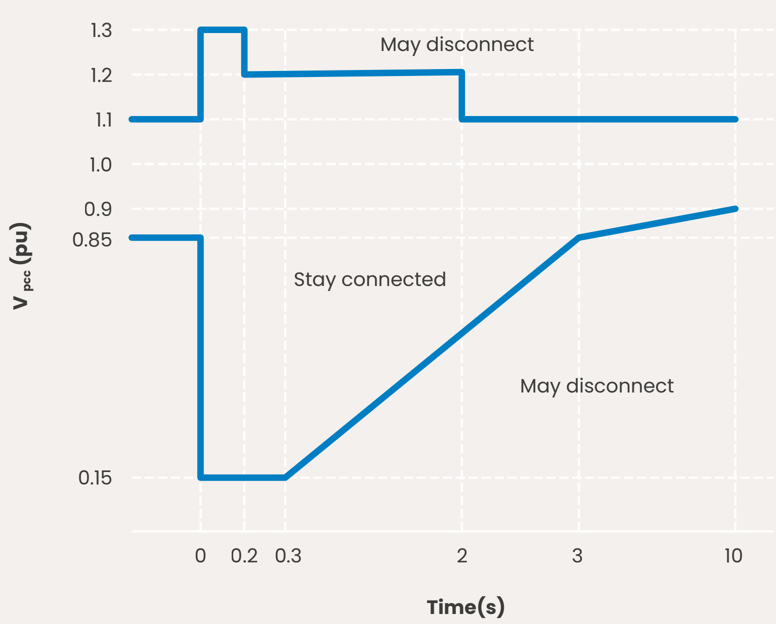


Figure 32. Voltage FRT characteristics adopted by the Indian grid code (Central Electricity Authority, 2019)

voltage FRT (Steck, 2017; Pukhraj Singh, 2020). Such initiatives are needed for the solar PV plants as well.

Status of anti-islanding protection

As the protection settings and tolerances of DGs on grid disturbance are relaxed to improve FRT, and as more IBR are deployed, failing to detect correctly islanding events is increasingly becoming an issue (Noor, Arumugam and Mohammad Vaziri, 2005; Mahat, Chen and Bak-Jensen, 2008; Dietmannsberger and Schulz, 2016; Dyśko, Tzelepis and Booth, 2016; Tzelepis, Dyśko and Booth, 2016). In Great Britain, the distribution code (Distribution Code Review Panel, 2020) applies to all users of the electricity distribution systems: G98 for generators up to 3.68 kW at 230 V (ENA, 2019), superseding G83; and G99 for generators over 3.68 kW (ENA, 2020b), superseding G59. Under these rules, smaller generators, up to 3.68 kW are required to temporarily disconnect from the grid in response to a disturbance and then reconnect when the grid is restored. Larger generators are required to have specified levels of FRT but still have to detect LoM. Following a consultation in August 2017, the electricity industry recognised the danger of false tripping by LoM detection equipment (National

Grid, 2017) and implemented new rules retrospectively on medium-sized and larger generators. Vector shift protection is now prohibited because it is more likely to cause false tripping and less sensitive to genuine islanding than RoCoF protection (Dyśko, Tzelepis and Booth, 2017). The maximum tolerated RoCoF rate is increased from 0.125 Hz/s to 1.0 Hz/s with a time delay of 0.5 s. The increase in the allowable frequency slew rate is due to the reduced system inertia because of more IBRs in the electricity mix. It was estimated that the cost of keeping the maximum RoCoF below 0.125 Hz/s exceeded £100 million/year (National Grid, 2017). Therefore, it was cheaper to change the settings on LoM protection, including an Accelerated LoM change Programme with subsidies paid to DG operators to make the necessary changes (ENA, 2020a). Methods other than RoCoF and vector shift detection are not prohibited in the distribution networks of Great Britain, but they are not specifically mentioned in the grid code.

In the Indian network, the generating units are required to abstain from back-energization of the network in the event of LoM. At the moment, there are no specific requirements on Anti-islanding protection in the Indian grid code. In the event of large-scale loss of generation or insufficient generating capacity, system frequency control is performed by load shedding based on low or falling frequency. Presently, there are four stages of Under-Frequency Load-Shedding (UFLS) relays which are set at 49.2 Hz, 49.0 Hz, 48.8 Hz, and 48.6 Hz in Northern region (NR), Western region (WR), Eastern region (ER), Southern region (SR), and North-eastern region (NER) (CERC, 2017a). These settings were last raised in 2013 prior to the synchronization of the Southern region with rest of the grid. In addition to UFLS relays, df/dt (RoCoF) relays are also installed in NR, WR, and SR networks. In NR and WR, df/dt relays are set to get armed at 49.9 Hz to shed load automatically if the rate of fall of frequency is faster than 0.1, 0.2, or 0.3 Hz/s (i.e. three stages). In SR, however, the frequency at which UFLS is armed and the rate thresholds are 49.5 Hz & 0.2 Hz/s, 49.3 Hz & 0.2 Hz/s, and 49.3 Hz & 0.3 Hz/s for the three stages, respectively (CERC, 2017a).

In Ireland, large generators are required to remain connected to the system with RoCoF rates of up to 0.5 Hz/s in the Republic of Ireland and up to 1.5 Hz/s in Northern Ireland (Eirgrid and Soni, 2012). The tolerance to greater RoCoF in Northern Ireland is so far considered not to be in significant danger of causing accidental islanding (Dyśko, Tzelepis and Booth, 2016; Dyśko *et al.*, 2018). EirGrid, the TSO of the all-Ireland electricity grid, has set a limit of 75% of generation from wind power and other IBRs or induction generator sources at any time to maintain sufficient inertia for stability, referred to as the System Non-Synchronous Penetration limit. The likely instability that would occur if the limit is exceeded remains a barrier to the Irish grid achieving 100% zero-carbon generation.

Future trends in anti-islanding involve smart meters and phasor monitoring units (PMUs). An increasing number of PMUs are being deployed in the GB network to enable improved real-time monitoring and early fault detection (Ashton *et al.*, 2012). PMUs or 'synchrophasors' allow for improved LoM detection by measuring the phase angle difference between an islanded network and the main grid (Laverty, Best and Morrow, 2015). The benefit is this case is that anti-islanding protection becomes a responsibility of the network, with no dedicated hardware or software in the PV system, which may bring down the implementation time and cost (Dutta *et al.*, 2018). Advanced digital signal processing techniques like Discrete Fractional Fourier Transform (DFrFT) and machine learning methods may prove to be a potential tool for islanding detection (Dutta *et al.*, 2018), especially when combined with impedance measurements to harmonics of the grid frequency (Malakondaiah *et al.*, 2019). More technical details on anti-islanding methods are given in the appendix.

B.4.3. Grid-forming control in PV systems

The dynamic response of an inverter-based resource like solar to a disturbance in the grid is governed mainly by the inverter controller rather than physical parameters, as it does not have any rotating mass like synchronous generators. The control scheme of the inverter plays a crucial role on how the plant perceives the disturbance and supports the grid during that time. There are mainly two different philosophies for this control scheme: grid-following and grid-forming. A schematic diagram illustrating the fundamental concepts of these schemes is shown in Figure 33.

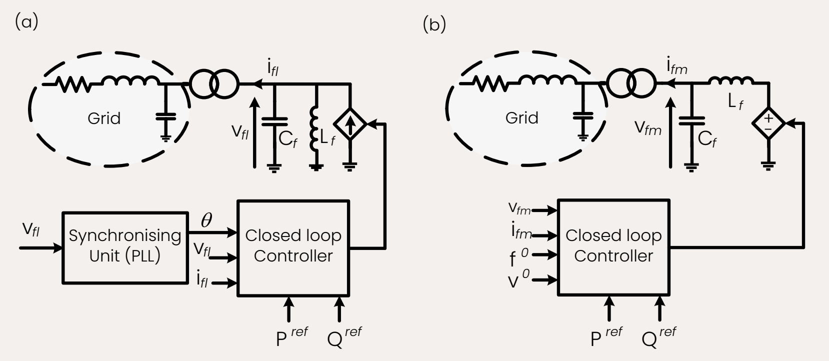


Figure 33. **Schematic diagram of (a) grid-following and (b) grid-forming inverter (Milano *et al*., 2018)**

At grid-following mode, the inverter is locked to the grid frequency by means of a synchronizing unit (phase-locked loop – PLL), and it delivers active and reactive power according to input setpoints. The inverter behaves essentially as a controllable current source that requires an already established voltage in the grid to function, formed by other sources such as synchronous generators. This may be a barrier to a future high-RES power system with lots of IBRs, such as solar, wind and batteries.

Most of today's grid-connected inverters are operating in grid-following mode under the assumption that the grid is stiff (high SCL) and the PLL can accurately track the voltage frequency and angle, due to a sufficient number of synchronous machines in the generation mix. However, IBRs displacing synchronous generation reduces the grid strength, which alongside delays and higher impedance lines in the regional network, may lead to PLL malfunction at severe disturbances that risk disconnection from the grid. Furthermore, whilst staying connected, a grid-following source can support the grid only in a limited fashion, suffering from synchronization and control delays that do not allow it to deploy its full potential.

In the grid-forming mode, the inverter generates the voltage magnitude and frequency on its own, without the use of a dedicated synchronization unit; it acts as a controllable voltage source connected to the grid through a low series impedance (Figure 33). Therefore, it can form the grid without the need from other sources, which is why this approach has been used in battery-inverters of stand-alone microgrids for years. With the increasing RES integration, it may be necessary to bring this control philosophy to the power system as well. In addition, the dynamic response of a grid-forming inverter to a disturbance is instantaneous and guaranteed, not involving any sensing or synchronization delays, which makes it a credible source in weak grids (low SCL). This is another reason to consider grid-forming control in solar PV plants as the IBRs integration increases.

The simplest grid-forming strategy is 'droop control', which adjusts the active and reactive power as a linear function of the grid frequency and voltage, much like the droop speed control of governors in synchronous generators. Other more sophisticated grid-forming control schemes in the literature include (Tayyebi Ali *et al*., 2018): 'virtual synchronous generator' that closely emulates the dynamics of the synchronous machine; 'matching control' that produces the frequency signal looking at both the ac and dc side of the inverter; 'virtual oscillator' that treats the plant like a non-linear oscillator. There may be small differences in the transient response of these techniques, but all schemes manage quite well to support the grid during disturbances.

With the increasing renewables penetration, there will be a need for robust synchronization, dynamic voltage and frequency support and even black start capability by inverter-based renewables, services that can be best, or only, provided by grid-forming inverters (Milano *et al*., 2018). A major inverter limitation that remains though is the limited overcurrent capacity, i.e. overcurrents up to 120%-160% the nominal value, due to the inherent limitations of the inverter switches (e.g. IGBTs). Furthermore, the dynamic interactions of the grid-forming sources with the rest of the system are yet to be fully understood, which means that there should be caution in wide adoption of this technology until a proper coordination framework is developed. This should be performed alongside new pricing and market mechanisms to reward and incentivise grid-forming sources.

Potential of grid-forming PV systems

The ancillary services a grid-forming source can provide to the grid are summarized in Table 11 (CIGRE/CIRED, 2018), presented here as a comparison to the grid-following. Services that refer to normal and steady-state operation, such as voltage control or harmonics compensation, are equally performed in the two modes. However, services to support the grid during disturbances in a rapid and dynamic manner, such as frequency response at generation loss or dynamic reactive current injection at faults, are provided more effectively and robustly with grid-forming control. Finally, services required from the plant to establish voltage in the network and form a grid, like operation in islanded mode or system restoration after blackout (black-start), are only possible with a grid-forming source. To explore this potential, National Grid UK is currently carrying out a number of projects to see how grid-forming can convert variable inverter-based generation to be more grid-friendly (National Grid UK, 2019b).

It is worth noting that a fundamental requirement for a grid-forming source is up- or down- regulation of its active power automatically in response to a disturbance. This implies ability to increase the output of the input primary source (e.g. PV arrays, batteries etc.) beyond the pre-disturbance operating level, i.e. to keep some power in reserve. Although this is straightforward at dispatchable IBRs, like battery energy storage systems, solar PV systems have been operating traditionally at a maximum power tracking mode (MPPT), which means that normally they cannot further upregulate their output. For the solar plants to gain power reserves and operate in grid-forming mode, there are mainly two options: either installing and collocating energy storage in the plant, or operating below capacity at all times (e.g. 90% of the maximum power – curtailing energy) to have a headroom for upregulation. These methods are discussed in more detail in the following.

B.4.4. Curtailments and power reserves in PV systems

Curtailing (rejecting) energy from solar plants or other renewables is a common practice followed by the network operators for security purposes. The solar-related challenges in balancing, stability, voltage and protection of the power system may put a limit on the maximum solar penetration at any time. Although it is easy to maintain the curtailments to low levels when RES integration is limited with simple interventions in the power system, at higher integration levels this is not the case as seen in many countries such as Ireland and Spain. Recommended measures include improved forecasting and scheduling, enhancing transmission capacity, increasing the system flexibility, installing energy storage and other directions discussed in this roadmap; however, it is unlikely that solar curtailment will ever be exactly zero.

Keeping power reserves in a PV system

A PV system with power reserves is much more grid-friendly, being able to provide a wide range of ancillary and balancing services to the network and operate in grid-forming mode. To have this option, either energy storage has to be installed

AVAILABLE IN BOTH SCHEMES	BETTER IN GRID-FORMING	ONLY POSSIBLE IN GRID-FORMING
Steady-state voltage control Power oscillation damping Harmonic voltage compensation	Inertial response Primary frequency response Dynamic reactive current injection	Islanded operation Act as reference for grid-following sources Black-start capability

Table 11. Ancillary services provided by grid-forming inverters as compared to grid-following.

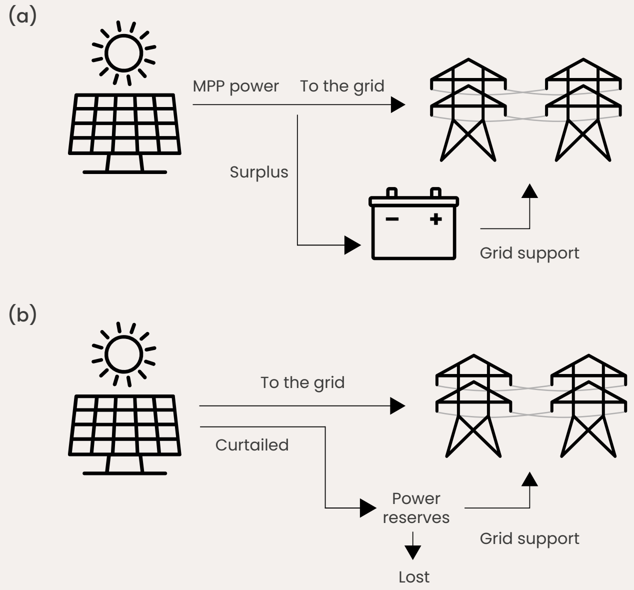


Figure 34. Keeping power reserves by (a) collocating energy storage and (b) operating below capacity (curtailing some power).

and collocated in the plant, or it must operate below capacity and curtail some energy on a constant basis.

The benefits of energy storage, especially when installed upstream of the inverter in a solar park, have already been discussed. Batteries are the most appropriate technology for this purpose, connected to the PV generator usually in a parallel fashion: the PV arrays continue to produce the maximum power available (MPPT), the excess part being diverted to the batteries only to be fed back into the grid later when needed (Figure 34a). This option paves the way for a truly grid-friendly energy source much like a conventional power station, but it comes at the cost of the additional investment and maintenance overheads of the energy storage system.

The alternative is to operate below capacity, i.e. deliberately track a suboptimal power level (e.g. 90% of the MPP), so that there is a power margin to deploy should the need arise (Figure 34b). In this case, there is no additional equipment or hardware costs, but some power is curtailed and the solar capacity is not fully utilised. In that sense, the solar plant is treated as a dispatchable power station with a zero-cost fuel (solar radiation). The barriers in this approach is that a market mechanism has to be developed to compensate for the unutilized capacity, and that the maintained reserves are not perfectly guaranteed in volatile weather.

Power reserves by curtailing power
Operating below capacity (or curtailing power or deloaded operation) results in lower energy yield but allows for immediate upregulation of the power output when needed to provide services (e.g. dispatchable operation, under-frequency primary response, inertial response, grid-forming control etc.). With the drastic fall of PV module prices and the very low LCOE of solar in many countries nowadays (Solar Power Europe, 2020), keeping power reserves through curtailment may be a viable solution in the near future for a quick conversion of existing PV systems to more grid-friendly power stations.

Large MW-scale plants comprising a multitude of identical PV clusters (PV arrays and individual inverters) may easily realise this curtailment function by instructing some of these clusters to reduce their power whilst keeping the remaining modules at MPPT mode (Loutan *et al.*, 2017), as shown in Figure 35a. This way, the MPPT-clusters monitor the varying maximum power available and extrapolate it to the entire plant. This approach is simple but requires identical components and conditions, which is not always guaranteed in MW plants (e.g. during cloud coverage (Gevorgian, 2019)) and is uncommon in smaller-size plants of the kW scale (e.g. small number of PV clusters or even a single one).

A more universal method that applies to any kind of PV system is the entire plant to operate at an off-MPPT mode, i.e. to shift the operating point of all PV clusters away from the MPP to a reduce power level (Figure 35b). An example is illustrated in Figure 36: conventionally the PV system would aim to operate at the MPP to extract the maximum available power (MPPT mode), but now the target is a reduced power level that creates a power margin (reserves, headroom) that can be deployed later if needed. This technique is currently under development by the scientific community, with open questions on monitoring the varying maximum power while away from the MPP, on the control scheme stability and operation at partial shading conditions (Batzelis, Kampitsis and Papathanassiou, 2017; Batzelis, Papathanassiou and Pal, 2018).

Although keeping reserves by curtailing power is a simple method to provide additional grid-friendly potential to existing plants without additional investment, there are important barriers to commercial application. An appropriate market mechanism should be developed to compensate for the unused PV capacity and unextracted solar energy, possibly through purchase of ancillary and balancing services. With such a market framework and the falling prices of the PV technology, it may be viable to oversize a PV plant by 5% or 10% and commit that capacity portion only for reserves and services.

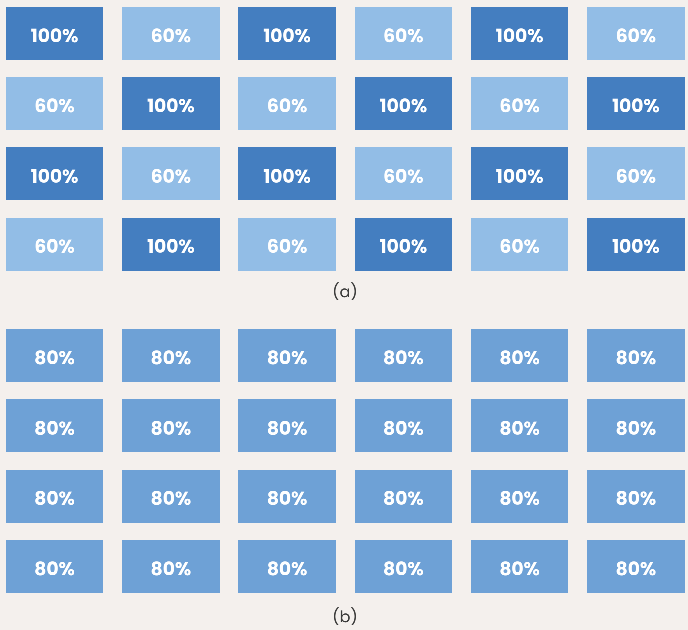


Figure 35. Keeping power reserves by operating below capacity: (a) some PV clusters in MPPT and some in off-MPPT, (b) the entire plant in off-MPPT mode.

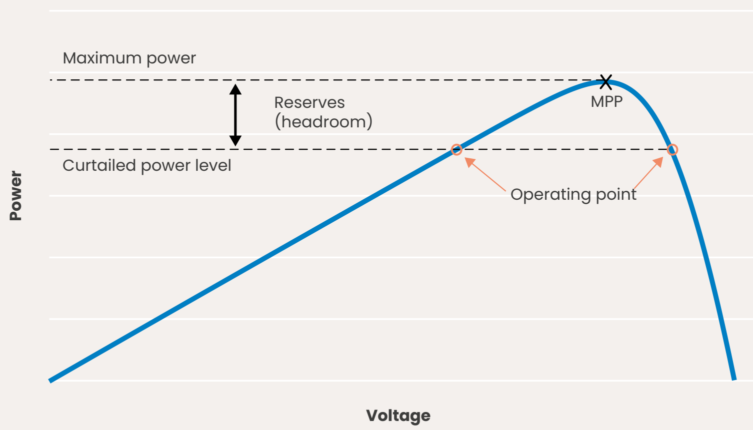
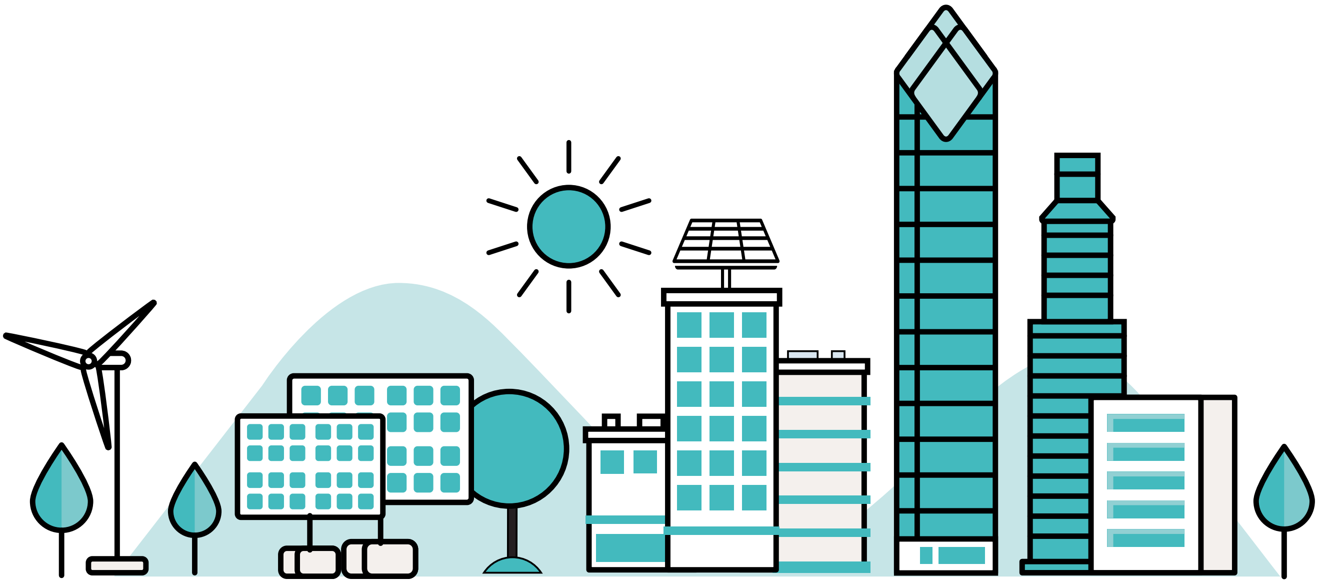


Figure 36. Power-Voltage curve of a PV system operating at off-MPPT mode and keeping power reserves.

Another major challenge in this approach is that the maintained reserves are weather-dependent and are not entirely guaranteed (Gevorgian, 2019). Coupling this method with accurate short-term solar forecasting is crucial to establish credibility and usefulness of the service, although it is highly unlikely to ever reach the reliability levels of alternatives like energy storage. It is possible that the solar PV systems of the future would need to implement a hybrid approach, installing some battery storage but also curtailing some power occasionally, to strike a balance between the costs and benefits of keeping power reserves and being more grid-friendly.



PART C: CONCLUSIONS

This report explores the current and future technical barriers against high solar integration in the UK and India. A team of researchers within the UK-India consortium for clean energy combined their complementary expertise to draw a roadmap with promising directions towards achieving high levels of solar generation into the power system.

The main findings of this report are summarized in Table 12 and Table 13 with a special focus on the synergies and differences between the two countries.

BARRIERS	SEVERITY	COMMON CHALLENGES IN THE UK AND INDIA	COMMENTS FOR THE UK	COMMENTS FOR INDIA
Balancing & flexibility challenges	Major	• Overgeneration of solar at midday • High ramping needs for solar retraction at evenings and intermittency on cloudy days • Need for high flexibility from other sources • Conventional generation has high technical minimum limits and low ramping rates	• Increasing electricity mix of variable solar, wind and EVs • Highly volatile weather leads to solar intermittency and forecast errors	• Developing grid code and ancillary services market • Need for robust ancillary service system • Lots of inflexible coal units
Stability issues	Medium	• Lowering of short circuit level • Frequency and voltage stability issues • Limited services by solar and poor communication infrastructure • Tripping of embedded solar at disturbances	• Expected low SCL in remote regions like North Scotland • Falling of power system inertia • Massive tripping of embedded generation recently in August 2019	• Relatively low regional grid strength • Largely weak grid infrastructure in rural areas • Stability issues in RES-rich states
Voltage issues	Medium	• Voltage rise phenomena • Reverse power flows • Deterioration of regulation devices (OLTCs etc.) due to frequent operation	• High levels of reverse power flows	• More severe voltage issues in regional networks
Protection challenges	Medium	• Difficulties in detecting faults • Low fault currents by solar and other IBRs • Need to redesign protection of the distribution networks • Unintentional tripping of solar at faults	• Unintentional DG disconnection due to high ROCOF or vector shift	• FRT performance certification is not ironclad
Power quality issues	Minor	• Harmonic emission by solar • Risk to worsen voltage unbalance with single-phase solar systems	• Potential resonance due to capacitive underground cables	• Already voltage distortion and unbalance in low-voltage networks

Table 12. Technical barriers to high solar integration in the UK and India

CHALLENGES	COMMON DIRECTIONS FOR THE UK AND INDIA	COMMENTS FOR THE UK	COMMENTS FOR INDIA
Balancing & flexibility challenges	• More flexible generation like hydro and gas over coal New ancillary services and markets • Generation scheduling more often, e.g. every 5 minutes • More accurate solar forecasting and access to solar resource data • Strengthening the role of demand response • More energy storage by pumped hydro, batteries and EVs • Multi-energy sector coupling	• Phasing out coal and increasing interconnections • Extending demand response to more residential and commercial customers • Energy storage also by compressed air • High potential for EVs as mobile energy storage	• Mainly hydro for flexibility • Electricity market should evolve faster • Demand response only partially explored • High potential for pumped hydro energy storage • Batteries storage also very competitive
Stability issues	• Continuous update and harmonizing of grid codes • More ancillary services and grid-forming operation by solar • Collocate solar and batteries, or oversize solar for power reserves via curtailment • Turn solar curtailment into an opportunity • Improved telecom and visibility to solar • TSO/DSO coordination	• Services by batteries and EVs energy storage • Going forward with TSO/DSO coordination • Black start by solar to assist in case of a blackout	• Strengthening the regional grid • Faster evolution of the grid codes and electricity market • Islanded and grid-forming solar operation for resilience to power cuts in rural areas
Voltage issues	• Improved voltage control • Leveraging the reactive power of solar and other DERs	• Co-optimization of regulation devices and DERs at a TSO/DSO level	• Strengthening grid infrastructure, especially in rural areas
Protection challenges	• Redesign the protection of distribution networks • Robust FRT by solar	• Revisiting the disconnection settings of existing solar	• Extending FRT requirement to low voltage networks and lower power levels
Power quality issues	• More stringent harmonic emission requirements	• Limit solar harmonics at both high and low generation	• Ensuring harmonic requirements are met in kW-scale PV systems • Improving voltage balance between phases in distribution networks

Table 13. Roadmap for high solar integration in the UK and India

BALANCING & FLEXIBILITY CHALLENGES

The primary barrier for a solar-intensive electricity mix is the variability and intermittency of solar generation that dictates higher flexibility in the power system not readily available from conventional power plants. That is expected to be a concern in the near future in the UK with lots of wind in the north, lots of solar in the south-east and a highly changeable and unpredictable weather. India on the other hand has still a more traditional generation mix with lots of inflexible coal plants and developing grid codes and market.

Recommendations shown in Table 13 include more flexible generation, more energy storage and demand response, more frequent generation scheduling and new ancillary service products to draw from the available flexibility in the network. The UK has rightly set out complete phase out of coal and increase of interconnections to neighbouring countries, but these should be coupled also with residential-level demand management and effective integration of the large anticipated EVs fleet. India should leverage the high hydro potential for flexibility and energy storage, but also make efforts to modernise and adapt faster the electricity market and grid regulations to the new reality.

STABILITY ISSUES

The stability concerns related to solar are linked to the diminishing grid strength in both countries, especially in remote areas, and lowering of the power system inertia mainly in the UK, which make the power system more susceptible to disturbances. In India in particular, the regional grid in rural areas is already weak with regular power cuts and low SCL that may cause trouble in accommodating the solar deployment foreseen. To this day, the risk for massive unintentional disconnection of solar and other embedded generation remains, as recently seen in the power cut of August 2019 in the UK. Furthermore, the limited services potential by solar plants and poor communication/ visibility render solar generation more of a burden than an asset to the grid operator.

There is a need for the PV systems to evolve into more grid-friendly power stations, providing a wider range of ancillary services and operating in grid-forming mode. The black start function is seen as highly beneficial to the UK power system to minimize restoration costs after a blackout, while islanded operation will be desirable to rural areas in India suffering from regular power cuts. These services are available only in grid-forming mode. This grid-friendly potential can be unlocked by placing battery storage within the solar plant or/and by oversizing the PV system and operating below capacity to keep power reserves. Especially for the solar curtailments, it is time we treated them as capacity under-utilization, rather than just energy loss, and explore the opportunities given the appropriate market framework. Furthermore, the UK should go forward with the TSO/ DSO coordination currently in pilot phases, while India should work towards strengthening the regional grid infrastructure and update the grid codes, balancing grid security and incentives for solar deployment.

VOLTAGE ISSUES

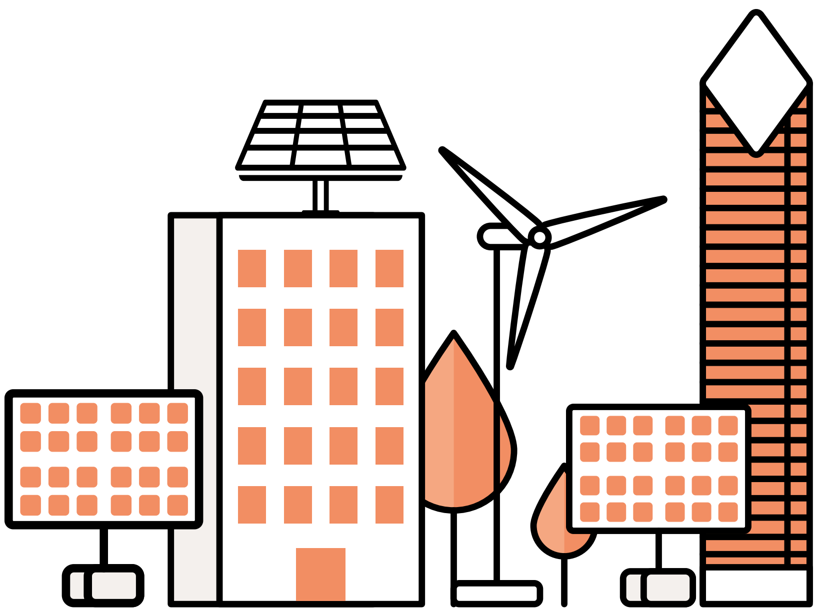
Connecting solar generation to nodes that used to have only load in the distribution network leads to transmission-like power flows and gives rise to voltage rise and reverse power flow phenomena. The UK already experiences a considerable amount of reverse power flows upstream through some substations, while India sees significant voltage rise in some areas. There is a need for improved voltage control in the distribution network to optimize the operation of conventional regulation devices (e.g. OLTCs, voltage regulators, switched capacitors) with the reactive power capacity of solar and other embedded generation. This is important for efficiency and security reasons, as well as to avoid excess wear and tear of the regulation devices due to continuous operation. This optimization should be carried out simultaneously for the transmission and distribution system, especially in the UK where the TSO/DSO coordination concept is already being explored. In India, these actions should be accompanied also by upgrades in the network infrastructure especially in remote rural regions.

PROTECTION CHALLENGES

The protection schemes in distribution networks are expected to face serious challenges in detecting and isolating faults, because of the irregular fault current flows in the network and low fault current contribution by solar and other IBRs. There may be a need to redesign the protection regime of the distribution network, possibly by mimicking mechanisms of microgrid protections. In addition, unintentional tripping of embedded generation at faults remains an issue in the UK, with ongoing efforts to revisit the disconnection settings. In India, the FRT regulations have become more stringent recently, but they should be extended to lower voltage levels and make sure that the existing solar plants comply fully.

POWER QUALITY ISSUES

The power quality is one of the minor issues related to high solar generation at the moment, but it has the potential to cause deterioration in utility assets if it worsens in the future. PV inverters inject harmonic distortion into the network, which although kept low at nominal generation levels, it may dominate when the solar output is reduced. There is nowadays the technology to allow for more stringent harmonic regulation at the kW level. Another power quality issue is the voltage phase unbalance, more commonly in India, which may be adversely affected by the connection of single-phase rooftop solar if not done properly.



REFERENCES

Achlerkar, P. D. *et al.* (2018) 'Distributed Control Framework for Autonomous Seamless Operation of Electronically Interfaced Distributed Generators in AC Microgrid', in *India International Conference on Power Electronics*, IICPE. doi: 10.1109/IICPE.2018.8709527.

Adib, P., Zarnikau, J. and Baldick, R. (2013) 'Texas Electricity Market: Getting Better', in *Evolution of Global Electricity Markets: New Paradigms, New Challenges, New Approaches*. Academic Press, pp. 265–296. doi: 10.1016/B978-0-12-397891-2.00010-9.

Aghahosseini, A. and Breyer, C. (2018) 'Assessment of geological resource potential for compressed air energy storage in global electricity supply', *Energy Conversion and Management*. Elsevier Ltd, 169, pp. 161–173. doi: 10.1016/j.enconman.2018.05.058.

Albadi, M. H. and El-Saadany, E. F. (2008) 'A summary of demand response in electricity markets', *Electric Power Systems Research*. doi: 10.1016/j.epsr.2008.04.002.

Alotto, P., Guarnieri, M. and Moro, F. (2014) 'Redox flow batteries for the storage of renewable energy: A review', *Renewable and Sustainable Energy Reviews*, 29, pp. 325–335. doi: 10.1016/j.rser.2013.08.001.

Anesco Limited (2014) *Industry partners collaborate on solar park battery storage*. Available at: https://anesco.co.uk/industry-partners-collaborate-on-solar-park-battery-storage/.

Von Appen, J. *et al.* (2014) 'Local voltage control strategies for PV storage systems in distribution grids', *IEEE Transactions on Smart Grid*. IEEE, 5(2), pp. 1002–1009. doi: 10.1109/TSG.2013.2291116.

Aroca-Delgado, R. *et al.* (2018) 'Compatibility between crops and solar panels: An overview from shading systems', *Sustainability (Switzerland)*. doi: 10.3390/su10030743.

Ashton, P. M. *et al.* (2012) 'Prospective Wide Area Monitoring of the Great Britain Transmission System using Phasor Measurement Units', in *IEEE Power and Energy Society General Meeting*. doi: 10.1109/PESGM.2012.6345306.

Balaguer, I. J. *et al.* (2008) 'Survey of photovoltaic power systems islanding detection methods', in *IECON Proceedings (Industrial Electronics Conference)*. doi: 10.1109/IECON.2008.4758306.

Barker, P. P. and De Mello, R. W. (2000) 'Determining the impact of distributed generation on power systems: Part 1 - Radial distribution systems', in *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*. Institute of Electrical and Electronics Engineers Inc., pp. 1645–1656. doi: 10.1109/pess.2000.868775.

Barton, J. *et al.* (2017) 'A Domestic Demand Model for India', in Avni, T. C. A. (ed.) *6th International Conference on Advances in Energy Research* (ICAER) 2017. Mumbai: Springer, p. 12.

Barton, J. P. (2018) CREST *Demand Model, Loughborough University figshare database*. Available at: https://figshare.com/s/6a1dc7f4b7fe851f1165.

Batzelis, E. *et al.* (2019) 'A state-space dynamic model for photovoltaic systems with full ancillary services support', *IEEE Transactions on Sustainable Energy*, 10(3), pp. 1399–1409. doi: 10.1109/TSTE.2018.2880082.

Batzelis, E. I., Kampitsis, G. E. and Papathanassiou, S. A. (2017) 'Power reserves control for PV systems with real-time MPP estimation via curve fitting', *IEEE Transactions on Sustainable Energy*, 8(3), pp. 1269–1280. doi: 10.1109/TSTE.2017.2674693.

Batzelis, E. I., Papathanassiou, S. and Pal, B. C. (2018) 'PV system control to provide active power reserves under partial shading conditions', *IEEE Transactions on Power Electronics*, 31(11), pp. 9163–9175. doi: 10.1109/TPEL.2018.2823426.

BEIS (2020) *Digest of UK Energy Statistics (DUKES): electricity*. Available at: https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes.

BEIS (2021) *Solar Photovoltaics Deployment in the UK*. Available at: https://www.gov.uk/government/statistics/solar-photovoltaics-deployment.

Benato, R. *et al.* (2015) 'Sodium nickel chloride battery technology for large-scale stationary storage in the high voltage network', *Journal of Power Sources*. doi: 10.1016/j.jpowsour.2015.05.037.

Bhagavathy, S. et al. (2019) 'Performance of UK Distribution Networks with single-phase PV systems under fault', *International Journal of Electrical Power and Energy Systems*. Elsevier Ltd, 113, pp. 713–725. doi: 10.1016/j.ijepes.2019.05.077.

Birkl, C. R. *et al.* (2017) 'Degradation diagnostics for lithium ion cells', *Journal of Power Sources*. Elsevier B.V., 341, pp. 373–386. doi: 10.1016/j.jpowsour.2016.12.011.

Borghetti, A. (2013) 'Using mixed integer programming for the volt/var optimization in distribution feeders', *Electric Power Systems Research*. Elsevier, 98, pp. 39–50. doi: 10.1016/j.epsr.2013.01.003.

Brancucci Martinez-Anido, C. *et al.* (2016) 'The value of day-ahead solar power forecasting improvement', *Solar Energy*. Elsevier Ltd, 129, pp. 192–203. doi: 10.1016/j.solener.2016.01.049.

Bridge to India (2020) *India Solar Rooftop Map | June 2020*. Available at: https://bridgetoindia.com/report/india-solar-rooftop-map-june-2020/ (Accessed: 16 November 2020).

Bryan Palmintier *et al.* (2016) *Emerging Issues and Challenges in Integrating Solar with the Distribution System*. NREL/TP-5D00-65331. Available at: https://www.nrel.gov/docs/fy16osti/65331.pdf.

Buckley, T. (2019) *How India is set to become a leader in Pumped Hydro Storage*, ET EnergyWorld. Available at: https://energy.economictimes.indiatimes.com/energy-speak/how-india-is-set-to-become-a-leader-in-pumped-hydro-storage/3484 (Accessed: 23 July 2020).

Budt, M. *et al*. (2016) 'A review on compressed air energy storage: Basic principles, past milestones and recent developments', *Applied Energy*. Elsevier, 170, pp. 250–268. doi: 10.1016/j.apenergy.2016.02.108.

CAISO (2017) *Impacts of Renewable Energy on Grid Operation*s. California Independent System Operator. Available at: https://www.caiso.com/documents/curtailmentfastfacts.pdf.

Central Electricity Authority (2019) *Technical standards for connectivity to the grid (amendment) regulations*. Ministry of Power, Government of India. Available at: http://www.cea.nic.in/reports/others/god/gm/notified_regulations.pdf.

Central Electricity Authority (2020) *All India Installed Capacity (In MW) of Power Stations*. Ministry of Power, Government of India. Available at: https://www.cea.nic.in/reports/monthly/installedcapacity/2020/installed_capacity-10.pdf (Accessed: 16 November 2020).

CERC (2014) *Central Electricity Regulatory Commission Petition*. Petition No. 420/MP/2014. Available at: http://www.cercind.gov.in/2016/orders/420_mp_2014.pdf.

CERC (2017a) *Report of Expert Group to review and suggest measures for bringing power system operation closer to National Reference Frequency* (Volume-I). New Delhi. Available at: http://www.cercind.gov.in/2018/Reports/50 Hz_Committee1.pdf.

CERC (2017b) *Review of the Principles of Deviation Settlement Mechanism (DSM), Including Linkage with Frequency, In light of Emerging Markets*. New Delhi. Available at: http://www.cercind.gov.in/2018/Reports/ASB.pdf.

CERC (2018) *Discussion Paper on Re-designing Ancillary Services Mechanism in India*. New Delhi. Available at: http://www.cercind.gov.in/2018/discussion_paper/RAS/3. FICCI Comments on Discussion Paper on Re-Designing Ancillary Services.pdf.

Chandel, S. S., Nagaraju Naik, M. and Chandel, R. (2015) 'Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies', *Renewable and Sustainable Energy Reviews*. doi: 10.1016/j.rser.2015.04.083.

Chowdhury, A. A. and Koval, D. O. (2000) '*Development of transmission system reliability performance benchmarks*', IEEE Transactions on Industry Applications. doi: 10.1109/28.845068.

CIGRE/CIRED (2018) *Modelling of inverter-based generation for power system dynamic studies*. The CIGRE/CIRED Joint Working Group C4/C6.35. Available at: https://e-cigre.org/publication/727-modelling-of-inverter-based-generation-for-power-system-dynamic-studies (Accessed: 27 May 2020).

Coffele, F., Booth, C. and Dyśko, A. (2015) 'An Adaptive Overcurrent Protection Scheme for Distribution Networks', *IEEE Transactions on Power Delivery*, 30(2), pp. 561–568. doi: 10.1109/TPWRD.2013.2294879.

Cole, I. *et al*. (2018) 'Impact Analysis of Irradiance Dataset Selection on Photovoltaic System Energy Yield Modelling', in 1st *International Conference on Large-Scale Grid Integration of Renewable Energy in India*. Delhi.

Crawford, A. J. *et al*. (2018) 'Lifecycle comparison of selected Li-ion battery chemistries under grid and electric vehicle duty cycle combinations', *Journal of Power Sources*. Elsevier B.V., 380, pp. 185–193. doi: 10.1016/j.jpowsour.2018.01.080.

Cunha, alvaro *et al*. (2015) 'Vanadium redox flow batteries: A technology review', *International Journal of Energy Research*, 39(7), pp. 889–918. doi: 10.1002/er.3260.

Dall'Anese, E. *et al*. (2014) 'Decentralized optimal dispatch of photovoltaic inverters in residential distribution systems', *IEEE Transactions on Energy Conversion*, 29(4), pp. 957–967. doi: 10.1109/TEC.2014.2357997.

Dall'Anese, E., Dhople, S. V. and Giannakis, G. B. (2014) 'Optimal dispatch of photovoltaic inverters in residential distribution systems', *IEEE Transactions on Sustainable Energy*, 5(2), pp. 487–497. doi: 10.1109/TSTE.2013.2292828.

Denholm, P., Clark, K. and O'Connell, M. (2016) *Emerging Issues and Challenges in Integrating High Levels of Solar into the Electrical Generation and Transmission System*. NREL/TP-6A20-65800. Available at: https://www.nrel.gov/docs/fy16osti/65800.pdf.

Denholm P. *et al*. (2015) *Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart*. NREL/TP-6A20-65023. Available at: https://www.nrel.gov/docs/fy16osti/65023.pdf.

Dewadasa, M. *et al*. (2009) 'Control and protection of a microgrid with converter interfaced micro sources', in *2009 International Conference on Power Systems*, ICPS '09. doi: 10.1109/ICPWS.2009.5442654.

Dewadasa, M., Ghosh, A. and Ledwich, G. (2011) 'Protection of microgrids using differential relays', in *2011 21st Australasian Universities Power Engineering Conference*, AUPEC 2011.

Diagne, M. *et al*. (2013) 'Review of solar irradiance forecasting methods and a proposition for small-scale insular grids', *Renewable and Sustainable Energy Reviews*, 27, pp. 65–76. doi: 10.1016/j.rser.2013.06.042.

Dietmannsberger, M. and Schulz, D. (2016) 'Compatibility of fault-ride-through capability and anti-islanding-detection in inverters connected to low voltage distribution grids', in *IECON Proceedings (Industrial Electronics Conference)*. doi: 10.1109/IECON.2016.7793389.

Dinesh, H. and Pearce, J. M. (2016) 'The potential of agrivoltaic systems', *Renewable and Sustainable Energy Reviews*. doi: 10.1016/j.rser.2015.10.024.

Distribution Code Review Panel (2020) *THE DISTRIBUTION CODE OF LICENSED DISTRIBUTION NETWORK OPERATORS OF GREAT BRITAIN*.

Dupraz, C. *et al.* (2011) 'Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes', *Renewable Energy*. doi: 10.1016/j.renene.2011.03.005.

Dutta, G. and Mitra, K. (2017) 'A literature review on dynamic pricing of electricity', *Journal of the Operational Research Society*. doi: 10.1057/s41274-016-0149-4.

Dutta, S. *et al.* (2018) 'Shifting of research trends in islanding detection method - a comprehensive survey', *Protection and Control of Modern Power Systems*. doi: 10.1186/s41601-017-0075-8.

Dyśko, A. *et al.* (2018) 'Practical risk assessment of the relaxation of LOM protection settings in NIE Networks' distribution system', *The Journal of Engineering*. doi: 10.1049/joe.2018.0203.

Dyśko, A., Tzelepis, D. and Booth, C. (2016) *Assessment of Increased Risks Imposed by a Relaxation of Loss-Of-Mains Protection Settings Applied to Generation Connected to the Electricity Network in Northern Ireland (WP1 and WP2)*. Glasgow.

Dyśko, A., Tzelepis, D. and Booth, C. (2017) Assessment of Risks Resulting from the Adjustment of Vector Shift (VS) *Based Loss of Mains Protection Settings*. Glasgow.

E3C (2020) *GB power system disruption on 9 August 2019*. Energy Emergencies Executive Committee (E3C): Final report, Department for Business, Energy and Industrial Strategy. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/855767/e3c-gb-power-disruption-9-august-2019-final-report.pdf.

Eirgrid and Soni (2012) *RoCoF Modification Proposal– TSOs' Recommendations*.

Ekren, O. and Ekren, B. Y. (2010) 'Size optimization of a PV/wind hybrid energy conversion system with battery storage using simulated annealing', *Applied energy*. Elsevier, 87(2), pp. 592–598. doi: 10.1016/j.apenergy.2009.05.022.

ENA (2019) *Engineering Recommendation G98 Issue 1 Amendment 4 June 2019*. United Kingdom.

ENA (2020a) *Accelerated Loss of Mains Change Programme, Energy Networks Association*.

ENA (2020b) *Engineering Recommendation G99 Issue 1 – Amendment 6 09 March 2020*.

Engelkemier, S. *et al.* (2019) 'Feasibility of pairing a low-cost positive displacement pump with low-energy pressure compensating drip irrigation emitters for smallholder farms in Africa', in *Proceedings of the ASME Design Engineering Technical Conference*. doi: 10.1115/DETC2019-98128.

ENTSO-E (2013) ENTSO-E *network code for requirements for grid connection applicable to all generators*. ENTSO-E. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0631&from=EN.

ENTSO-E (2016) *Fault current contribution from PPMS & HVDC* -. ENTSO-E guidance document for national implementation for network codes on grid connection. Available at: https://consultations.entsoe.eu/system-development/entso-e-connection-codes-implementation-guidance-d-3/user_uploads/igd-fault-current-contribution.pdf.

EU Commission (2020) *Recovery plan for Europe*. Available at: https://ec.europa.eu/info/strategy/recovery-plan-europe_en.

EURAMET (2018) *Evaluation report on the problem of ROCOF measurement in the context of actual use cases and the "wish list" of accuracy and latency from an end-user point of view*. Available at: http://www.rocofmetrology.eu/wp-content/uploads/sites/21/2018/10/ROCOF-Uses-Cases-and-Test-Conditions-V1.pdf (Accessed: 15 October 2019).

Faiman, D. (2008) 'Assessing the outdoor operating temperature of photovoltaic modules', *Progress in Photovoltaics: Research and Applications*. doi: 10.1002/pip.813.

Few, S. *et al.* (2016) *Energy Storage for Balancing Intermittent Renewables: Outlook for a Range of Technologies up to 2030, Informed by Expert Elicitation and Historical Data*. Available at: https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/website/UKES2015_Poster_SFew.pdf.

G. Lammert (2019) *Modelling, Control and Stability Analysis of Photovoltaic Systems in Power System Dynamic Studies*. University of Kassel, Germany. Available at: https://www.uni-kassel.de/upress/online/OpenAccess/978-3-7376-0716-2.OpenAccess.pdf.

Gaebler, J. (2017) *Analysis of Indian Electricity Distribution Systems for the Integration of High Shares of Rooftop PV*. Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ). Available at: http://www.comsolar.in/fileadmin/user_upload/I-RE_-_Grid_Study/GIZ_Mainreport.pdf.

Gammon, R. (2007) 'The Role of Hydrogen & Fuel Cells in Future Energy Markets', in *Fuel Cell Early Markets 2007*. Brussels, Belgium: Bryte Energy Ltd.

Garvey, S. D. *et al.* (2015) 'On generation-integrated energy storage', *Energy Policy*. doi: 10.1016/j.enpol.2015.08.001.

Gaur, K. *et al.* (2017) 'Analysing the electricity demand pattern', in 2016 *National Power Systems Conference*, NPSC 2016. doi: 10.1109/NPSC.2016.7858969.

Gevorgian, V. (2019) *Highly accurate method for real-time active power reserve estimation for utility-scale Photovoltaic power plants*. NREL/TP-5D00-73207. Available at: https://www.nrel.gov/docs/fy19osti/73207.pdf.

Gils, H. C. (2014) 'Assessment of the theoretical demand response potential in Europe', *Energy*. doi: 10.1016/j.energy.2014.02.019.

González, R. M. *et al.* (2018) 'Demand response of medical freezers in a Business Park Microgrid', in *SMARTGREENS 2018 - Proceedings of the 7th International Conference on Smart Cities and Green ICT Systems*. doi: 10.5220/0006801001200129.

Grundy, A. (2020) 'Solar smashes peak generation records as it soars to 9.68GW', *Solar Power Portal*, April. Available at: https://www.solarpowerportal.co.uk/news/solar_smashes_peak_generation_records_as_it_soars_to_9.68gw.

GTG-RISE (2020) *Flexible Power Generation*. Available at: https://www.gtg-india.com/flexible-power-generation/.

H. Qasem (2013) 'Effect of accumulated dust on the performance of photovoltaic modules', *PhD thesis, Loughborough University Institutional Repository*. Available at: https://dspace.lboro.ac.uk/dspace-jspui/bitstream/2134/11735/4/Thesis-2 .

H. Urdal *et al.* (2016) *Future System Challenges in Europe - Contributions to Solutions from Connection Network Codes*. 2016 CIGRÉ USNC International Colloquium.

Harish, S. M., Morgan, G. M. and Subrahmanian, E. (2014) 'When does unreliable grid supply become unacceptable policy? Costs of power supply and outages in rural India', *Energy Policy*. doi: 10.1016/j.enpol.2014.01.037.

He, W. *et al.* (2020) 'Field demonstration of a cost-optimized solar powered electrodialysis reversal desalination system in rural India', *Desalination*. Elsevier, 476. doi: 10.1016/j.desal.2019.114217.

He, W. and Wang, J. (2018) 'Optimal selection of air expansion machine in Compressed Air Energy Storage: A review', *Renewable and Sustainable Energy Reviews*, 87. doi: 10.1016/j.rser.2018.01.013.

Hesse, H. *et al.* (2017) 'Lithium-Ion Battery Storage for the Grid—A Review of Stationary Battery Storage System Design Tailored for Applications in Modern Power Grids', *Energies*. MDPI AG, 10(12), p. 2107. doi: 10.3390/en10122107.

Hirst, D. (2020) *Electric vehicles and infrastructure*. House of Commons Library, UK. Available at: https://researchbriefings.files.parliament.uk/documents/CBP-7480/CBP-7480.pdf.

HM Government (2020) *The Ten Point Plan for a Green Industrial Revolution*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf.

Hobbs, I. K. (2009) Evaluation and Implementation of Anti-Islanding Methods for Converter-Fed Distributed Generation. University of Stellenbosch.

Honda (2020) *HONDA TO INTRODUCE "E:PROGRESS" FIRST COMMERCIAL ENERGY MANAGEMENT SERVICE WITH FLEXIBLE TARIFF FOR EV OWNERS*. Available at: https://hondanews.eu/gb/en/cars/media/pressreleases/201803/honda-to-introduce-eprogress-first-commercial-energy-management-service-with-flexible-tariff-for-ev.

Hooshyar, A. and Iravani, R. (2017) 'Microgrid Protection', in Proceedings of the IEEE, pp. 1332–1353. doi: 10.1109/JPROC.2017.2669342.

Hunt, J. D., de Freitas, M. A. V. and Junior, A. O. P. (2017) 'A review of seasonal pumped-storage combined with dams in cascade in Brazil', *Renewable and Sustainable Energy Reviews*. Elsevier, 70, pp. 385–398. doi: 10.1016/j.rser.2016.11.255.

Hussain, A. and Torres, M. P. (2020) *Time to pick up pace of dynamic electricity pricing*. Available at: http://www.frontier-economics.com/uk/en/news-and-articles/articles/article-i6106-time-to-pick-up-pace-of-dynamic-electricity-pricing/.

Ibrahim, H., Ilinca, A. and Perron, J. (2008) 'Energy storage systems—Characteristics and comparisons', *Renewable and sustainable energy reviews*. Elsevier, 12(5), pp. 1221–1250. doi: 10.1016/j.rser.2007.01.023.

IEA (2020) *Jawaharlal Nehru National Solar Mission (Phase I, II and III) – Policies*. Available at: https://www.iea.org/policies/4916-jawaharlal-nehru-national-solar-mission-phase-i-ii-and-iii.

IEEE/NERC (2018) *Impact of Inverter Based Generation on Bulk Power System Dynamics and Short-Circuit Performance*. PES-TR68. Available at: https://resourcecenter.ieee-pes.org/technical-publications/technical-reports/PES_TR_7-18_0068.html.

IEEE (2003) *IEEE Standard for interconnecting distributed resources with electric power systems*. IEEE 1547-2003. Available at: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1225051.

IEEE (2018) *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*. IEEE 1547-2018. Available at: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8332112.

IEEE (2019) *Microgrid Protection systems*. PES-TR71. Available at: https://resourcecenter.ieee-pes.org/technical-publications/technical-reports/PES_TP_TR71_PSRC_microgrid_082019.html.

IEEFA Australasia (2019) *Pumped Hydro Storage in India*. Available at: https://ieefa.org/wp-content/uploads/2019/03/IEEFA-India_Pumped-Hydro-Storage_Mar-2019.pdf.

India Smart Grid Forum (2019) *Energy storage system roadmap for India: 2019-2032*. Available at: http://www.indiaenvironmentportal.org.in/content/466097/energy-storage-system-roadmap-for-india-2019-2032/.

IRENA (2019) *ELECTRIC-VEHICLE SMART CHARGING INNOVATION LANDSCAPE BRIEF*. Available at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_EV_Smart_Charging_2019.pdf?

IRENA (2020a) *Country Rankings: Solar PV installed capacity*. Available at: https://www.irena.org/Statistics/View-Data-by-Topic/Capacity-and-Generation/Country-Rankings.

IRENA (2020b) *Renewable power generation costs in 2019*. IRENA. Available at: https://irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019.

Jabr, R. A. (2018) 'Linear Decision Rules for Control of Reactive Power by Distributed Photovoltaic Generators', *IEEE Transactions on Power Systems*, 33(2), pp. 2165–2174. doi: 10.1109/TPWRS.2017.2734694.

Jabr, R. A. (2019) 'Robust volt/var control with photovoltaics', *IEEE Transactions on Power Systems*. Institute of Electrical and Electronics Engineers Inc., 34(3), pp. 2401–2408. doi: 10.1109/TPWRS.2018.2890767.

Jaradat, M. A. *et al.* (2016) 'A fully portable robot system for cleaning solar panels', in ISMA 2015 - *10th International Symposium on Mechatronics and its Applications*. doi: 10.1109/ISMA.2015.7373479.

Jia, K. *et al.* (2014) 'Advanced islanding detection utilized in distribution systems with DFIG', *International Journal of Electrical Power and Energy Systems*. doi: 10.1016/j.ijepes.2014.05.003.

Joshi, K. A. and Pindoriya, N. M. (2013) 'Risk assessment of unintentional islanding in a spot network with roof-top photovoltaic system - A case study in India', in *2013 IEEE Innovative Smart Grid Technologies - Asia, ISGT Asia 2013*. doi: 10.1109/ISGT-Asia.2013.6698722.

Kamaludeen, M. *et al.* (1991) 'Sodium Sulphur Battery', *Bulletin of Electrochemistry*, 7(11), pp. 531–532.

Kar, S., Samantaray, S. R. and Zadeh, M. D. (2017) 'Data-Mining Model Based Intelligent Differential Microgrid Protection Scheme', *IEEE Systems Journal*, 11(2), pp. 1161–1169. doi: 10.1109/JSYST.2014.2380432.

Karthikeyan, N. *et al.* (2009) 'Power quality survey in a technological institute', in *2009 International Conference on Power Systems*, ICPS '09. doi: 10.1109/ICPWS.2009.5442703.

Kekatos, V. *et al.* (2015) 'Stochastic Reactive Power Management in Microgrids with Renewables', *IEEE Transactions on Power Systems*, 30(6), pp. 3386–3395. doi: 10.1109/TPWRS.2014.2369452.

Kosi, F. F. *et al.* (2016) 'Cold thermal energy storage', in *Renewable and Alternative Energy: Concepts, Methodologies*, Tools, and Applications. doi: 10.4018/978-1-5225-1671-2.ch004.

Kumar, K. V. N. P. *et al.* (2018) 'Expanding the Ambit of Ancillary Services in India - Implementation and Challenges', in *2018 20th National Power Systems Conference, NPSC 2018*. doi: 10.1109/NPSC.2018.8771784.

Laaksonen, H., Ishchenko, D. and Oudalov, A. (2014) 'Adaptive protection and microgrid control design for Hailuoto Island', *IEEE Transactions on Smart Grid*, 5(3), pp. 1486–1493. doi: 10.1109/TSG.2013.2287672.

Lakshmanan, V. *et al.* (2016) 'Provision of secondary frequency control via demand response activation on thermostatically controlled loads: Solutions and experiences from Denmark', *Applied Energy*. doi: 10.1016/j.apenergy.2016.04.054.

Lane, S. *et al.* (2017) *Increasing Food Production in Drylands Using Agrivoltaics*. Available at: https://digitalcommons.calpoly.edu/star/455.

Laverty, D. M., Best, R. J. and Morrow, D. J. (2015) 'Loss-of-mains protection system by application of phasor measurement unit technology with experimentally assessed threshold settings', *IET Generation, Transmission and Distribution*. doi: 10.1049/iet-gtd.2014.0106.

Li, C. and Reinmuller, R. (2018) 'Fault Responses of Inverter-based Renewable Generation: On Fault Ride-Through and Momentary Cessation', in *IEEE Power and Energy Society General Meeting*. doi: 10.1109/PESGM.2018.8585978.

Li, R. *et al.* (2016) 'A systematic evaluation of network protection responses in future converter-dominated power systems', in *IET Conference Publications*. Institution of Engineering and Technology. doi: 10.1049/cp.2016.0063.

Li, X., Hui, D. and Lai, X. (2013) 'Battery energy storage station (BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations', *IEEE transactions on sustainable energy*. IEEE, 4(2), pp. 464–473. doi: 10.1109/TSTE.2013.2247428.

Lipari, G. *et al.* (2018) 'A real-time commercial aggregator for distributed energy resources flexibility management', *Sustainable Energy, Grids and Networks*. doi: 10.1016/j.segan.2017.07.002.

Liu, N. *et al.* (2015) 'Passive Islanding Detection Approach Based on Tracking the Frequency-Dependent Impedance Change', *IEEE Transactions on Power Delivery*. doi: 10.1109/TPWRD.2015.2418580.

Loix, T., Wijnhoven, T. and Deconinck, G. (2009) 'Protection of microgrids with a high penetration of inverter-coupled energy sources', in *2009 CIGRE/IEEE PES Joint Symposium Integration of Wide-Scale Renewable Resources into the Power Delivery System, CIGRE/PES 2009*.

Loutan, C. *et al*. (2017) *Demonstration of essential reliability services by a 300-MW solar Photovoltaic power plant*. NREL/TP-5D00-67799. Available at: https://www.nrel.gov/docs/fy17osti/67799.pdf.

Lu, N. and Nguyen, T. (2005) 'Grid friendlyTM appliances - load-side solution for congestion management', in *2005/2006 IEEE/PES Transmission and Distribution Conference and Exhibition*. Div. of Energy Sci. & Technol., Pacific Northwest Nat. Lab., Richland, WA USA: IEEE.

Luo, X. *et al*. (2015) 'Overview of current development in electrical energy storage technologies and the application potential in power system operation', *Applied Energy*, 137, pp. 511–536. doi: 10.1016/j.apenergy.2014.09.081.

Lux research Frankel, D., Laslau, C. and Torbey, H. (2016) *How to make money in stationary energy storage: Establishing threshold values for emerging storage applications*. Available at: https://members.luxresearchinc.com/research/report/19465.

Ma, O. *et al*. (2013) 'Demand response for ancillary services', *IEEE Transactions on Smart Grid*. doi: 10.1109/TSG.2013.2258049.

Mahat, P. *et al*. (2011) 'A simple adaptive overcurrent protection of distribution systems with distributed generation', *IEEE Transactions on Smart Grid*, 2(3), pp. 428–437. doi: 10.1109/TSG.2011.2149550.

Mahat, P., Chen, Z. and Bak-Jensen, B. (2008) 'Review of islanding detection methods for distributed generation', in *3rd International Conference on Deregulation and Restructuring and Power Technologies, DRPT 2008*. doi: 10.1109/DRPT.2008.4523877.

Malakondaiah, M. *et al*. (2019) 'Second harmonic impedance drift-based islanding detection method', *IET Generation, Transmission and Distribution*. doi: 10.1049/iet-gtd.2018.6838.

Masters, C. L. (2002) 'Voltage rise the big issue when connecting embedded generation to long 11 kv overhead lines', *Power Engineering Journal*. Institution of Engineering and Technology, 16(1), pp. 5–12. doi: 10.1049/pe:20020101.

Menke, R. *et al*. (2016) 'Demonstrating demand response from water distribution system through pump scheduling', *Applied Energy*. doi: 10.1016/j.apenergy.2016.02.136.

Milano, F. *et al*. (2018) 'Foundations and challenges of low-inertia systems', in *20th Power Systems Computation Conference*, PSCC 2018. doi: 10.23919/PSCC.2018.8450880.

Mohamad, A. M. I. and Mohamed, Y. A. R. I. (2018) 'Impedance-Based Analysis and Stabilization of Active DC Distribution Systems with Positive Feedback Islanding Detection Schemes', *IEEE Transactions on Power Electronics*. doi: 10.1109/TPEL.2018.2790945.

Mondal, A. K. and Bansal, K. (2015) 'A brief history and future aspects in automatic cleaning systems for solar photovoltaic panels', *Advanced Robotics*. doi: 10.1080/01691864.2014.996602.

Mouli-Castillo, J. *et al*. (2019) 'Inter-seasonal compressed-air energy storage using saline aquifers', *Nature Energy*. Nature Publishing Group, 4(2), pp. 131–139. doi: 10.1038/s41560-018-0311-0.

Müller, J. *et al*. (2017) 'Towards building solar in India - A combined mapping and monitoring approach for creating a new solar atlas', *Energy for Sustainable Development*. Elsevier B.V., 40, pp. 31–40. doi: 10.1016/j.esd.2017.05.004.

Muñoz-García, M. A. *et al*. (2012) 'Characterization of thin film PV modules under standard test conditions: Results of indoor and outdoor measurements and the effects of sunlight exposure', *Solar Energy*. doi: 10.1016/j.solener.2012.07.015.

Murugesan, S. and Murali, V. (2020) 'Disturbance Injection Based Decentralized Identification of Accidental Islanding', *IEEE Transactions on Industrial Electronics*. doi: 10.1109/TIE.2019.2917361.

Muzathik, A. M. (2014) 'Photovoltaic Modules Operating Temperature Estimation Using a Simple Correlation', *International Journal of Energy engineering*.

National Grid (2017) *DC0079 Frequency Changes during Large Disturbances and their Impact on the Total System*.

National Grid UK (2016) *System Operability Framework 2016*. Available at: https://www.nationalgrid.com/sites/default/files/documents/8589937803-SOF 2016 - Full Interactive Document.pdf.

National Grid UK (2018a) *Future Energy Scenarios*. Available at: https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2019-documents.

National Grid UK (2018b) *System Operability Framework: Impact of declining short circuit levels*. Available at: https://www.nationalgrideso.com/document/135561/download.

National Grid UK (2019a) *Black Start from Non-Traditional Generation Technologies*. Available at: https://www.nationalgrideso.com/future-energy/projects/distributed-restart.

National Grid UK (2019b) *Operability Strategy Report 2019*. Available at: https://www.nationalgrideso.com/document/146506/download.

National Grid UK (2019c) *Technical Report on the events of 9 August 2019*. Available at: https://www.nationalgrideso.com/document/152346/download.

National Grid UK (2019d) *The Enhanced Frequency Control Capability (EFCC) project closing down report*. Available at: https://www.nationalgrideso.com/document/144566/download.

National Grid UK (2020a) *Balancing Services*. Available at: https://www.nationalgrideso.com/industry-information/balancing-services.

National Grid UK (2020b) *Power Potential project*. Joint project between National Grid and UKPN. Available at: https://www.nationalgrideso.com/future-energy/innovation/projects/power-potential.

Natural England (2010) *Agricultural Land Classification Map East Midlands Region (ALC005)*. Available at: http://publications.naturalengland.org.uk/publication/143027

Ndiaye, A. *et al.* (2014) 'Degradation evaluation of crystalline-silicon photovoltaic modules after a few operation years in a tropical environment', *Solar Energy*. doi: 10.1016/j.solener.2014.02.006.

Nduka, O. S., Yu, Y., *et al.* (2020) 'A Robust Augmented Nodal Analysis Approach to Distribution Network Solution', *IEEE Transactions on Smart Grid*. Institute of Electrical and Electronics Engineers Inc., 11(3), pp. 2140–2150. doi: 10.1109/TSG.2019.2948282.

Nduka, O. S., Kunjumuhammed, L. P., *et al.* (2020) 'Field Trial of Coordinated Control of PV and Energy Storage Units and Analysis of Power Quality Measurements', *IEEE Access*. Institute of Electrical and Electronics Engineers Inc., 8, pp. 1962–1974. doi: 10.1109/ACCESS.2019.2961134.

Nduka, O. S. and Pal, B. C. (2017) 'Harmonic Domain Modeling of PV System for the Assessment of Grid Integration Impact', *IEEE Transactions on Sustainable Energy*. Institute of Electrical and Electronics Engineers Inc., 8(3), pp. 1154–1165. doi: 10.1109/TSTE.2016.2640658.

NERC (2017) *1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report*. Available at: https://www.nerc.com/pa/rrm/ea/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_/1200_MW_Fault_Induced_Solar_Photovoltaic_Resource_Interruption_Final.pdf.

Nguyen, D. T., Negnevitsky, M. and De Groot, M. (2012) 'Walrasian market clearing for demand response exchange', *IEEE Transactions on Power Systems*. doi: 10.1109/TPWRS.2011.2161497.

Nikolaidis, A. I. *et al.* (2016) *Reliable integration of a concentrating solar power plant in a small isolated system through an appropriately sized battery energy storage system, IET Renewable Power Generation*. IET. doi: 10.1049/iet-rpg.2015.0337.

NITI (2015) *Report of the expert group on 175 GW RE by 2022*. National Institution for Transforming India.

Noor, F., Arumugam, R. and Mohammad Vaziri, Y. (2005) 'Unintentional islanding and comparison of prevention techniques', in *Proceedings of the 37th Annual North American Power Symposium, 2005*. doi: 10.1109/NAPS.2005.1560507.

NREL (2020) *National Solar Radiation Database*. Meteosat, hourly data, 2000-2014. Available at: https://nsrdb.nrel.gov/index.php.

Octopus Energy (2020) *Intorducing Agile Octopus*. Available at: https://octopus.energy/agile/.

Odeh, I., Yohanis, Y. G. and Norton, B. (2006) 'Economic viability of photovoltaic water pumping systems', *Solar Energy*. doi: 10.1016/j.solener.2005.05.008.

Palmer, D. *et al.* (2018) 'Satellite or ground-based measurements for production of site specific hourly irradiance data: Which is most accurate and where?', *Solar Energy*. Elsevier Ltd, 165, pp. 240–255. doi: 10.1016/j.solener.2018.03.029.

Parkes, D. *et al.* (2018) 'Estimating available salt volume for potential CAES development: A case study using the Northwich Halite of the Cheshire Basin', *Journal of Energy Storage*, 18, pp. 50–61. doi: https://doi.org/10.1016/j.est.2018.04.019.

Patsios, C. *et al.* (2016) 'An integrated approach for the analysis and control of grid connected energy storage systems', *Journal of Energy Storage*. Elsevier Ltd, 5, pp. 48–61. doi: 10.1016/j.est.2015.11.011.

Pazos, F. J. *et al.* (2013) 'Failure analysis of inverter based anti-islanding systems in photovoltaic islanding events', in *IET Conference Publications*. doi: 10.1049/cp.2013.0800.

Peng, J. and Lu, L. (2013) 'Investigation on the development potential of rooftop PV system in Hong Kong and its environmental benefits', *Renewable and Sustainable Energy Reviews*. doi: 10.1016/j.rser.2013.06.030.

Pfeifroth, U. *et al.* (2017) *Surface Radiation Data Set - Heliosat (SARAH) - Edition 2, Satellite Application Facility on Climate Monitoring*. doi: 10.5676/EUM_SAF_CM/SARAH/V002.

Priolkar, J. G. (2015) 'Ancillary Services for Power Sector', *Electrical India*, June. Available at: https://www.electricalindia.in/ancillary-services-for-power-sector/.

Pukhraj Singh (2020) *Indian Electricity Grid Code Revision: Suggestions for technical requirements for wind, solar and storage*. Expert Group on Grid Code Review, India. Available at: http://www.cercind.gov.in/2019/expert-group/Stakeholders Presentation/suzlon.pdf.

Purohit, I. and Purohit, P. (2015) 'Inter-comparability of solar radiation databases in Indian context', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, pp. 735–747. doi: 10.1016/j.rser.2015.05.020.

Qaiser Naqvi, S. B., Kumar, S. and Singh, B. (2019) 'A Multifunctional PV-BES-Utility System with Seamless Islanding and Resynchronization Capability', in *Proceedings - 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2019*. doi: 10.1109/EEEIC.2019.8783444.

Quan, Y. Y. and Zhang, L. Z. (2017) 'Experimental investigation of the anti-dust effect of transparent hydrophobic coatings applied for solar cell covering glass', *Solar Energy Materials and Solar Cells*. doi: 10.1016/j.solmat.2016.10.043.

Rajabi, A. *et al.* (2017) 'Aggregation of small loads for demand response programs - Implementation and challenges: A review', in *Conference Proceedings - 2017 17th IEEE International Conference on Environment and Electrical Engineering and 2017 1st IEEE Industrial and Commercial Power Systems Europe, EEEIC / I and CPS Europe 2017*. doi: 10.1109/EEEIC.2017.7977631.

Rajesh, M. *et al.* (2016) 'Power quality analysis on academic and hostel buildings of educational institute - Part i', in *2016 International Conference on Energy Efficient Technologies for Sustainability, ICEETS 2016*. Institute of Electrical and Electronics Engineers Inc., pp. 932–941. doi: 10.1109/ICEETS.2016.7583882.

Ranjan, R. (2020) 'World's Largest Solar Park at Karnataka's Pavagada Is Now Fully Operational', *Mercom India (blog)*, December. Available at: https://mercomindia.com/karnatakas-pavagada-solar-operational/.

Renewable Energy Association (2015) *Energy Storage in the UK An Overview*. London. Available at: https://www.r-e-a.net/wp-content/uploads/2019/10/Energy-Storage-FINAL6.pdf.

Reniers, J. M., Mulder, G. and Howey, D. A. (2019) 'Review and Performance Comparison of Mechanical-Chemical Degradation Models for Lithium-Ion Batteries', *Journal of The Electrochemical Society*. The Electrochemical Society, 166(14), pp. A3189–A3200. doi: 10.1149/2.0281914jes.

Richardson, I., Thomson, M. and Infield, D. (2008) 'A high-resolution domestic building occupancy model for energy demand simulations', *Energy and Buildings*. Elsevier, 40(8), pp. 1560–1566. doi: 10.1016/j.enbuild.2008.02.006.

Ropp, M. *et al.* (2016) 'Effect of grid support functions and VRT/FRT capability on autonomous anti-islanding schemes in photovoltaic converters', in *Conference Record of the IEEE Photovoltaic Specialists Conference*. doi: 10.1109/PVSC.2016.7749942.

Roscoe, A. J. *et al.* (2017) 'The Case for Redefinition of Frequency and ROCOF to Account for AC Power System Phase Steps', in *AMPS 2017 - IEEE International Workshop on Applied Measurements for Power Systems, Proceedings*. Institute of Electrical and Electronics Engineers Inc. doi: 10.1109/AMPS.2017.8078330.

Sahraei, N. *et al.* (2018) 'Adaptive power consumption improves the reliability of solar-powered devices for internet of things', *Applied energy*. Elsevier, 224, pp. 322–329. doi: 10.1016/j.apenergy.2018.04.091.

Sanjay, P. (2019) 'With 2,245 MW of Commissioned Solar Projects, World's Largest Solar Park Is Now at Bhadla', *Mercom India (blog)*, March. Available at: https://mercomindia.com/world-largest-solar-park-bhadla/.

Santra, P. *et al.* (2017) 'Agri-voltaics or solar farming: The concept of integrating solar PV based electricity generation and crop production in a single land use system', *International Journal of Renewable Energy Research*, 7(2), pp. 694–699.

Schittekatte, T. and Meeus, L. (2020) 'Flexibility markets: Q&A with project pioneers', *Utilities Policy*. doi: 10.1016/j.jup.2020.101017.

Schledde, D. *et al.* (2018) *Support to R&D strategy for battery-based energy storage: Technical analysis of ongoing projects (D12)*. European Commission - N° ENER C2/2015-410. Available at: https://ec.europa.eu/energy/sites/ener/files/technology_analysis_-ongoing_projects_on_battery_based_energy_storage.pdf.

Schmidt, O., Gambhir, A., *et al.* (2017) 'Future cost and performance of water electrolysis: An expert elicitation study', *International Journal of Hydrogen Energy*. Elsevier Ltd, 42(52), pp. 30470–30492. doi: 10.1016/j.ijhydene.2017.10.045.

Schmidt, O., Hawkes, A., *et al.* (2017) 'The future cost of electrical energy storage based on experience rates', *Nature Energy*. Springer Nature, 2(8), pp. 1–8. doi: 10.1038/nenergy.2017.110.

Schmidt, O. *et al.* (2019) 'Projecting the Future Levelized Cost of Electricity Storage Technologies', *Joule*. Cell Press, 3(1), pp. 81–100. doi: 10.1016/j.joule.2018.12.008.

Schofield, J. R. (2015) *Dynamic Time-of-Use electricity pricing for residential Demand Response: Design and analysis of the Low Carbon London smart metering trial, Ph.D. Thesis, Imperial College London*. Available at: https://spiral.imperial.ac.uk/bitstream/10044/1/25575/3/Schofield-J-2015-PhD-Thesis.pdf.

Scottish Renewables (2016) *The Benefits of Pumped Storage Hydro to the UK*. Scottish_Renewables_PSH_OPE_SEA_01. Available at: http://www.british-hydro.org/downloads/TypesofHydro/Pumped Storage report.pdf.

Shibata, T. *et al.* (2013) 'Redox flow batteries for the stable supply of renewable energy', *SEI Technical Review*, pp. 14–22.

Shiles, J. *et al.* (2018) 'Microgrid protection: An overview of protection strategies in North American microgrid projects', in *IEEE Power and Energy Society General Meeting*. IEEE Computer Society, pp. 1–5. doi: 10.1109/PESGM.2017.8274519.

Short, J. A., Infield, D. G. and Freris, L. L. (2007) 'Stabilization of grid frequency through dynamic demand control', *IEEE Transactions on Power Systems*. Country of Publication: USA: IEEE, 22(3), pp. 1284–1293. doi: DOI: dx.doi.org/10.1109/TPWRS.2007.901489.

Shukla, R. *et al.* (2017) 'Impact of delayed fault clearance on the load in Indian Power System', in *2016 National Power Systems Conference, NPSC 2016*. Bhubaneswar, India. doi: 10.1109/NPSC.2016.7858902.

Singhvi, S. (2019) *Ancillary services market still at an early stage of development*. Available at: https://bridgetoindia.com/ancillary-services-market-still-at-an-early-stage-of-development/.

Skoplaki, E. and Palyvos, J. A. (2009) 'On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations', *Solar Energy*, 83(5), pp. 614–624. doi: 10.1016/j.solener.2008.10.008.

Skyllas-Kazacos, M. *et al.* (2011) 'Progress in Flow Battery Research and Development', *Journal of The Electrochemical Society*. The Electrochemical Society, 158(8), p. R55. doi: 10.1149/1.3599565.

SmartNet project (2019) *SmartNet project*. EU Horizon project No 691405. Available at: http://smartnet-project.eu/.

Smith, J. *et al.* (2017) 'Power quality aspects of solar power - Results from CIGRE JWG C4/C6.29', in *CIRED - Open Access Proceedings Journal*. Institution of Engineering and Technology, pp. 809–813. doi: 10.1049/oap-cired.2017.0351.

Sobri, S., Koohi-Kamali, S. and Rahim, N. A. (2018) 'Solar photovoltaic generation forecasting methods: A review', *Energy Conversion and Management*. Elsevier Ltd, pp. 459–497. doi: 10.1016/j.enconman.2017.11.019.

Solar Power Europe (2020) *Global Market Outlook for Solar Power / 2020-2024*. Available at: https://www.solarpowereurope.org/global-market-outlook-2020-2024/.

Sortomme, E., Ren, J. and Venkata, S. S. (2013) 'A differential zone protection scheme for microgrids', in *IEEE Power and Energy Society General Meeting*. doi: 10.1109/PESMG.2013.6672113.

Sortomme, E., Venkata, S. S. and Mitra, J. (2010) 'Microgrid protection using communication-assisted digital relays', *IEEE Transactions on Power Delivery*, 25(4), pp. 2789–2796. doi: 10.1109/TPWRD.2009.2035810.

SP Energy Networks (2017) *Accelerating renewable connections: Learning report 2 - The changing nature of the* transmission and distribution boundaries. Available at: https://www.spenergynetworks.co.uk/userfiles/file/SPEN_ARC_Learning_Report_2.pdf.

SRLDC (2020) *System Operation Report, Southern Region 2020-2021*. Available at: https://srldc.in/var/ftp/reports/Monthly/System Operation Report/2020-21/aug-month.pdf.

Steck, M. (2017) *DNV GL launches LVRT testing services in India to support grid stability, DNV GL*. Available at: https://www.dnvgl.com/news/dnv-gl-launches-lvrt-testing-services-in-india-to-support-grid-stability-90391 (Accessed: 27 May 2020).

Stoker, L. (2019) *Subsidy-free solar-plus-storage at UK's 'most technologically advanced' large-scale project*. Available at: https://www.energy-storage.news/news/subsidy-free-solar-plus-storage-at-uks-most-technologically-advanced-large.

Strbac, G. *et al.* (2002) *Integration of operation of embedded generation and distribution networks*. Manchester centre for electrical energy.

Stronberg, J. B. (2019) *What Happens When Communities Say No to Solar and Wind?, Civil Notion*. Available at: https://civilnotionblog.weebly.com/home/what-happens-when-communities-say-no-to-solar-and-wind#.

Su, D., Batzelis, E. and Pal, B. (2019) 'Machine learning algorithms in forecasting of Photovoltaic power generation', in *2019 International Conference on Smart Energy Systems and Technologies (SEST)*. Porto, Portugal: IEEE. doi: 10.1109/SEST.2019.8849106.

Sudworth, J. L. (1984) 'The sodium/sulphur battery', *Journal of Power Sources*. doi: 10.1016/0378-7753(84)80080-4.

Sun, H. *et al.* (2019) 'Review of Challenges and Research Opportunities for Voltage Control in Smart Grids', *IEEE Transactions on Power Systems*. Institute of Electrical and Electronics Engineers Inc., 34(4), pp. 2790–2801. doi: 10.1109/TPWRS.2019.2897948.

Tant, J. *et al.* (2012) 'Multiobjective battery storage to improve PV integration in residential distribution grids', IEEE Transactions on Sustainable Energy. IEEE, 4(1), pp. 182–191. doi: 10.1109/TSTE.2012.2211387.

Tayyebi Ali *et al.* (2018) 'Grid-forming converters - an inevitability, control strategies and challenges in future grids application', in *CIRED Workshop on Microgrids and Local Energy Communities*.

Tongia, R., Harish, S. and Walawalkar, R. (2018) *Integrating Renewable Energy Into India's Grid - Harder Than It Looks*. New Delhi. Available at: https://think-asia.org/handle/11540/9489.

Tuladhar, L. R. and Banerjee, K. (2019) 'Impact of the Penetration of Inverter-Based Systems on Grid Protection', in *2019 Grid of the Future Symposium*.

Tummasit, N., Premrudeepreechacharn, S. and Tantichayakorn, N. (2016) 'Adaptive overcurrent protection considering critical clearing time for a microgrid system', in *Proceedings of the 2015 IEEE Innovative Smart Grid Technologies* - Asia, ISGT ASIA 2015. doi: 10.1109/ISGT-Asia.2015.7387061.

Tzelepis, D., Dyśko, A. and Booth, C. (2016) 'Performance of loss-of-mains detection in multi-generator power islands', in *IET Conference Publications*.

Uddin, K. *et al.* (2017) 'On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system', *Energy*. Elsevier Ltd, 133, pp. 710–722. doi: 10.1016/j.energy.2017.04.116.

UKPN (2015a) *Flexible plug and play: Implementation of active voltage and active power flow management within FPP trial area – SDRC 9.6*. Available at: https://docplayer.net/14074887-Flexible-plug-and-play-implementation-of-active-voltage-and-active-power-flow-management-within-fpp-trial-area-sdrc-9-6.html.

UKPN (2015b) Validation of photovoltaic connection assessment tool - Closedown report. Version 1.1. Available at: https://www.ofgem.gov.uk/ofgem-publications/93938/pvtoolcdrfinal-pdf.

Ul Nazir, F., Pal, B. C. and Jabr, R. A. (2019) 'A Two-Stage Chance Constrained Volt/Var Control Scheme for Active Distribution Networks With Nodal Power Uncertainties', *IEEE Transactions on Power Systems*, 34(1), pp. 314–325. doi: 10.1109/TPWRS.2018.2859759.

US DOE (2020) *DOE OE Global Energy Storage Database*. Available at: https://www.sandia.gov/ess-ssl/global-energy-storage-database-home/.

USAID and Government of India (2017) *Greening the grid: Pathways to integrate 175 gigawatts of renewable energy into India's electric grid*. Available at: https://www.nrel.gov/docs/fy17osti/68530.pdf.

Wai, C. H. *et al.* (2015) 'Cooling devices in demand response: A comparison of control methods', *IEEE Transactions on Smart Grid*. doi: 10.1109/TSG.2014.2358579.

Wald, L. (2016) *Synthesis Wald*. Available at: http://www.soda-pro.com/help/camsradiation- service/validation/synthesis-wald-nov-2016 (Accessed: 6 February 2018).

Wang, W. *et al.* (2013) 'Recent progress in redox flow battery research and development', *Advanced Functional Materials*. doi: 10.1002/adfm.201200694.

Weber, A. Z. *et al.* (2011) 'Redox flow batteries: a review', *Journal of Applied Electrochemistry*, 41(10), pp. 1137–1164. doi: 10.1007/s10800-011-0348-2.

Weitzl, Z. and Varjasi, I. (2010) 'Fault ride-through versus anti-islanding in distributed generation', in *Proceedings of EPE-PEMC 2010 - 14th International Power Electronics and Motion Control Conference*. doi: 10.1109/EPEPEMC.2010.5606652.

Wiginton, L. K., Nguyen, H. T. and Pearce, J. M. (2010) 'Quantifying rooftop solar photovoltaic potential for regional renewable energy policy', *Computers, Environment and Urban Systems*. doi: 10.1016/j.compenvurbsys.2010.01.001.

Womack, G. *et al.* (2019) 'The performance and durability of single-layer sol-gel anti-reflection coatings applied to solar module cover glass', *Surface and Coatings Technology*. doi: 10.1016/j.surfcoat.2018.11.030.

World Energy Council (2019) *Energy Storage Monitor: Latest trends in energy storage*. Available at: https://www.worldenergy.org/assets/downloads/ESM_Final_Report_05-Nov-2019.pdf.

Xiao, X. *et al.* (2006) 'Mapping paddy rice agriculture in South and Southeast Asia using multi-temporal MODIS images', *Remote Sensing of Environment*. Elsevier, 100(1), pp. 95–113. doi: 10.1016/j.rse.2005.10.004.

Xing, Y. *et al.* (2014) 'State of charge estimation of lithium-ion batteries using the open-circuit voltage at various ambient temperatures', *Applied Energy*. Elsevier Ltd, 113, pp. 106–115. doi: 10.1016/j.apenergy.2013.07.008.

Xu, M. *et al.* (2016) 'Positive sequence differential impedance protection for distribution network with IBDGs', in *2016 IEEE International Conference on Power System Technology*, POWERCON 2016. doi: 10.1109/POWERCON.2016.7753871.

Yu, W., Jamasb, T. and Pollitt, M. (2009) 'Does weather explain cost and quality performance? An analysis of UK electricity distribution companies', *Energy Policy*. doi: 10.1016/j.enpol.2009.05.030.

Zavattoni, S. *et al.* (2017) 'CFD modeling and experimental validation of the TES system exploited in the Pollegio AA-CAES prototype', in *SCCER Heat and Electricity Storage – 5° Symposium*. Available at: https://repository.supsi.ch/7878/1/SCCER-5th-symposium-PSI-A1.pdf.

Zhang, W. *et al.* (2013) 'Aggregated modeling and control of air conditioning loads for demand response', *IEEE Transactions on Power Systems*. doi: 10.1109/TPWRS.2013.2266121.

Zhao, B. *et al.* (2015) 'A comprehensive review of Li4Ti5O12-based electrodes for lithium-ion batteries: The latest advancements and future perspectives', *Materials Science and Engineering R: Reports*. Elsevier Ltd, pp. 1–71. doi: 10.1016/j.mser.2015.10.001.

APPENDIX A: FAULT RIDE THROUGH (FRT) OPERATION

A generator that has fault ride through capability can withstand distortions in voltage and frequency and remain connected to the grid, while it may be possible to further support the network with active and reactive power adjustment.

VOLTAGE FRT IN SOLAR PV SYSTEMS

The voltage FRT function dictates that the generator stays synchronized to the grid when the terminal voltage gets out of limits, either above or below. The fundamentals of this mechanism are shown in Figure 37 for a two-stage PV system (dc-dc converter and inverter). Following a variation in the terminal (PCC) voltage, the predominantly effected parameters are the DC bus voltage and the inverter current, thereby affecting the power injected to the grid. At high voltage, the output current will be reduced for the same power intake with no further implications. During a mild low-voltage fault, we will have a proportional current increase within the inverter's current rating alongside a short-term DC bus voltage overshoot. At a severe low-voltage fault, however, the inverter cannot handle the over-the-limit current, which will lead to uncontrollable DC bus voltage excursion and tripping of the system if no additional measures are taken. Common such measures to avoid tripping include: off-MPPT mode and solar curtailment, a DC crowbar circuit to direct the excess energy, or energy storage to absorb and store the power surplus (Shukla *et al.*, 2017).

Whilst staying connected to the grid, the solar system can further support the network by injecting reactive current to sustain the voltage levels. In order to achieve a quick restoration of the system voltage, the network operator needs to inject significant amounts of reactive power during and after the fault; leveraging the reactive power capability of the solar plants is a highly effective and economic solution, over alternatives like sending massive amounts of reactive power from the substation or installing additional reactive power compensation devices within the network.

Injecting reactive current by the PV system is nowadays a straightforward task implemented by the inverter control. A main limitation though is that the total current of the inverter (active and reactive) should not exceed the nominal rating by more than usually 20% to 60% even for short times or the power switches will be irreversibly damaged. That may result in a bottleneck between the solar generation (active power) and grid support (reactive power); common solutions are oversizing of the inverter and/or active power curtailment during the fault. It is worth noting that active power curtailment is not a panacea though, since in resistive networks lowering the active power too much in favour of the reactive power may lead to the opposite effect in the voltage.

FREQUENCY FRT IN SOLAR PV SYSTEMS

A frequency distortion is the result of a power imbalance in the system followed usually by loss of generation or load. It may also result from undesired massive tripping of embedded generation like solar in response to a fault in the network that should have been ridden through, such as in the power cut of August 2019 in the UK or the Blue cut fire in California in 2016. It is imperative therefore for all DERs to withstand frequency distortions so as to avoid domino-like disconnections and wider implications in the system.

An IBR like solar does not have any inherent limitation on the frequency operating range, as machine-based generators do, so theoretically can function in frequencies much higher or lower than 50 Hz. However, the main challenge for solar PV systems operating in grid-following mode is the sensing mechanism that extracts the grid frequency (PLL); the PLL is found to be prone to distorted voltage waveforms during faults and may mistakenly detect frequency change when there is not. While the PLL is still being improved and developed to become invulnerable at these distortions, there is also the alternative of grid-forming control that does not require a PLL during normal operation and features an inherent immunity to frequency disturbances.

While withstanding a frequency fluctuation, the PV system may also assist the network by adjusting its active power towards balancing the power gap in the system, i.e. to provide primary frequency response. At over-frequency events the plant can easily reduce its output, but to upregulate its output at under-frequencies there is a need for power reserves. These aspects are discussed in detail in a previous section.

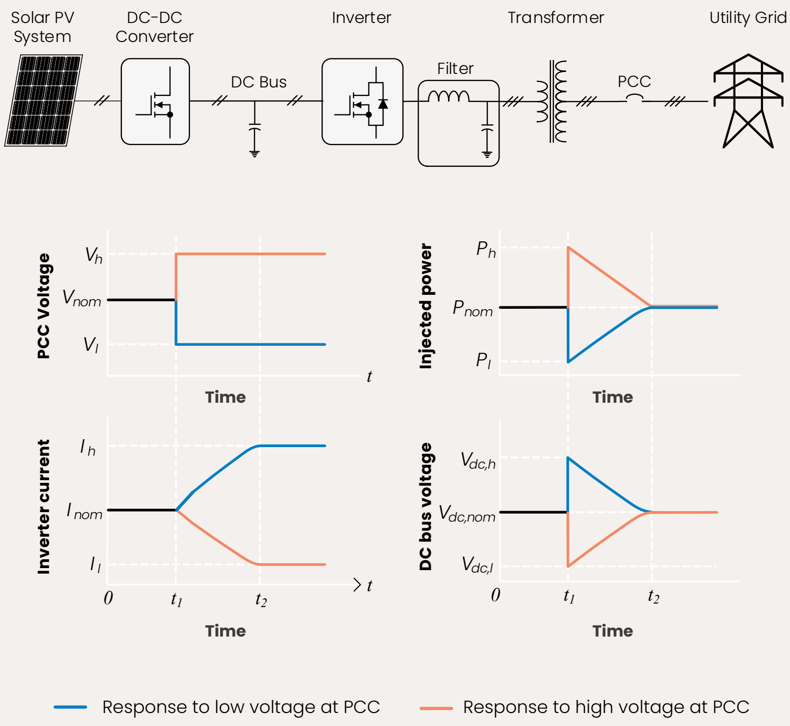


Figure 37. Voltage FRT in a PV system. (a) Power circuit of a grid-connected PV system. (b) PV system's response to terminal voltage fluctuations.

CASE STUDY AT IIT KHARAGPUR CAMPUS NETWORK IN INDIA

To highlight the importance of FRT, a case study on the distribution network of Indian Institute of Technology, Kharagpur (IIT KGP) campus is shown here. The distribution network operates at 11kV, 50Hz with solar generation and load conditions as depicted in Figure 38, while the upstream network beyond the PCC is represented with a Thevenin equivalent circuit of an X/R ratio equal to 5. The response of the test system is simulated to a symmetrical three-phase voltage sag at the PCC for three different operating modes of the solar plant: no voltage FRT function, voltage FRT without reactive power support, and voltage FRT with reactive power support.

Clearly in the no-FRT case the PV system trips, resulting in further lowering of the terminal voltage during the fault and a predominant delayed voltage recovery after the fault. Such disconnection may lead to cascaded implications in the power system and pose stability risks. Here it is assumed that although the PV system trips, the capacitor bank of the grid-side filter remains connected and provides some much-needed reactive power to the network. Much improved voltage profile is apparent when the PV plant has FRT, with expectedly better performance when the PV system injects additional reactive power as well. These results indicate how important staying connected to the grid during disturbances is for solar plants, and how critical the FRT function is to allow higher levels of solar integration.

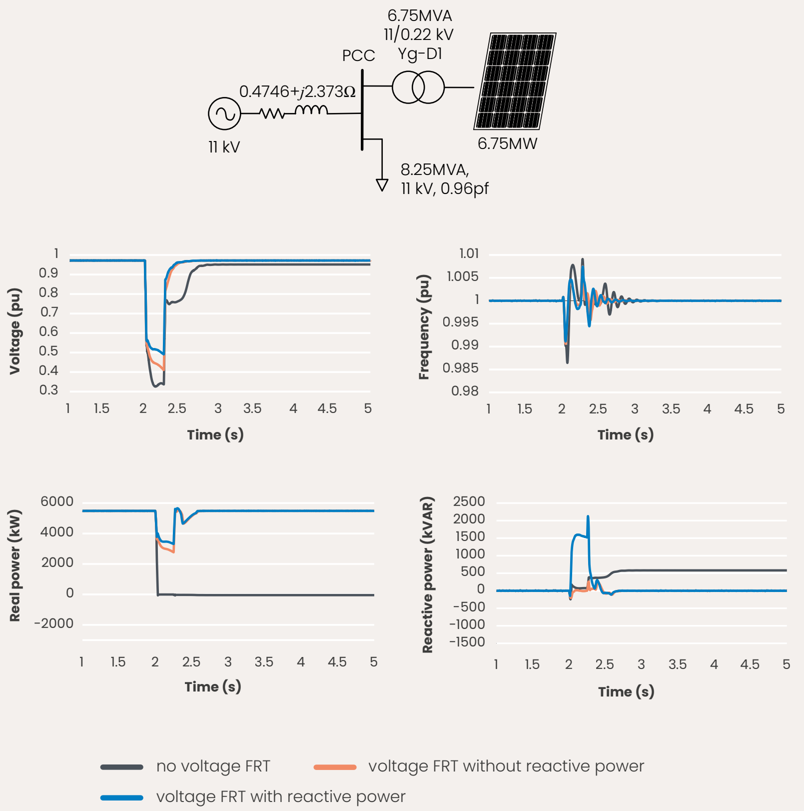


Figure 38. Simulated response of the IIT KGP campus network to low voltage on the upstream network. (a) Thevenin equivalent circuit of the IIT KGP campus distribution network with solar penetration. (b) PCC voltage. (c) System frequency. (d) Real power output from the PV system. (e) Reactive power output from the PV system.

APPENDIX B: ISLANDING

Islanding in the network can be unintentional or intentional. Un-intentional islanding is the scenario in which islanding occurs without the prior knowledge of the utility supply or the power producer. Unintentional islanding events mostly occur due to network and switching actions of loads and generators. Intentional islanding is primarily implemented for safety reasons and system maintenance purposes.

UNINTENTIONAL ISLANDING

There are many local and remote schemes to detect islanding (Noor, Arumugam and Mohammad Vaziri, 2005; Balaguer *et al.*, 2008; Mahat, Chen and Bak-Jensen, 2008; Dutta *et al.*, 2018). Local detection methods may be active, passive or hybrid. Remote anti-islanding (AID) schemes function by detecting changes or differences across a network, for example: the opening of breakers; or the grid phase angle difference between the DG and other locations on the grid using synchrophasors (Laverty, Best and Morrow, 2015). Remote methods require communications between the utility and generators but can virtually eliminate the Non-Detection Zone (NDZ), the conditions under which local generation and demand are so closely balanced prior to the LoM that an islanding event is not detected.

The most common local and passive method of AID is using the rate-of-change of frequency (RoCoF) (Jia *et al.*, 2014). However, RoCoF relays can lead to block tripping. An inter-lock method (Jia *et al.*, 2014) can improve the RoCoF performance by applying a system of impedance estimation, demonstrated though only on rotating generators rather than IBRs. Other local passive AID methods include detection of voltage change, high/low frequency, high/low voltage (Hobbs, 2009), voltage vector shift (Noor, Arumugam and Mohammad Vaziri, 2005) and more sophisticated methods including detection algorithms (Dietmannsberger and Schulz, 2016). One drawback of local passive methods is that the NDZ cannot be entirely eliminated.

Local active AID methods involve injection of some disturbance, for example a small-amplitude second harmonic current signal (Malakondaiah *et al.*, 2019) or an added inductance (Murugesan and Murali, 2020) and measuring its effect on voltage in order to measure system impedance via the measured voltage signal. Both active and passive impedance-based local islanding detection methods exist in the literature and are proven to be effective at detecting the occurrence of islanding (Liu *et al.*, 2015; Mohamad and Mohamed, 2018).

INTENTIONAL ISLANDING

Intentional islanding generally is not an issue and embedded DGs can theoretically continue to be online as long as everyone working on the system is aware and the power quality is maintained during the islanding and after the resynchronization. Micrograds can be designed to transition smoothly between grid-connected mode and stand-alone mode (Achlerkar *et al.*, 2018; Qaiser Naqvi, Kumar and Singh, 2019) with now commercially available equipment. However, a small microgrid is not expected to have FRT capability in its grid connection.