Technical challenges in Integration of Small-Scale and Large-scale PV Systems into the Grid

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Abstract: Decarbonisation, energy security and expanding energy access are the main driving forces behind the worldwide increasing attention in renewable energy. This paper focuses on the solar photovoltaic (PV) technology because, currently, it has the most attention in the energy sector due to the sharp drop in the solar PV system cost, which was one of the main barriers of PV large-scale deployment. Firstly, this paper extensively reviews the technical challenges, potential technical solutions and the research carried out in integrating high shares of small-scale PV systems into the distribution network of the grid in order to give a clearer picture of the impact since most of the PV systems installations were at small scales and connected into the distribution network. The paper reviews the localised technical challenges, grid stability challenges and technical solutions on integrating large-scale PV systems into the transmission network of the grid. In addition, the current practices for managing the variability of large-scale PV systems by the grid operators are discussed. Finally, this paper concludes by summarising the critical technical aspects facing the integration of the PV system depending on their size into the grid, in which it provides a strong point of reference and a useful framework for the researchers planning to exploit this field further on.

Keywords: Small-scale PV system; Large-scale PV system; PV system integration; High penetration; Technical challenges; Power system stability

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1. Introduction

Energy from renewable sources is becoming a growing component of the electricity grid around the world, due to its contribution to achieving decarbonisation, energy security and improving the energy access. The integration of renewable energy resources into existing electrical grids is the way forward to achieve clean and sustainable power generation due to the rapid depletion of the conventional power sources, better known as fossil fuels, which contribute to the increasing greenhouse gas emissions and create environmental concerns such as the depletion of the ozone layer, change in global climate and acid rain [1]. On the other hand, the usage of nuclear energy can raise hazardous concerns to the health of living creatures and the environment, and this gives renewable energy the advantage for future sustainable power generation [2].

The average energy supplied from the sun's radiation that the Earth's surface receives is approximately 1.2×10^{17} W of solar power, which is enormous: less than an hour of this can meet the demand of the whole population for a whole year [3]. However, most renewable energy resources are not available for use all the time due to factors that are outside our control, better known as intermittent nature. Intermittent renewable energy resources may be predictable, but they cannot be

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dispatched in a flexible way for meeting the fluctuating demand because their output cannot be altered quickly. Thus, there is a relationship between the intermittency and dispatchability of the electricity resources in which most non-dispatchable electricity sources are often highly intermittent. There are many different types of non-dispatchable renewable energy, including tidal and wave energy, but the two main types of non-dispatchable renewable energy that contribute noticeably to the electrical grid are wind and solar energy.

Photovoltaic (PV) technology is considered as one of the major sources of distributed renewable energy that has no limitation in supply [4,5]. It is predicted that, by 2040, PV technology will become the most significant electricity generation contributor among all other candidates of renewable energy [6]. In the emerging countries, there is currently a great interest for small-scale PV systems' installations in the form of roof-top domestic systems from customers at their premises that are interconnected with the distribution network of the grid, thus leading to a sharp increase in penetration levels of that distributed renewable energy. The interest for small-scale PV system installations in the form of roof-top domestic systems from the customers at their premises is due to the sharp decrease in the PV technology prices, in addition to the continuous rise of electricity prices from the grid and various incentives that are provided from the governments to make the PV technology a viable and cost-effective option [7]. There is a large volume of material in the literature that assesses the impact of integrating high penetration levels of small-scale PV systems into the distribution network of the grid. However, the research that is recently published and showed a more explicit assessment of this impact is available in [8–10]. Figure 1 presents the world solar energy map, and it clearly shows the potential of solar energy as one of the major renewable energy sources.

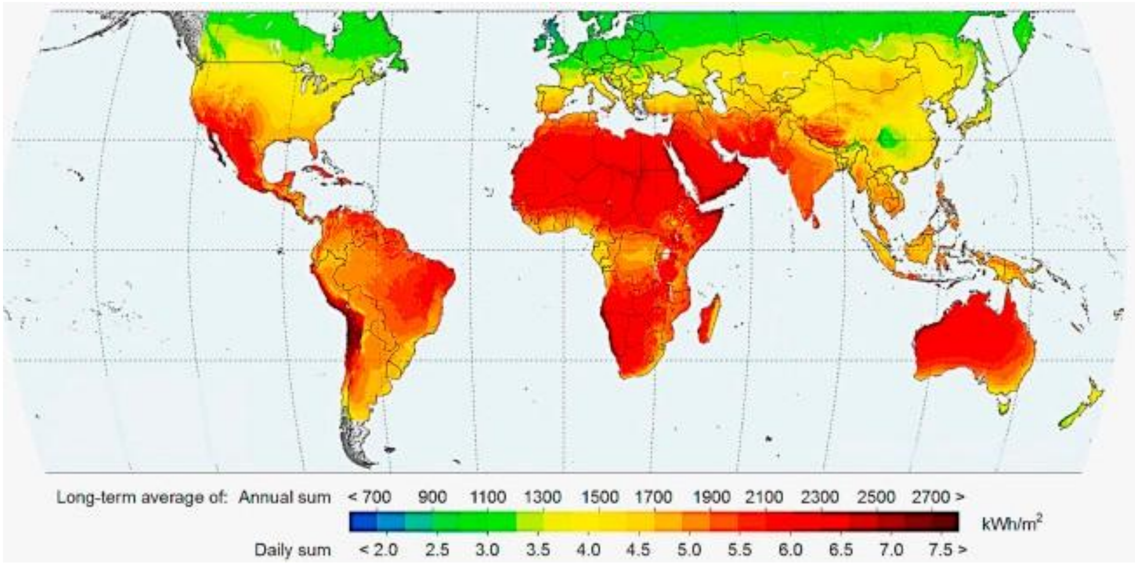

Figure 1. World solar energy map [11].

It is expected that large-scale renewable energy will be injected into existing grid in the near future in many countries. Wind and solar energy are the most promising renewable energy (RE) sources that have the capability of producing large quantities of electricity. Wind energy conversion is more efficient and the technical challenges of large-scale integration of wind energy to the grid are similar to those of solar [12]. In addition to the technical challenges, integration of large-scale wind energy also poses some environmental issues compared to solar energy. The availability, unpredictability and variability of wind is harder to forecast, unlike solar energy which can easily be predicted: is only available during the day except when there are clouds [13]. A general comparison of typical costs of various types of power generation system[redacted] shown in Table 1, according to the US energy information administration (EIA) [14]. There are many publications in the literature that assess the impact of integrating large-scale PV systems into the electricity transmission network of grid. However,

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the most recently published works that present a more explicit assessment of the impact of integrating large-scale PV systems into grid system are shown in [15–18]. The current paper seeks to illustrate the key technical aspects facing the integration of the large-scale PV systems into the grid, and includes both recent studies that have been carried out to tackle the voltage regulation issue in high penetration levels of small-scale PV systems and the current practices for managing the variability of large-scale PV systems by the grid operators. Thus, this review provides a strong point of reference and a useful background for the researchers planning to exploit this field further.

Table 1. General comparison of the typical costs among conventional gas/oil combined cycle, wind and PV power plants.

Characteristics	Conventional Gas/Oil Combined Cycle Generators	Wind	PV
Capital cost (2018 $/kW)	999	1624	1969 for tracking 1783 for fixed tilt
Variable O&M (2018 $/MWh)	3.61	0	0
Fixed O&M (2018 $/kW/year)	11.33	48.42	22.46

The present paper is organised as follows, Section 2 highlights the distinct characteristics of the renewable energy intermittency generation that impacts the grid. Section 3 illustrates the technical challenges, possible solutions and the research carried out on integrating high penetration levels of small-scale PV systems to the distribution network of the grid. Section 4 illustrates the localised technical challenges, grid stability challenges and possible solutions on integrating large-scale centralised PV systems to the transmission network of the grid. Section 5 reviews the current practices for managing the variability of large-scale PV systems by the grid operators. The paper concludes by summarising the key aspects facing the integration of the PV systems depending on their size scale into the grid.

2. The Distinct Characteristics of Renewable Energy Generation That Impacts the Grid System

The intermittency experienced from both wind and solar energies brings the following distinct characteristics of power generation, including partial unpredictability, non-controllable variability and location dependence. Those distinct characteristics of the intermittent renewable energy sources can impact both the operation and security of the grid when integration is considered. Thus, this section illustrates these characteristics, because each creates new challenges to the owners of the generation and the grid operators.

Partial Unpredictability

Partial unpredictability can be referred to as the uncertainty or the inability to predict the exact available energy production of the intermittent renewable energy power generation at a time-scale of an hour or a day from the present time. Thus, it complicates the grid's management for the operators, because of their usage of the process "unit commitment" that schedules the generation in advance [19]. At present, the "unit commitment" process is considered largely deterministic because, once the generator is scheduled to operate, it is expected to be available and ready to operate at full capacity, which shows the relative predictability and controllability that traditional power plants such as coal brings.

However, the operation of the "unit commitment" becomes more complex when dealing with a stochastic generation that has an output at the active time displaying some degree of uncertainty resulting in an increased cost of the function due to the need of balancing the actual production with the predicted one [20]. Forecasting technologies can be used here to predict the weather and hence the generation output of the intermittent renewable energy sources at various time scales to allow the grid operators to facilitate the schedulin[redacted]nd dispatching of the sources more effectively. In addition, the grid operators will need an advanced "unit commitment" process that is unlike the

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deterministic one and capable of predicting the uncertain outcomes that the forecasting technologies cannot predict [21]. Therefore, it is recommended that the resources scheduling of the system take into account the stochastic nature of intermittent renewable energy power generation and their level of concentration on the system, which results in a cost-effective way to maintain the system's flexibility and avoids risking the system's reliability [22].

Non-Controllable Variability

Variability in terms of the intermittent renewable energy sources such as wind and solar refers to the fact that their output is not constant, which is a quite distinct character of the term unpredictability. Thus, even if the operator is successful in predicting the output of the intermittent renewable energy power generation correctly, the output would still be variable, posing great challenges to the grid. Each type of renewable energy has its typical and unique generation pattern, which can be clearly observed in Figure 2.

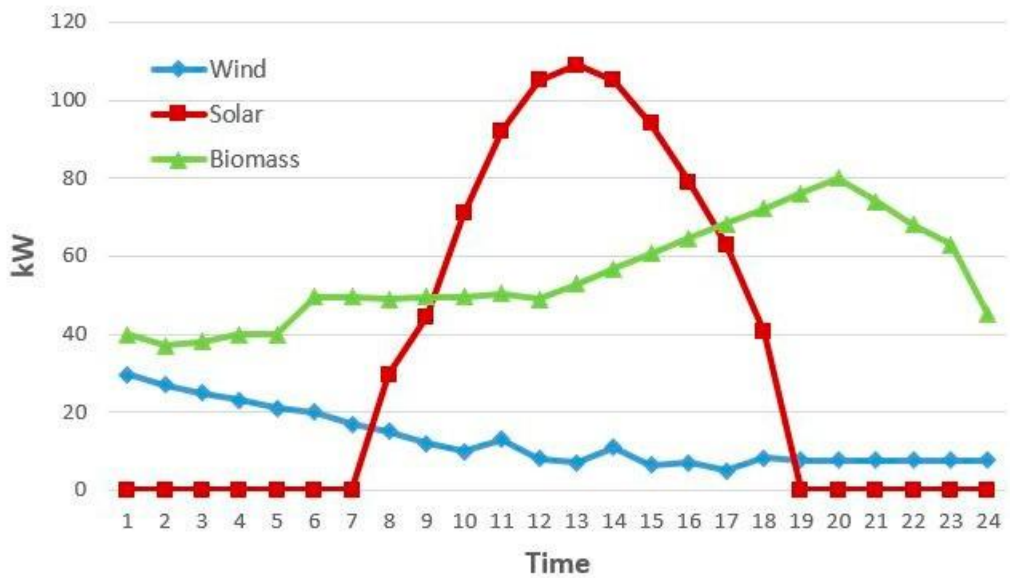

Figure 2. Example of renewable energy power generation patterns [23].

Grid operators must deal in the transmission system with fluctuations in terms of frequency and voltage on a time-scale of seconds to minutes so that the system and its equipment are not affected. It is performed through ancillary systems which order generators to inject active or reactive power into the grid in order to balance the actual and predicted power, thus maintaining the frequency and voltage levels of the grid. The followings are the types of ancillary services:

- Voltage suppor uses the reactive power of the generators to raise the voltage whenever it is necessary.
- Frequency regulation is performed through signals to the generators from the automatic generation control (AGC) on the basis of seconds to minutes [24].
- Spinning and non-spinning reserves use the generator's available power to act as a generation reserve whenever the system goes down. If the generator provides the power within a couple of few minutes it is classified as spinning and if it takes a longer time it is classified as non-spinning.
- Black-start capacity is the generator's ability to start the system in the case of a black-out.

In addition, the grid operators must track the demand of the loads for electricity from the consumption side to ensure that the generation an[redacted]oad are matching all the time. This function is called load-following, which becomes vital at peak demand times and is met through ancillary services. The aforementioned functions are not new to the grid because the load is variable itself. The consumers

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demand for electricity can be predictable but not controllable, thus adding a degree of variability. In addition, the conventional generator can experience problems of not performing as scheduled all of the time. Therefore, the grid can deal with a low-level variability added to it in the form of intermittent renewable energy at a low level of penetration because the integration challenges are primarily specific on the device and local-grid such as harmonics and sub-synchronous resonance [25]. On the other hand, at high penetration levels of intermittent renewable energy, the grid will experience more variability than it has managed in the past, leading to an increase in demand for those ancillary services and energy balancing overall, which is quite challenging to manage at device level. Thus, grid level actions, strategies and technologies are needed to overcome this.

Location Dependent

Intermittent renewable energy sources are usually located in remote locations far away from the centre of the loads except for solar energy, which may be installed near the load vicinity. Thus, apart from day-to-day management of the grid system, the long-term planning of the siting of the renewable energy power generation and the utilisation of new transmission lines to carry out the renewable energy to the market is very crucial. Transmission planning for renewables is very complex because it is influenced by the regional politics affecting the capacity of generation, the location of transmission and the load sizes. In addition, technical needs will arise of the type of transmission technology used since it will carry primarily partially unpredictable and variable electricity. On the other hand, using a distributed renewable energy generation topology rather than a central one will give the grid an alternative future vision, which is the micro-grid. This is because it will eliminate the costs of the line losses and the expensive cost of the transmission lines making the electricity grid conceptualised as a dependent collection of micro-grids [26].

3. Technical Challenges of Integrating High Penetration Levels of Small-Scale PV Systems into the Grid

The challenges for integration here can be classified into technical, commercial and regulatory challenges that are needed to be dealt with in order to fully utilise the available renewable energy. The commercial and regulatory challenges are not mentioned here because the focus is on the technical challenges only. The technical challenges of integrating high penetration levels of small-scale PV systems into the distribution network of the grid come in the form of voltage regulation, power quality, harmonics and protection challenges according to the majority of published papers [8–10,27–33]. The reason for the majority of those technical challenges is that the distribution network when constructed did not consider the possibility of large penetration levels of PV technology connected to it, altering the operation of the network from passive (unidirectional) to active (bidirectional).

Voltage Regulation

Due to the intermittent nature of the PV technology, implementing a large amount of it in the distribution network of the grid will cause fluctuations and unbalance in the voltage profile. The voltage change in the distribution network is sensitive to short-term fluctuations which can cause the malfunction of the voltage regulation equipment due to the rapid alternations between sunshine and clouds [34]. In general, the PV system can create irradiance fluctuations either for a short or long period due to climate change, which affects the voltage output from the PV system in the point of common coupling (PCC). The voltage problem of the distribution network due to the connection of large amounts of PV systems can be characterised as voltage unbalance, voltage rise and voltage flickers in the network.

Power Quality

Power quality can be defined as the concept o[redacted]wering and grounding sensitive equipment in a suitable way for the operation of that equipment [35]. Despite this definition, the term power quality

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is being used generically. Commonly, power quality considers two important aspects: the transient voltage variations and the harmonic distortion of the network voltage. It is known that power quality is improved when there is power supplied on-site such as PV. However, it comes with a cost when connected to the grid; such issues that might arise are voltage flickers, voltage sag, harmonics and stress on the distribution transformer [9]. The authors of [36] suggested that the change in the network voltage profile and the reversal of power flow caused by distributed generation are the main issues of power quality.

Harmonics Distortion

The harmonic distortion of the current and the voltage waveforms is becoming an important issue that needs addressing as the penetration levels of the PV systems increase in the distribution network. Harmonic distortion is a result of current conversion from dc to ac, which is provided via an inverter with inherent non-linearity and results in an injection of current harmonics [37]. Therefore, the inverters of the PV systems are the main source of current harmonics injected into the distribution system, which can cause the voltage harmonic and total harmonic distortion (THD) in the network [38]. These harmonics contribute to the increase of the losses in the distribution network via heat generation.

Protection Challenges

The straight protection scheme of each feeder in the distribution network was designed with the assumption that the feeder is radial, meaning the power flow is unidirectional. However, the presence of PV systems on the feeder will cause bidirectional power flow resulting in the feeder no longer being radial, thus creating several problems to the current protection schemes used [39]. When connecting high penetration levels of PV systems to the distribution network, it is necessary to address some aspects such as the protection of the generation equipment from internal fault, anti-islanding protection and fault current protection of the distribution network [40]. An islanding scenario is often considered as the final undesirable initiative to save the system before it completely collapses [41]. Figure 3 shows a typical system configuration of detecting the islanding scenario in which the point of common coupling (PCC) will play the role of the point of interface between the local distribution system and the grid.

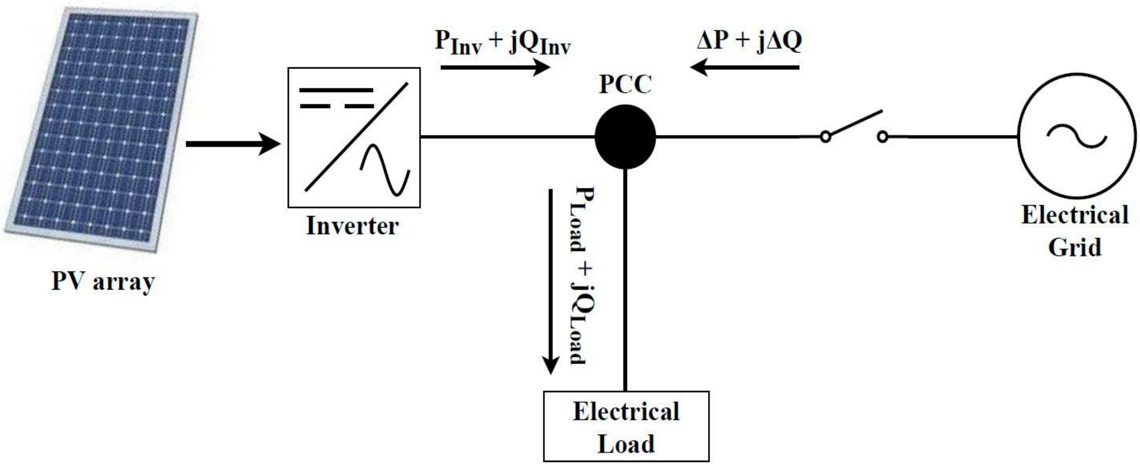

Figure 3. Typical system configuration of islanding detection.

Technical Solutions

The authors of [42] suggested that, of the above-mentioned technical challenges, voltage regulation is the most significant technical challenge that prev[redacted] or limits the penetration level of the distributed generation in the distribution network, in which the [redacted]ollowing are the advanced methods or solutions to help mitigate this issue:

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- Area based on load tap changer (OLTC) coordinated voltage control
- Generation curtailment during low demand
- Consumption shifting and curtailing
- Energy storage system with coordination
- Reactive power control

There has been much research on how these advanced methods can increase the penetration levels of the PV systems in the distribution network [43–55]. In [43], a new supervisory tool based on the voltage control scheme for control and data acquisition to coordinate among the DGs, OLTC and capacitor banks is presented, which sets a new principle for selecting the tap positions of an OLTC. The first stage of the new principle for selecting the tap positions of an OLTC is done through a micro-genetic algorithm and the second stage involves using a recursive genetic algorithm to reduce power losses to find the optimal reactive powers for the distribution network. The results suggest that the proposed method can reduce the complexity of the voltage regulation process. The authors of [44] introduced a three-stage fuzzy-based voltage regulator without needing to run an optimisation algorithm in order to manage the violations of the voltage ranges. The first stage involves utilising reactive power provision at the DG units and, if it is not enough, the second stage is used, which triggers the OLTC operation. The last stage is real power curtailment for when the OLTC is not enough to tackle the problem. This method showed proper voltage regulation with a lower cost of communication compared to centralised and distributed methods of controlling the voltage. The authors of [45] introduced a new voltage control system for selecting the tap position of the OLTC based on the Fuzzy Logic (FL) concept, which aids the integration of large shares of PV systems to the residential area networks in Saudi Arabia. The implementations of the proposed method showed its novelty, but the drawback of this method is the dependency on both the characteristics of the load and the network's parameters.

In [46], a centralised optimisation approach is proposed to reduce the MW curtailment of the distributed generation (DG), which eliminates the voltage constraints, and it is done through coordination between various interactions control means such as OLTC, shunt banks, active/reactive power management and remotely controlled switches (RCS). The outcomes showed that using RCS in the case of voltage constraints on transferring DG between the feeders will reduce the curtailment of DG. The authors of [47] proposed an adaptive method for capping real power to make sure that voltage is regulated within the permissible limit while keeping the power curtailment share of the customers PV systems fair. The work reported in [48] shows that overvoltage in LV feeders can be prevented using droop based active power curtailment techniques, which achieves an increase in both PV system installed capacity and energy yield.

The research presented in [49] addresses the scheduling of the distributed generation's available opportunities of consumption reduction and shifting aiming to optimally minimise the operation costs via using demand response programs and virtual power player that manages the distributed generation resources with consumption shifting constraints into account. In [50], a robust multi-objective optimisation based integrated scheduling approach is proposed and investigated to solve the micro-grid supply and demand scheduling problem under uncertainty. The approach uses a minimaxmulti-objective optimisation formulation to minimise the operating costs and emissions under the worst case realisation of that intermittent renewable and the uncertainty of the loads.

The research efforts in [51] show a coordinated control method that includes distributed and localised controls for the energy storage system to aid voltage regulation for the distribution network with high penetration levels of rooftop PV systems during the period of PV systems peak generation. The findings demonstrate that the proposed control method ensures that the voltages in the networks are maintained within the required limits during daily operation. The authors of [52] proposed a coordinated use of PV system, battery energy st[redacted]ge (BES) and the reactive capability of the PV system's inverter to address voltage regulation problem, which is evaluated for rural and urban View publication stats scenarios. The results show that coordinated PV system and BES support is required for the rural scenario with the high resistance feeder to maintain acceptable voltage profile, whereas reactive compensation from the PV system's inverters alone is sufficient to maintain acceptable voltage profile in an urban scenario.

The authors of [54] presented a distributed control method for a residential battery energy storage (BES) units connected to PV system that aims to utilise the customer-owned BES units for solving the over-voltage issues caused by high PV system penetration levels without significantly affecting the owners BES unit local objectives. This method utilises the reactive power when the active power is not enough, and the results show that the aim has been met. The authors of [55] attempted to increase the penetration levels of PV systems in the distribution network using solar inverters that are capable of reactive power control. They introduced a reactive control method that is based on sensitivity analysis, which illustrates that, if the solar inverter is located at the end of a feeder, then the same amount of reactive power becomes more effective for the grid's voltage support.

This section shows a brief assessment of the technical challenges, technical solutions and the research done on integrating high shares of small-scale PV systems into the distribution network of the grid. We feel that this area of work is well addressed for the consumer purposes because it has had the most attention in the recent years, leaving the integration of large-scale PV systems connected to the grid's transmission network for utility purposes not being fully addressed well.

4. Technical Challenges of Integrating Large-Scale PV Systems into the Grid

A power plant is a centralised system that independently supplies power to the grid system and not to a particular customer that complies with the grid system's regulations. To enhance the grid's stability, security and reliability, grid codes and standards are established to define the requirements for the power plants to be connected to the grid which were traditionally based for the conventional power plants. However, the usage of renewable energy to produce electricity at large-scale (for utility purposes) compared to the conventional power plants were initially very low. However, recently, this has changed drastically, making the development of grid codes for renewable energy power plants that avoids affecting the operation of the grid quite the necessity.

The grid codes development path for wind power plants attained more interest, i.e. stepped up, due to its early entry to the utility market. The purpose of the grid codes development for the wind power plants is to enable it to operate as closely as possible to the operation of the conventional power plant, by providing support to the grid in terms of voltage regulation, frequency regulation, reactive power regulation and active power regulation. In [56], the authors illustrated wind power plants integration with in-depth analysis of the grid codes. On the other hand, the PV's standards such as IEEE 1547 were designed for small-scale PV systems that are interconnected to the distribution network of the grid for residential, commercial and industrial purposes that resulted in the prevention of that small-scale PV systems from providing ancillary services [57].

However, owing to the advancements in power electronics, semiconductor technology and cost reduction of the technology, which makes the penetrations of PV systems not only limited to the distribution network but also in the transmission network at large-scale. The global cumulative power in GW of utility and non-utility PV systems up to 2019 can be shown in Figure 4. The most significant large-scale PV plants worldwide are listed in Table 2. Thus, due to the growth of PV systems at large-scale for utility purpose in the recent years, there has been a development of grid codes to allow the integration of large-scale PV systems in the transmission network of the grid. Germany, in 2008, developed the first grid code that is specifically for large-scale PV systems interconnected to the transmission network of the grid, which was four years after the first grid code was developed for wind power plants by Denmark [58]. It is worth mentioning that, after Germany developed the first grid code for the large-scale PV systems integration, other countries created their version. If a comparison is required of the different requirements requested by different countries grid codes to interconnect large-scale PV systems to the transmi[redacted]on network of the grid, then the following four specific categories should be considered [15]:

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- Fault-ride through requirements
- Active power and frequency control
- Reactive power and voltage control
- Voltage and frequency boundaries

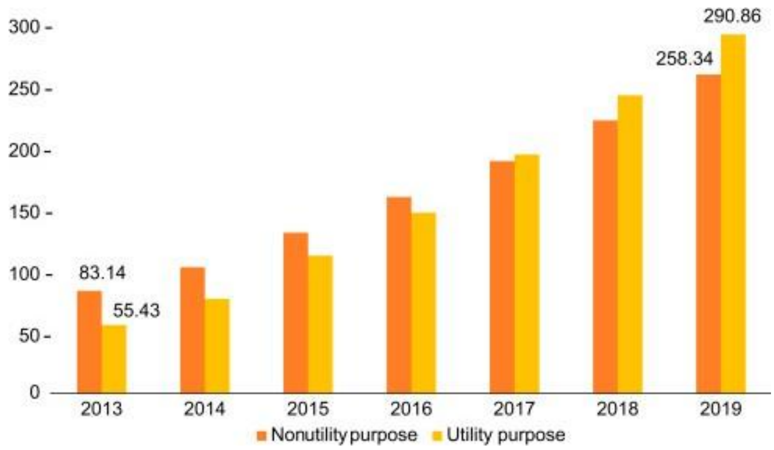

Figure 4. Global cumulative power (GW) of utility and non-utility PV systems up to 2019 [15].

Table 2. Significant large-scale PV plants worldwide [59].

PV Plant Name	Location	Size (MW)	Commissioned Year
Yanchi Solar PV Station	China	1000	2016
Solar Star Projects	USA	575	2015
Desert Sunlight Solar Farm	USA	550	2015
Topaz Solar Farm	USA	550	2011–2014
Longyangxia Hydro-Solar PV Station	China	480	2013–2015
Copper Mountain III Solar Facility	USA	350	2015
Charanka Park PV power plant	India	345	2012–2015

Several thousand PV modules need to be connected to get the MW range of power to be considered a large-scale PV system, which requires a significant land area for the deployment of that large-scale system. In addition, with the requirement of significant land area for the deployment comes a higher set up cost with lower capacity factor compared to other renewable technologies. The authors of [60] presented an extensive review of the topologies for the large-scale PV plants taking into consideration the internal topology and the AC collection grid. The authors of [61] illustrated an thorough analysis of control strategies of grid-connected inverters with their applications in PV plants. Therefore, it is essential to know the impact of integrating large-scale PV systems to the transmission network of a grid for utility purposes since it will outgrow the PV systems shortly for non-utility purposes. An interesting comparison between the characteristics of various PV inverter topologies for large-scale PV system are shown in Figure 5.

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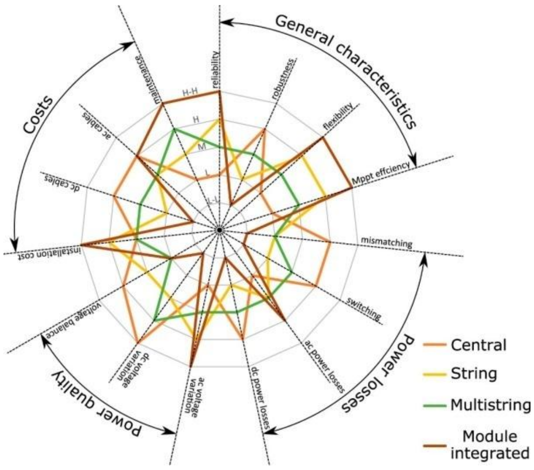

Figure 5. Comparison between the characteristics of various PV system inverter topologies for large-scale PV system [60].

Localised Technical Challenges of the PV Plant

The localised technical challenges of integrating large-scale of PV systems into the transmission network of the grid comes in the form of active power regulation, reactive power regulation and power quality, according to the majority of published papers on this topic [15–18]. A PV solar power plant should meet the minimum requirements given by the grid codes of the different countries, and, because of these grid codes, there are many challenges of integration.

Active Power Regulation

The current PV system inverters' operating power point is set to give the maximum active power that varies according to the solar irradiance, which is thanks to the development of various algorithms such as particle swarm optimisation, ripple correlation and fuzzy logic control that are explained by the research efforts in [62,63]. However, these algorithms bring drawbacks such as the number of sensors used, time of response and the delay to notice the radiation changing. Using these algorithms means that the large-scale PV system will always be working at the maximum power in each solar radiation, which increases the system's risk of large and quick fluctuations of active power due to cloud transition affecting power balance in the grid. Thus, most grid codes require at least two types of active power control, which are ramp rate control and power curtailment, as well as power reserve in some countries. In this case, the maximum power point tracker will suffer modification as it does not need to operate at maximum power all day; instead, it needs to track the required power by the operator. It is worth mentioning that the maximum operating point of the large-scale PV system should be less than its power capacity; otherwise, energy storage should be deployed. In addition, due to the current control and technology of the large-scale PV system, it will not be easy to reduce the power at a constant ramp rate.

Reactive Power Regulation

The technology of the current PV system inverters that are used in the distribution network of the grid does not have a PQ control as the IEEE 1547 regulation does not require this, although the inverters are capable of performing according to the regulation. The MPPT control used in the normal PV system's operation does not allow complete control of the PQ capability during the day, which limits the performance of the system. However, according to the grid code requirements of integrating large-scale PV systems to the grid, the PV system inverters are responsible for controlling reactive power and active power [64]. Therefore, it [redacted]mportant to understand the limitations of the PV system inverters because they were developed wit[redacted]t reflecting the variations of the solar radiation, temperature and the dc voltage on their capability curve. In the case of wind power plants, there are

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already deep studies on their reactive power capability [65]. For instance, the authors of [66] studied the reactive power capability curve of a doubly-fed induction generator, in which when the wind power plant does not provide sufficient amounts of reactive power to meet the grid requirements, thus other pieces of equipment are installed such as STATCOMs, SVCs or capacitor banks to meet the required amount of reactive power. The quadrants of the inverter's operation are clearly shown in Figure 6.

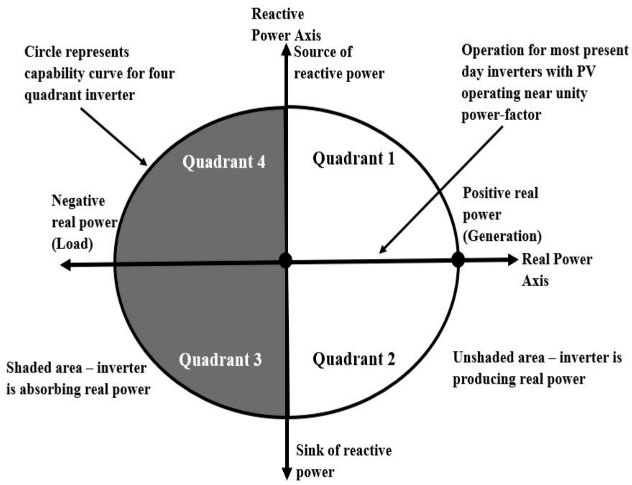

Figure 6. Quadrants of inverter operation [67].

Power Quality

The integration of large-scale PV systems into the grid involves many power electronics devices that will cause the injection of harmonics into the grid. Harmonic is usually the result of the switch delay of the inverter, which becomes quite significant when the output power of the PV fluctuates. The experience from the practical operation of a large-scale PV system shows that the output current harmonics is small for a single grid-tied inverter, but, with the case of multiple shunt inverters, their output current harmonics might greatly exceed the normal standard [68]. The research efforts in [69] analyse the resonance caused by a filter capacitor when large-scale PV systems are integrated to a weak network through a long distance cable in which some specific harmonics might be amplified due to the resonance.

Grid System Stability Challenges

The grid power system is the largest and most complex human-made dynamic system that has been ever created. Therefore, due to the size and complexity of the grid power system, it makes the stability factor extremely important. Power system stability according to Kundur et al. [70] is defined as "*The ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact*" by both the Institute of Electrical and Electronics Engineers (IEEE) and the International Council for Large Electric Systems (CIGRE). The following are the classification of grid stability:

- Voltage stability is the ability of the power system to sustain the acceptable voltage levels across all the buses of the system during normal operating conditions and after being subjected to a disturbance. Instability of the voltage levels may occur as a result of an uncontrollable and progressive rise or fall in voltage levels of some buses in the system.
- Rotor angle stability is the ability of the traditional synchronised generators in the grid power system to maintain that synchronism after b[redacted]g subjected to a disturbance. To have a better understanding of rotor angle stability, it is useful to separate it into small disturbance rotor angle

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stability, better known small signal stability, and large disturbance rotor angle stability, better known as transient stability.

- Frequency stability is the ability of the power system to maintain or restore the balance between the generation and load after being subjected to a disturbance, which is done by maintaining the frequency within its applicable limit. The disturbance causes a significant mismatch between generation and load.

Grid system instability can be shown in several ways depending on the configuration and operating conditions of the grid system. Since the grid system is a highly non-linear system, it tends to keep operating continuously under small disturbances such as the alteration in the loads or generators. Furthermore, due to the grid system covering a large geographical area, it is likely exposed to large disturbances such as the loss of their main components. However, the grid system must have the ability to respond to these disturbances and remain stable by returning to the original operating conditions or reaching new operating conditions [71].

Grid system stability classes can be categorised by their time frame and their disturbance size, which is clearly shown in Figure 7. Stability concerning time frame can be categorised into short- and long-term stability. The stability concerning the size of disturbance can be categorised into small and large disturbances stability, in which the first can be examined via the linearisation of the system's dynamic equation while the second can be examined via non-linear simulation [72].

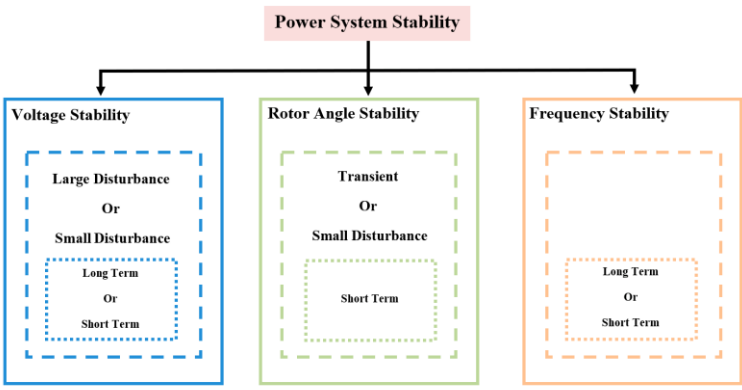

Figure 7. Stability classifications of the grid system.

Grid system stability is a core requirement to ensure the security and reliability of the grid system's operation while reducing the chances of a blackout occurring, which is done through the maintenance of that stability that becomes more challenging to the system operators due to the large-scale integration of variable renewable energy such as solar. Therefore, it is crucial to comprehensively understand the grid system stability with large-scale solar energy generation, which means it is essential to analyse the operational reliability of the grid system to aid the development of the methods to mitigate the adverse effects that large-scale solar energy integration has on the grid system stability.

Voltage Stability

Voltage stability relates to the ability of the power system to maintain at all the nodes its voltage levels at an acceptable level during normal operating conditions and after being encountered with a disturbance. Generally, voltage instability is a local phenomenon, but the widespread impact of, e.g., the voltage collapse of the entire system can happen as a result of the voltage instability [73]. In addition, severe voltage collapse of the entire power system can be linked with rotor angle instability due to a gradual loss of synchronism, i.e. rotor angle separation of the traditional generators, which will result in a rapid voltage drop in the power [redacted]tem [74]. Voltage stability can be divided into the following:

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- Large disturbance voltage stability is when the power system must uphold constant voltages after being ejected with a severe disturbance such as a loss of large generator. The voltage stability phenomenon can be either long term or short term. Therefore, the time frame of this kind of study may vary from a few seconds to minutes to capture the performance of the power system equipment [73].
- Small disturbance voltage stability is when the power system must uphold constant voltages after being ejected with a small disturbance such as the changes in the load of the system. Small disturbance voltage stability can be investigated via linearising the power system equations considering the appropriate computation assumptions. However, it is better to keep in mind that, with the linearised method, non-linear effects such as time delays and tap changer controls are not considered [75]. The time frame to conduct this study is similar to the large disturbance voltage stability time frame.

The distinct characteristics of the PV system and the current grid codes will significantly affect the voltage stability of the system when large-scale PV systems are introduced to the transmission network of the grid. The effects of large-scale PV systems integration on the voltage stability of the transmission network of the grid are studied in [76–79].

The authors of [76] studied the impact of increasing the penetration of the PV systems on the static performance and the transient stability in the transmission network and showed that the system from the steady state stability point of view could experience both beneficial and detrimental effects. The authors of [77] investigated the effects on the static voltage stability of the Ontario power system from integrating large-scale centralised PV system and distributed PV system. They considered various penetration levels and found that the distributed PV system might improve the static voltage stability of the system while the large-scale centralised PV system experienced less improvement in terms of voltage stability margin.

In [78], the authors studied the impact on the voltage profile from installing large-scale PV system at different sites of the grid and showed that the voltage at the feeder gives a parabolic trend when the output power of the large-scale PV system increases. They concluded that the maximum point of the voltage profile is dependent on the total impedance of the transmission line and the large-scale PV system. The authors of [79] presented a detailed theoretical analysis of the impact of integrating large-scale PV system on the static voltage stability of the grid and found that the integration of large-scale PV system brings a positive impact in terms of static voltage stability in the grid. The studies above considered that the large-scale PV system supplies the maximum possible power without considering the output power variations during the day such as cloud coverage. Therefore, it is essential to understand the effects on the voltage profile from integrating large-scale PV systems to the grid by accounting for its source variability, the cloud coverage and the temperature.

Rotor Angle Stability

Rotor angle stability relates to the ability of the traditional synchronised generators in the grid to remain synchronised after being encountered with a disturbance. Normally, all the connected traditional generators to the grid are rotating at the same speed level, meaning the there is a balance between the mechanical input and the electromagnetic output of each traditional generator in the grid. However, a disturbance occurring would lead those traditional generators to accelerate or deaccelerate their rotating speed, affecting the angular position between the rotors, i.e. the balance between the mechanical input and the electromagnetic output. The grid can maintain the rotor angle stability if the difference between the rotor's angular position is reduced until the synchronised speed level has been reached again. Otherwise, the rotor angle stability will be lost, resulting in the generator losing its synchronism with the rest of generators and leading to large fluctuations in its output in the form of power, voltage and current. Therefore, the grid sy[redacted]m stability for any particular condition can be deduced by whether the deviations in the angular position of the rotors are capable of resulting in

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sufficient restoring torques [73]. Rotor angle stability is categorised as a short-term phenomenon and can be divided into the following:

- Large disturbance rotor angle stability, better known as transient stability, is when the power system must remain synchronised after being ejected with a severe disturbance such as transmission line short circuit. The transient stability depends on both the original operating state of the system and the severity of the disturbance.
- Small disturbance rotor angle stability, better known as small signal stability, is when the power system must remain synchronised after being ejected with small disturbance such as the changes in the load of the system. The small signal stability depends on the strength of the system, the original operating state of the system and the type of generator excitation controls used.

A static source element such as the PV system will not contribute in the power angle oscillation leading to a significant reduction of the grid system equivalent inertia due to the intermittent power output of the integrated large-scale PV system. In addition, the integration of large-scale PV system into the grid will cause an alteration in the original grid power flow and the power of transmission channel, which means that, during fault ride-through of the PV system, it will present a different dynamic support characteristic compared to the conventional generators [80]. The rotor angle stability is mainly affected by the topology of the power network, the mode that the grid operates at, the PV system's capacity, its location and its control strategy [17]. The PV system's inability to cope with the fault ride-through may lead to it being off-grid, which would have a severe impact on the stability of the system, especially when there is a centralised large-scale PV system integrated to the grid. Therefore, the aforementioned shows the importance of rotor angle stability, which should not be ignored when integrating the large-scale PV system to the grid.

Frequency Stability

Frequency stability relates to the ability of the grid system to keep the frequency levels within its acceptable limits after being subjected to a disturbance, which results in the mismatch between the generation and the load [81]. Figure 8 illustrates the concept of the grid's frequency stability using the analogy of the water-level in a container. Frequency stability depends on the ability of the grid system to either maintain or restore equilibrium between the generation and load [70]. Generally, frequency stability issues are linked with the inadequate responses from components of the system, the insufficient generation reserve or the poor coordination of control and protection equipment. The time frame of this kind of study may vary from a fraction of a second to several minutes. The longer time corresponds to the response for example load voltage regulators, whereas the shorter time corresponds to the response for example under frequency load shedding relays [74].

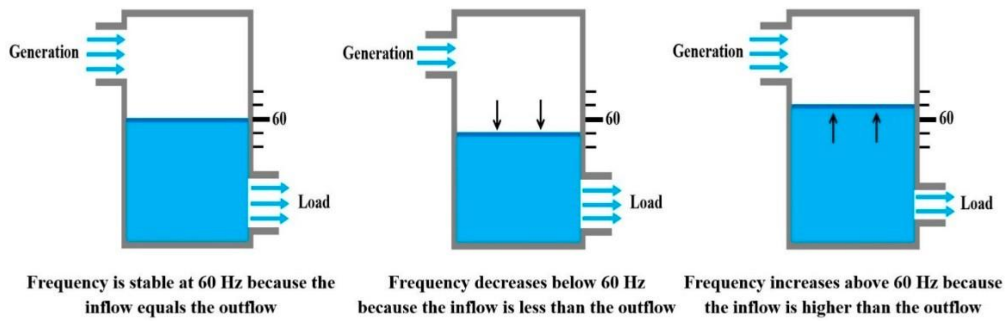

Figure 8. Concept of grid's frequency stability using the water-level in a container analogy.

Currently, the grid's frequency is related to the rotating speed of the conventional synchronous generators in which the control of these genera[redacted]s manages the frequency by accelerating or deaccelerating them depending on the balance between the load and the power generated in order to

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increase or decrease the frequency. Therefore, this kinetic energy limits the initial rate of frequency decline in the case of power imbalance occurring, which means this inertial response of the conventional synchronous generators plays a crucial role in frequency control in the grid system [82]. The PV technology lacks rotating machinery, i.e. inertial support, which together with its power variability causes problems in the grid in terms of frequency stability [83]. The authors of [84] studied the effects of four 50 MW PV power plants as well as four 700 MW conventional power plants on the frequency stability of the grid and concluded that the frequency stability is not drastically affected by the PV power plants, but they did not consider any reduction of the conventional power plants. Therefore, the lack of inertia from the large-scale PV system needs more attention from in-depth studies to understand its impact on the current grid, which might be beneficial. The study by Rahmann and Castillo [85] gives a good start to understanding this phenomenon.

Technical Solutions

Nowadays, the grid codes and the operators are demanding that the integrated large-scale PV system has as similar as possible operational behaviour to the conventional power plants. Therefore, the integrated large-scale PV system should be capable of controlling the active power to provide frequency support to the grid, control the reactive power to provide voltage support to the grid and possess the fault ride through capability during various disturbances. Without controlling the aforementioned, the grid will face new challenges in grid balancing, which affects the flexibility of the grid through the frequent mismatches between the supply and the demand in which matching the response of the supply to the demand becomes less predictable due to the integration of the large-scale PV systems into the transmission network of the grid [86]. Thus, to maintain the balance of the grid flexibility is essential on both the demand and supply sides, whereas the supply side flexibility can be achieved via energy storage, renewable energy curtailment and flexible generation while the demand side flexibility can be achieved via energy storage, demand response and smart loads [87]. The common denominator between achieving flexibility to the supply and demand side is energy storage, as shown in Figure 9.

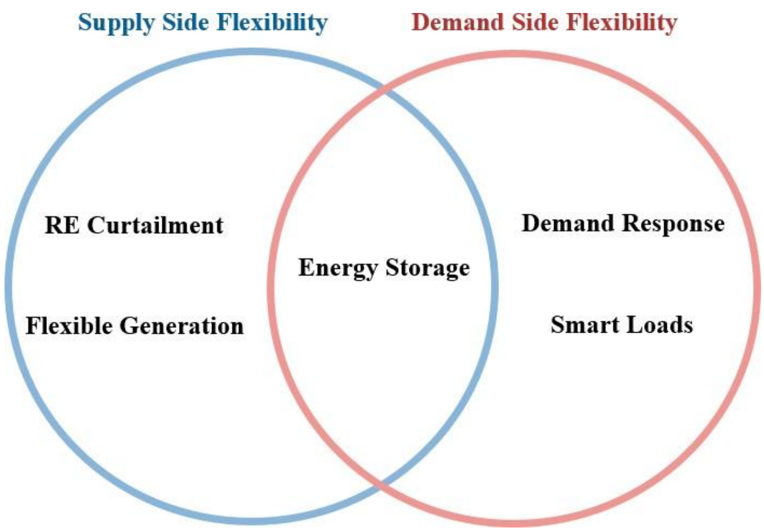

Figure 9. Overview of flexibility in supply-demand side.

In addition, the research efforts in [88] suggest that the flexibility of the grid system can increase by applying the following methods:

- Upgrading the grid is done to strengthen and [redacted]prove the grid via processes such as expansion and integration. However, grid upgrade can [redacted]onsidered a costly option among other aspects.

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- Improving the forecasting of renewable energy successfully eliminates the uncertainty aspect of renewable energy but not its output variability.
- Increasing back-up power is done through using the traditional dispatchable power. However, this method emits large quantities of greenhouse gas (GHS) because it is hydrocarbon-based.
- Demand side management (DSM) reduces its potential for viability due to the consumer's behavioural aspects in decision making [89].
- Integration of energy storage technologies is a very promising method because it can offer time-shifting ability, decouple the supply and demand, reduce curtailment, relieve the grid's congestion and regulate the grid by smoothing the fluctuations of the frequency and voltage to ensure both security and reliability of the grid [90].

The authors of [15] illustrated that during the last years two solutions had been developed to aid the integration of the large-scale PV systems into the transmission network of the grid: the addition of various equipment such as energy storage and developing smart controls for the large-scale PV system. The research efforts in [91–93] review the state of the art for the energy storage technologies and their applications, which is quite useful for enabling more renewables in the grid. Figure 10 presents an interesting comparison of the energy storage technologies in terms of storage capacity and discharge power duration. Table 3 summarises a list of the technical characteristics of the energy storage technologies [93]. Furthermore, at the current time, there is no storage technology that can satisfy or meet all the aspects of the grid's needs. This means that different energy storage technologies target different aspects of the grid's needs, which is clearly shown in Figure 10. Thus, a hybrid energy storage system can be utilised to satisfy the needs of the grid, which can be done by the combination of two or more energy storage technologies chosen specifically to fill the gaps or drawbacks of the other energy storage technology.

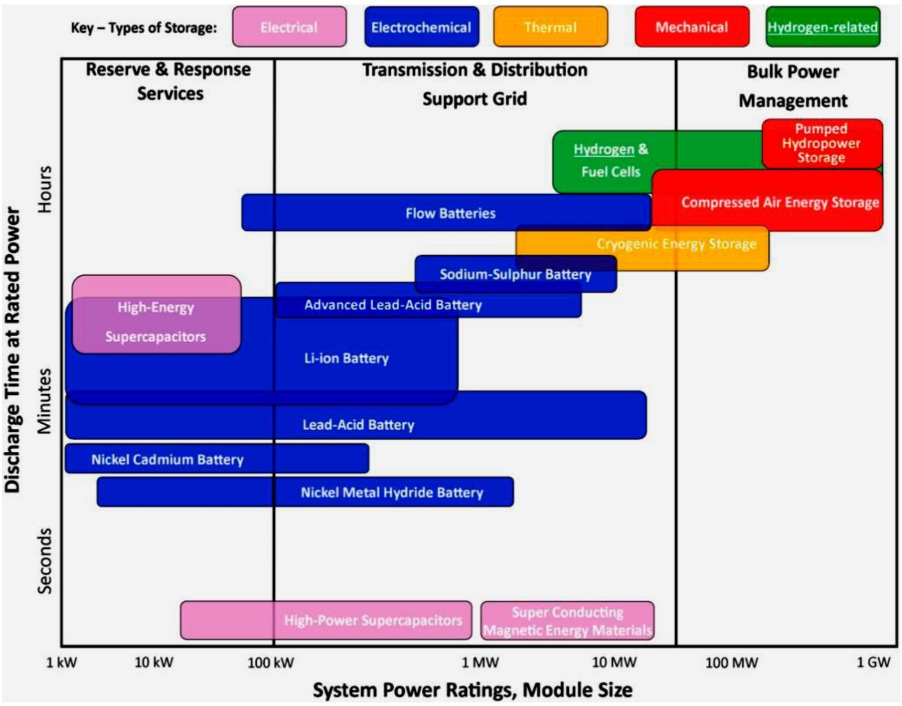

Figure 10. Energy storage technologies comparison in terms of storage capacity and discharge power duration [94].

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Table 3. Technical characteristics of the energy storage technologies.

ESS Technology	Configuration	Round Trip Efficiency	Life Time (Year)
Pumped Hydro	Conventional	0.70–0.82	50–60
Compressed Air	Underground	0.70–0.89	20–40
	Aboveground	0.70–0.90	20–40
Flywheel	High Speed	0.93–0.95	15–20
Battery	Lead-acid	0.70–0.90	5–15
	Na-S	0.75–0.90	10–15
	ZEBRA	0.86–0.88	15–15
	Li-ion	0.85–0.95	5–15
	VRFB	0.65–0.85	5–10
	Zn-Br	0.60–0.70	5–10
	Fe-Cr	0.72–0.75	10–15
	Ni-Cd	0.60–0.73	10–20
	PSB	0.65–0.85	10–15
	Zn-air	0.60–0.70	5–10
Supercapacitor	Double Layer	0.85–0.95	10–20
SMES	SMES	0.95–0.98	15–20
Hydrogen	Fuel Cell	0.33–0.42	15–20
	Gas Turbine	0.33–0.42	15–20

5. The Current Practices for Managing the Variability of Large-Scale PV Systems by the Grid Operators

In the early 2000s, many utilities expressed concerns about the intermittent nature of solar generation [95]. Accurately, it is a fluctuating output that possibly could stress their systems, producing voltage issues on the grid and increasing the wear on the conventional power plants [96]. The increased growth in solar energy did not eliminate the integration issues facing both utilities and grid operators. However, both the utilities and grid operators are getting better at handling the issues using new software systems, updating the infrastructure of both grid and generation and the installation of new technologies such as smart inverter and electricity storage. This section discusses the current methods or precautions used by grid operators in some regions in dealing with the variability of the grid-connected PV plants. Among some of the many places where renewable energy installation is increasingly taking place, Germany and California (USA) are the two regions chosen due to their high shares of solar energy in their generation mix. In doing so, we give a better insight into studying the current methods or precautions used by these two regions grid operators in dealing with the variability of the grid-connected PV plants.

Germany

Germany is categorised as the largest European energy market with the most ambitious energy transition “Energiewende” to renewable energies, thus the share of renewable energy production has increased dramatically from 17% to 28% between June 2011 and 2015 [97]. Germany’s carbon emissions rose slightly in 2015 after years of decline because it is forcing conventional power plants to keep operating even if there is a sufficient amount of renewable energy capable of supplying nearly all of the demand to deal with its variability in generation output, which leads the country to generate more electricity than it needs [98]. The German feed-in tariff system played an important role in increasing the penetration levels of renewable energy to the grid. Taking the solar PV technology as an example, from 2004 to 2011, the installed capacity of PV technology sharply increased from below 1 GW to 24 GW [99]. Figure 11 shows an interesting pie chart of the PV system share by cumulative capacity in Germany 2017 [100].

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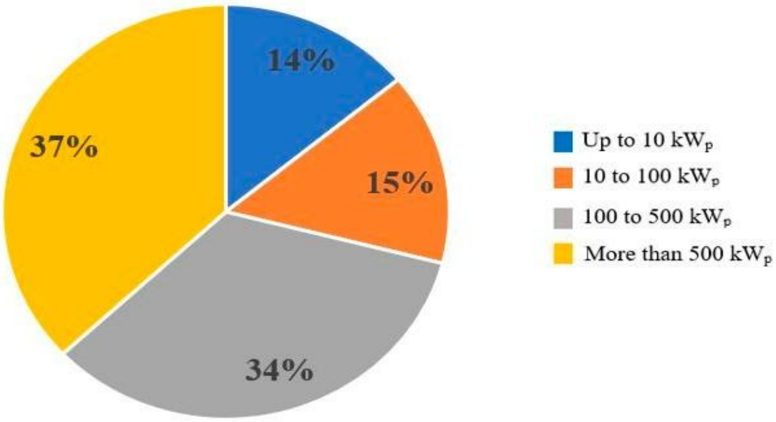

Figure 11. PV system share by cumulative capacity in Germany 2017.

The authors of [101] stated the following seven reasons for enabling Germany to manage to balance the integration of close to a 30% of renewable energy share with the very modest alteration to its power system:

1. The existing strength of the grid implies that outages rarely occur and it possesses more capacity than required for the given current demand. However, Germany has needed to increase the strength of its transmission lines with planning to increase its capacity further to accommodate more renewable energy [102].
2. The operational flexibility of the conventional power plants means there is a surplus of conventional power capacity that is being utilised effectively to provide the required balancing power to offset the variability that comes with renewable generation. Most of the conventional power plants were originally designed or later modified to provide a flexible output by being able to ramp on an hourly basis to a value much lower than the highest output and being able daily to cycle on and off [103]. In addition, these conventional power plants can sell their power into the ancillary electricity market to provide minute-by-minute and hour-by-hour balancing in order to eliminate any mismatch between the supply and demand [99]. However, these conventional power plants are not selling much of their power on the day-ahead wholesale market because of solar and wind energy receiving priority of dispatch in the mentioned market [104].
3. The improved design of the ancillary power markets implies that both the balancing and intraday electricity market have been modified to provide greater flexibility to accommodate renewables.
4. The improved system control software and day-ahead weather forecasting means that the grid operators have greatly improved their software to accommodate higher ramp rates, evolving the system's reliability calculations to consider renewables. In addition, improving the day ahead weather forecasting is a vital part of improving the balancing of renewable energy in the grid.
5. The technical adjustments to the local-level distribution system is executed to cope with the reverse power flow effect due to the presence of the renewable in the distribution level.
6. The ability to export power to the neighbouring countries: The high levels of renewable energy generation on peak days causes the prices of the electricity market to drop to zero or even be negative, which leads to the effect of reducing the output of the conventional power plants and exporting power to neighbouring countries. However, the approach of importing and exporting power from the neighbouring countries has a very modest part in balancing renewables because of the regulation of the markets in the form of prohibiting importing power in Germany for example and the bidding time frame is too long for importing or exporting power for renewable energy balancing purposes [101]. The electricity exported from Germany throughout the recent years are shown in Figure 12 [100]. [redacted]

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7. Solving the 50.2 Hz inverter issue implies that the inverters cut-off frequency has been modified to vary rather than having it all the same to avoid a massive threat on the grid's stability as it has much solar energy.

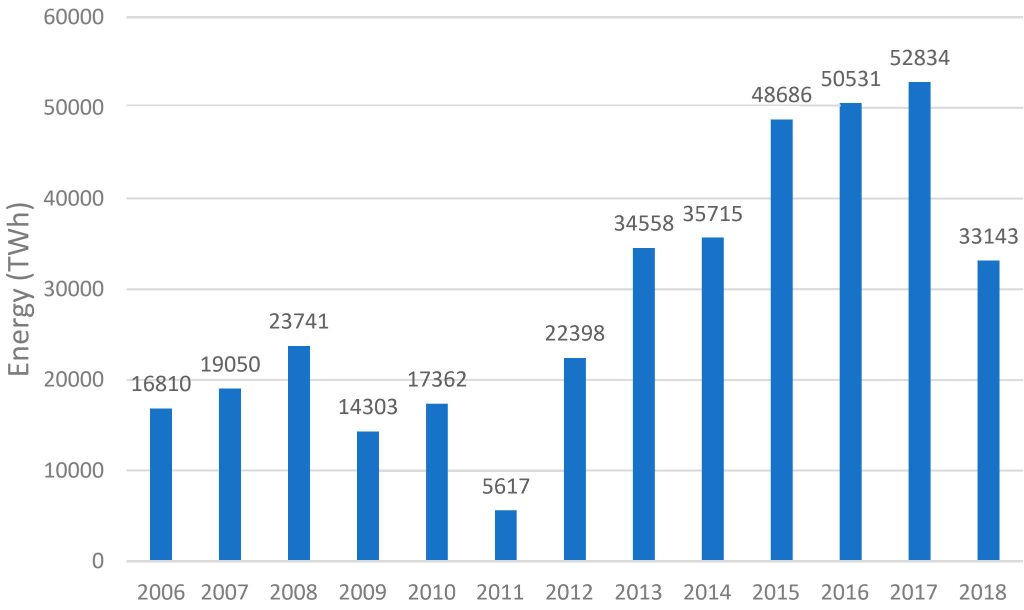

Figure 12. Electricity exported for Germany.

By 2020, the Germans aim to satisfy 35% of their demand from renewable energy but the article in [105] states that, in the first half of 2017, Germany has exceeded its 2020 target for renewable energy by having 37.6% of renewable energy resulting in Germany becoming Europe's leading exporter at that time. It is worth mentioning that large-scale energy storage had almost no part in integrating and balancing renewable energy because they do not expect it to play a role until the share of renewable exceeds 40% [101]. Therefore, in the future, bigger changes will be necessary to ensure that large-scale renewables are integrated with being able to balance their variability effect.

California (USA)

California is categorised as a well-known world leader in the renewable energy technology deployment, especially when it is reported that the state's utilities are well ahead of their Renewables Portfolio Standard (RPS) target of 33% by 2020 and 50% by 2030 [106]. Furthermore, California is likely to meet its 2030 RPS target by 2020. Figure 13 presents the existing and projected solar and wind installed generation in CAISO (the California Independent System Operator). CAISO handles the over generation phenomenon of renewable energy using curtailment of the renewable generation, which is a quite wasteful approach in utilising clean energy, and it leads to relying more on the use of non-clean energy sources [107]. This section presents how the California ISO grid operator manages the integration of the large-scale PV systems.

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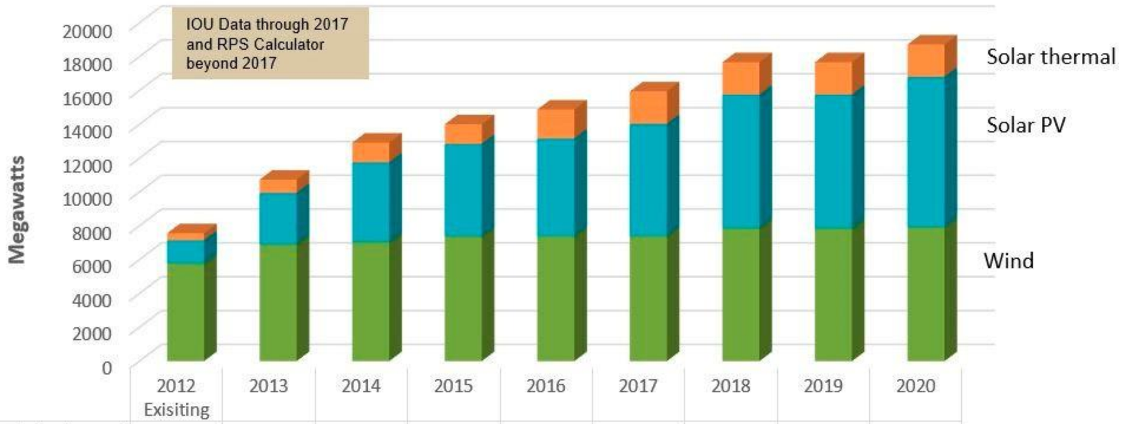

	2012 Exisiting	2013	2014	2015	2016	2017	2018	2019	2020
Solar thermal	419	792	1167	1167	1717	1917	1917	1917	1917
Solar PV	1345	3022	4693	5445	5756	6628	7881	7881	8872
Wind	5800	6922	7058	7396	7406	7406	7877	7877	7934

Figure 13. Existing and projected solar and wind installed generation in CAISO [108].

California ISO Using Utility-Scale PV Systems to Provide Ancillary Services

The increase of renewable energy integration has sparked concerns over the resilience and reliability of the grid. However, some grid operators such as the California ISO have demonstrated how to successfully integrate large-scale of renewable energy sources such as solar PV systems with keeping the reliability of the grid intact as successfully as a natural gas plant [109]. Currently, the California state performs much of its essential and ancillary grid services with natural gas plants. However, the methane leak incident from the Aliso Canyon storage facility has led stakeholders to advocate for a more reliable and diverse resource, in which renewable energy arguably fits the role [110].

The reason for this rise in need of reliability services to manage the increasing penetration levels of renewables is because the California ISO experienced in 2015 its first event of not having the required ancillary services [111]. Therefore, California ISO collaborated with the National Renewable Energy Laboratory (NREL) and First Solar on a 300 MW solar power plant project that illustrated the ability of renewable energy to sustain the reliability of the power system as effectively as the natural gas plant with more efficiency [109]. This result is due to the presence of the intelligent inverters combined with advanced plant controls that provide the ability to respond accurately, making the solar power plant have the three fundamental services of ramping capability, voltage and frequency control [109].

California ISO Dealing with a Solar Eclipse

Today's solar eclipse can be used to assess how grid operators that rely on the supply of large-scale solar energy manage this phenomenon without compromising the operation of its system. The United States of America experienced a solar eclipse on the morning of 21 August 2017 [112]. Since the California relies on solar energy to generate more than a quarter of its electricity, thus it would be hit harder than neighbouring states by an eclipse covering more of the sun's rays [113]. The article in [114] shows a clear illustration of how the grid operator has managed to deal with this phenomenon that has been projected to knock out an estimate of 5600 MW of solar energy at an expected up to 70 MW per minute drop and rebound. The grid operator has dealt with this in the past on certain days when moving clouds met with the sunset or sunrise. The biggest challenge for the grid operator is not replacing that lost energy with another source but managing that strong ramp down and sharp ramp up. The California ISO managed that strong ramp down and sharp ramp up of solar energy using its established sources of flexibility including the following [114]:

- The adjustable-rapid power plants such as gas[redacted]ired and hydroelectric ones
- The regional power market that is built purpose[redacted] to balance the quick shifting of renewable energy
- The growing capability of storing electricity via energy storage

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- The capability of shaping the demand of power in real time via demand response

The California ISO still did not take any chances with the solar eclipse even with its established sources of flexibility mentioned above and more than doubled the amount of reserve power beyond the 350 MW that they normally have secured during these hours [114]. This approach undertaken by the California ISO of bulking up reserve power is done by following the example of what European countries such as Germany did to counter the solar eclipse that occurred in 2015, in which nearly 17 GW of solar power generation across the continent was knocked out, yet their frequency of the grid remained stable [115,116]. However, the California ISO is planning to exploit battery storage to the maximum extent and demand response in order to lower the strains on the grid.

It is worth mentioning how the grid operator known as Duke Energy of North Carolina managed the solar eclipse, which estimated that its solar generation would be falling from about 2.5 GW to 0.2 GW at the peak of the eclipse [117]. Therefore, to manage that fall and subsequent rise, it followed Italy's lead of requesting their solar power suppliers to ramp down their output ahead of the eclipse, which aided in reducing the rate of ramping up the gas-fired plants. This method can be compared to gently pressing the gas pedal rather than a costly stamping on it.

6. Discussion and Way Forwards

Large-scale PV systems bring up a new set of technical challenges if connected to grid because of their uncontrollable variability in generation and their location dependency, which is often far from the population demand centres due to the requirement of large area of land for the installation. The cause of variability in renewable energy is the weather fluctuations that brings up uncertainties to the generation output in the scale of seconds up to days in which those uncertainties can affect up to 70% of day time solar capacity due to the passing clouds [118]. Furthermore, the aggregation of the large-scale renewable energy over large areas reduces the variability of the individual components. However, this does not eliminate the uncertainty, which is sometimes greater than the relative predictable variation in demand that the grid can deal with regularly.

The impact of the variation of renewable energy generation could be mitigated if the grid were capable of matching the supply of the renewables to the demand, meaning they both rise and fall together [119]. However, if the supply of the renewables and demand moved in the opposite directions, it would become very costly to accommodate it. For example, if there were a large supply of renewables when there were a low demand meaning, the excess renewables could only be used if the conventional baseload generators were curtailed. This would be a costly and inefficient approach that might lead to significant reliability issues. On the other hand, if there were a low supply of renewables when there were a high demand, the peak demand would be reached completely by the conventional generators. This means that there would be a requirement of having a conventional reserve that can successfully match the capacity of the renewable energy. Therefore, it is a major challenge facing the integration of renewables to the grid, in reducing the cost of dealing with the two aforementioned cases.

This paper focuses on the variability in the generation of the large-scale PV system and the current approaches used to deal with that variability by the grid operators. Germany and California are the two regions examined due to their high shares of solar energy in their generation mix. In the case of Germany, it managed balancing the integration of close to a 30% of renewable energy share with very modest alteration to its power system. It is worth mentioning that large-scale energy storage had almost no part in integrating and balancing renewable energy. This is because Germany does not expect it to play a role until the share of renewable exceeds 40% of its generation. This might be due to the neighbouring countries not requiring much excess power that can be exported to them.

In the case of California, the biggest challenge for the grid operator during the solar eclipse was not replacing that lost energy with another source but rather managing that strong ramp down and sharp ramp up, which they managed by the[redacted]stablished sources of flexibility. Furthermore, the overgeneration phenomenon of renewable energy was handled by means of curtailment in the

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renewable generation. This is a quite wasteful approach in utilising clean energy and it leads to more reliance on the use of non-clean energy sources.

A debate is therefore whether curtailing renewable energy is seen as a problem or a solution. On the one hand, curtailing renewable energy can be problematic because it reduces the capacity factor of the renewable energy, which can potentially decrease the revenue of the plant. This can lead to the weakening of the confidence of renewable energy investors since the intermittent renewable energy such as solar PV systems have low operating expenses but large capital costs that can be recovered by maximising the energy output. Similarly, negative wholesale prices sustained can occur when the conventional generation system in the grid cannot be turned down to a lower output in order to accommodate more available renewable energy, which leads to the reduction in the attractiveness of investing in renewable energy generation [120]. This debate can lead to a point in which it is possible for a power system to technically at all hours of the year meet the demand at a given penetration level of renewable energy, assuming that the curtailing measure of the renewable energy's output is not considered. There is an interesting analysis illustrating that increasing the curtailment beyond a certain threshold, in this case 5%, will result in a significant risk of the owners not being able to pay off the loans taken for the existing project [121]. It is worth mentioning that many utility scale PV power plants can already receive curtailments signals from the operators of the grid, which means that the transition to the automatic generation control operation is simply viable.

Currently, the grid operators handle the variability of renewable energy almost exclusively by ramping up or down the conventional generators or reserves based on the weather forecast. This will increase the stress and wear on the conventional power plants. Furthermore, in the near future, the grid will experience large shares of renewables, making the current approach costly and unreliable in some cases. This leads to the need of a cost effective and reliable approach from the generation side in dealing with this matter, which can be in the form of the following:

- By installing large-scale energy storage to balance the surplus and shortage of renewable energy generation and hence stabilise the grid
- By increasing transmission flexibility to enable accessing large shares of resources in order to aid balancing both local and regional deficits or excesses

Some of these ideas are discussed in [122], which gives a realistic assessment on future scenarios with suggestions of making the global agenda move towards grid connected large-scale PV at a multi-TW scale. The study includes the technical, economical, policy and infrastructure barriers that needs to be overcome in order for the grid connected PV technology to grow to the multi-TW scale. This study also concludes that storage and increasing transmission flexibility among other factors makes it possible to reach that multi-TW scale.

7. Conclusions

To achieve decarbonisation, energy security, expanding the energy access and with the current sharp decrease of the PV technology prices, solar PV technology gained the most attention in the energy sector. This paper illustrates first the challenges of integrating high penetration levels of small-scale PV systems into the distribution network of the grid, including their technical challenges and the advanced methods to tackle those technical challenges with mentioning related work that has been done in solving the voltage regulation issue. Then, the paper focuses on the challenges of integrating large-scale PV systems into the transmission network of the grid, including their localised technical challenges, grid stability challenges and technical solutions. The challenges associated with integrating large-scale PV systems into the transmission network are different from the challenges associated with integrating high penetration levels of small-scale PV systems into the distribution network. For example, when there is a moving cloud, the output of the PV system will change sharply, which becomes one of the main problems in the distribution level; however, [redacted] the transmission level, it is minimised because of the natural averaging effect since the PV plant is installed over a large area of land. It is worth

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mentioning that voltage regulation is the most significant technical challenge that prevents or limits the penetration levels of the small-scale PV systems into the distribution network of the grid. It is believed that this area of work is well addressed for the consumer purposes because it had the most attention in the recent years, leaving the integration of large-scale PV systems into the transmission network for utility purposes not being fully addressed well. Then, this paper focuses on the localised technical challenges, grid stability challenges and possible solutions on integrating large-scale of PV systems into the transmission network of the grid mentioning the current practices used by the grid operators in dealing with the variability that accompanies that large-scale PV system generation. The grid needs to deal with the greater variability and uncertainty, which operators currently handle almost exclusively by the ramping up or down of the conventional generators or reserves by forecasting the weather on a minute by minute or an hourly basis. However, in the near future, the grid will experience large shares of renewables making this current approach costly and unreliable in some cases leading to the need of a cost-effective and reliable approach from the generation side and that approach is likely storage and flexible transmission.

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