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Comprehensive Overview of Power System Flexibility during the Scenario of High Penetration of Renewable Energy in Utility Grid

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Abstract: Increased deployment of variable renewable energy (VRE) has posed significant challenges to ensure reliable power system operations. As VRE penetration increases beyond 80%, the power system will require long duration energy storage and flexibility. Detailed uncertainty analysis, identifying challenges, and opportunities to provide sufficient flexibility will help to achieve smooth operations of power system networks during the scenario of high share of VRE sources. Hence, this paper presents a comprehensive overview of the power system flexibility (PSF). The intention of this review is to provide a wide spectrum of power system flexibility, PSF drivers, PSF resources, PSF provisions, methods used for assessment of flexibility and flexibility planning to the researchers, academicians, power system planners, and engineers working on the integration of VRE into the utility grid to achieve high share of these sources. More than 100 research papers on the basic concepts of PSF, drivers of the PSF, resources of PSF, requirement of the PSF, metrics used for assessment of the flexibility, methods and approaches used for measurement of flexibility level in network of the power system, and methods used for the PSF planning and flexibility provisions have been thoroughly reviewed and classified for quick reference considering different dimensions.

Keywords: demand side management; flexibility planning; generation expansion planning; power system flexibility; variable renewable energy; unit commitment

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1. Introduction

Global warming and depletion of fossil fuels are driving the electrical utilities to shift from thermal-dominated power generation to renewable energy (RE)-dominated electrical power [1]. The major share of RE is supplied from the wind energy and solar energy sources. Generation from these energy sources is variable and uncertain in nature. Hence, these sources are considered as variable renewable energy (VRE) sources. More than 50% of Denmark's electricity was supplied by wind energy and solar energy in the year 2020. Similarly, more than 30% of Ireland's electricity was supplied by VRE sources in the year 2020. China is planning to achieve VRE share of more than 60% by 2050 and United States planned to achieve VRE share of 80% by 2050 [2–4]. Hence, due to high share of VRE sources in future power generation scenarios, the high variability on the supply side has become a major concern. This has initiated an interest in the strategies and technologies which are capable of mitigating variability of renewable energy (RE) sources [5]. Hence, it is becoming extremely important to ensure adequate grid flexibility [6]. The PSF is defined as "Ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant time scales, from ensuring instantaneous stability of the power system to supporting long term security of supply" [7]. Recently, PSF is an emerging topic of research for academicians, working engineers, and the scientific community. Many studies have reported on the power system flexibility. These studies are mainly focused on mitigating issues of VRE integration to the utility grids and investigation of the PSF features, resources of PSF, requirements of PSF, PSF metrics, measurement of PSF, drivers of PSF, PSF provisions, and PSF planning. In [8], authors presented a study for quantifying the flexibility of systems used for hydrogen production to achieve large-scale grid integration of VRE sources, and an algorithm was proposed to achieve valley filling, ramping mitigation, and peak shaving. The method is based on the interactions among fuel cell electric vehicles (FCEVs), hydrogen production facilities, and the electric power grid. Results indicate that oversizing electrolyzers are effective to mitigate intermittent nature of RE sources and they support the deployment of hydrogen vehicles which helps to decarbonize the transportation sector. Nossair et al. [9] presented an approach for reconstructing the operating reserve to meet the power system flexibility with high share of RE. Dynamical envelopes are used to characterize the PSF requirements and flexibility provisions. A problem for optimal flexibility planning is formulated with envelopes considering unit commitment (UC) and economic dispatch. It is established that adequacy of flexibility is directly linked to aggregate flexibility envelope formed by flexibility resources, flexibility requirement envelope, and its dynamics over operational planning horizons. An energy-centric approach for flexibility management in power systems considering systematic energy limits of operating reserve is reported in [10]. The benefits of receding-horizon economic dispatch are achieved by integrating energy storage. It is established that anticipatory energy storage strategy exploits the energy-based operating reserve which is able to perform significantly better compared to a myopic energy storage dispatch strategy. Pfeifer et al. [11], modeled various flexibility options, including storage systems and demand response technologies, and applied them to energy systems on a national level. It is established that flexibility options play a key role when energy transition to an RE system is 70%, 80%, 90%, and 100%. In [12], authors proposed a coordinated scheduling method for charge and discharge of electrical vehicle (EV) fleets for maximizing the charging cost of EV in vehicle-to-grid (V2G) setup and helping in improvement of flexibility of load. A detailed study for comparing the characteristics of different scenarios mainly focused on quantum and types of flexibility is presented by authors in [13]. It is established that the 100% RE scenarios are more expensive compared to RE penetration level below 50%. Prediction of the cost of electricity generation for a particular class of energy system scenario considering 100% renewable energy is also estimated.

A critical review of the different aspects of PSF, drivers of PSF, resources of PSF, requirement of PSF, techniques used for measurement of PSF, PSF provisions, and power system flexibility planning will be useful for the academicians, power system engineers and scientists to carry out further research on the flexibility and increase the penetration level of VRE into the utility grids. Hence, this paper aims to present a comprehensive review on the topic of PSF. More than 120 research papers [1–123] are critically reviewed and classified in nine categories. The first category [1–13] details the general concepts of the power system flexibility. The second category [14–27] is related to different definitions and indicators of the PSF. The third category [28–35] describes the drivers of the power system flexibility. The fourth category [36–67] is related to the description of resources of flexibility. The fifth category [68–80] elaborates the requirement of flexibility in the power system network. The sixth category [81–92] discusses the metrics used for assessment of the flexibility. The seventh category [93–111] describes the methods and approaches used for measurement of level of flexibility in the network of power system. The eighth category [112–118] details the provisions of flexibility. The ninth category [119–123] presents the methods used for the power system flexibility planning. Some references have also been included in more than one category dependingn on their relevance. The main contributions of this paper are as follows:

- To understand the basics of the PSF and different philosophies used to define the PSF.
- Provide an overview of drivers of PSF, resources of PSF, and requirements of PSF with high share of VRE in utility grids.
- Discuss flexibility metrics and measurement techniques used for assessment of PSF in detail.
- Identify and discuss the provisions of PSF for utilities.
- Understand the planning practices to improve PSF.
- Identify knowledge gaps and open topics for future research work.

The contents of the paper are arranged in eleven sections. Starting with an introduction in Section 1, the proposed review methodology is discussed in Section 2. Power system flexibility is defined in detail in Section 3. Drivers of the power system flexibility are described in Section 4. Section 5 details the resources of flexibility. Section 6 elaborates the requirement of flexibility in the power system network. Section 7 describes the metrics used for assessment of the flexibility. The methods and approaches used for measurement of level of flexibility in the network of power system are described in Section 8. Provisions of flexibility are discussed in Section 9. Section 10 details the methods used for the PSF planning. Finally, conclusions are included in Section 11.

2. Review Methodology

Methodology adopted for review of literature related to power system flexibility during the scenario of high penetration of RE in the utility grid is briefly discussed in this section. In this work, authors intend to deepen the understanding of power system flexibility, drivers of flexibility, resources of flexibility, flexibility provisions, methods used for assessment of flexibility, and flexibility planning. Research papers are categorized into nine categories (RC1 to RC9) as detailed below:

1. Basic concepts of power system flexibility (RC1).
2. Definitions of power system flexibility (RC2).
3. Drivers of power system flexibility (RC3).
4. Resources of power system flexibility (RC4).
5. Requirements of power system flexibility (RC5).
6. Flexibility metrics (RC6).
7. Methods used for measurement of PSF (RC7).
8. Power system flexibility provisions (RC8).
9. PSF flexibility planning (RC9).

Review methodology used for the study and different steps of the methodology are described in Figure 1. Various categories of PSF focused on for the study are identified and categorized as RC1 to RC9. Research papers are searched on the Web of Science and Scopus databases, including the term power system flexibility (N1). Furthermore, research papers appearing in the reference lists (N2) of searched papers were also analyzed and considered for the study. The first review stage includes the screening of titles, abstract, introduction, and conclusion of the research papers (N1 + N2) to identify the techniques and methods used for the study of specific category (RC1 to RC9). Research papers which do not fall in the categories RC1 to RC9 are excluded (N3). The second review stage includes the screening of all contents of the papers (N1 + N2-N3), and papers which do not fall in the investigated categories based on the methods used in the papers are excluded (N4). Full review of the papers (N1 + N2-N3-N4) is carried out and relevant information is extracted and synthesized in this paper.

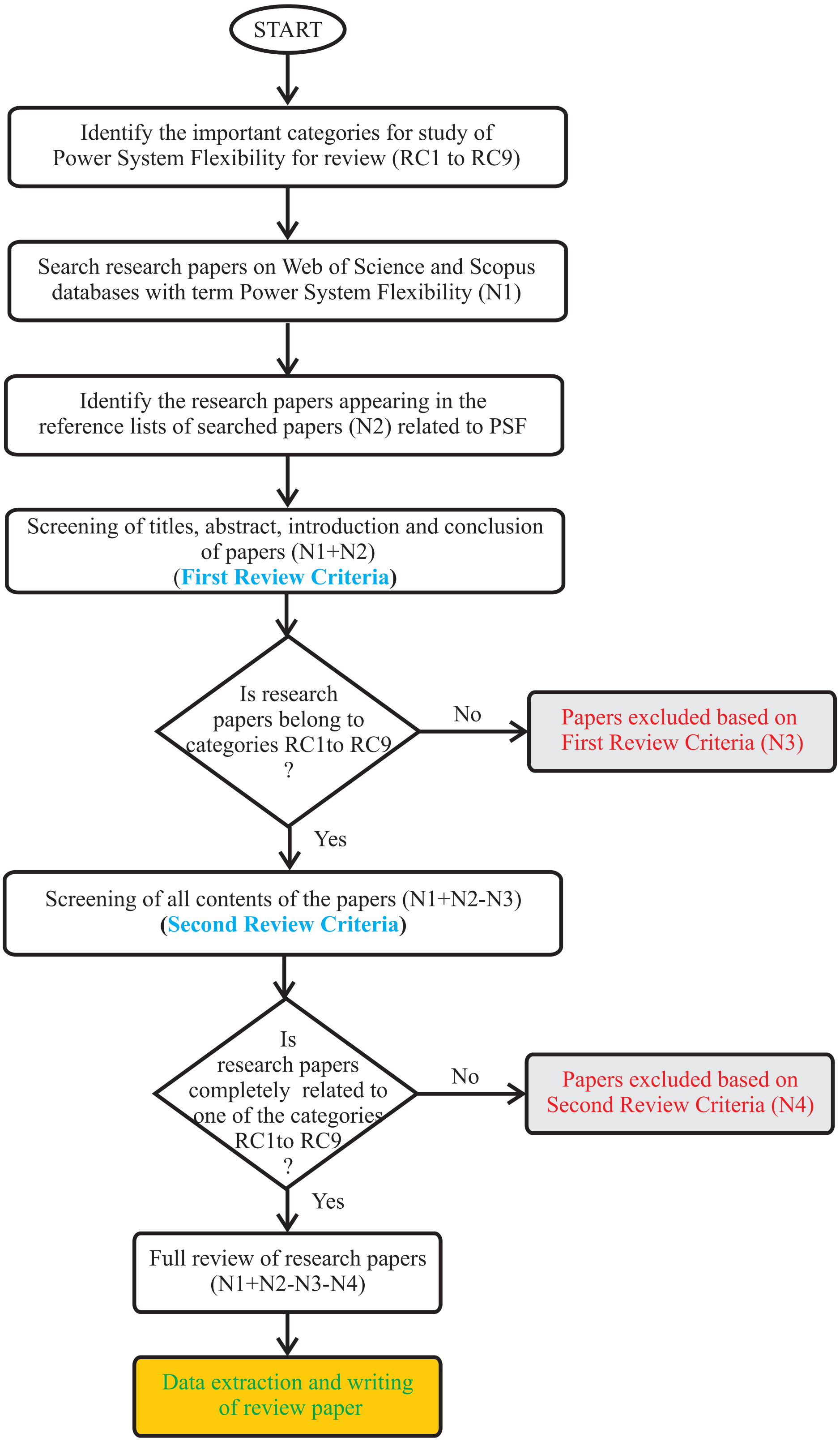

Figure 1. Review methodology used for the study.

All the research papers were categorized into nine categories which are described in Figure 2. Most of the reviewed papers are included in the category RC4 (27%), followed by RC7 (16%), RC2 (12%), and the least in the category RC9 (4%).

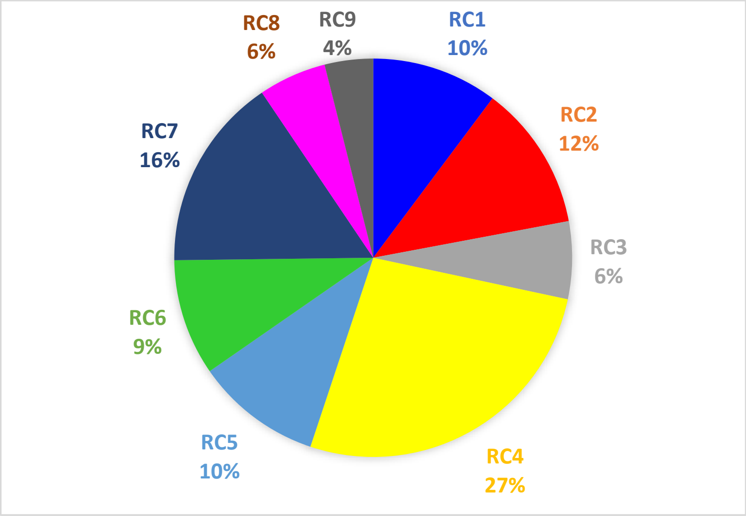

Figure 2. Categorization of reviewed papers.

3. Power System Flexibility

PSF was recognized recently by International Energy Agency (IEA) and North American Reliability Corporation (NERC). PSF is considered as the ability to demand and generate side resources connected to the network of a utility grid to mitigate the system changes and uncertainties. This indicates the capability of the network of the power system to manage the variability and uncertainties of variable renewable energy (VRE) generation [14]. The power system operator (PSO) balances generation and load demand continuously to respond to expected and unexpected variations associated with the power supply and power demand. This minimizes the variations of voltage and frequency so that high reliable power can be supplied to the consumers. Hence, PSO has to increase or decrease the output of generated power to minimize the demand variations for fulfilling the flexibility requirement. Insufficient flexibility leads to load shedding during the periods of low RE generation and curtailment of renewable energy (RE) power during the periods of high RE generation. Hence, insufficient flexibility requires additional capacity of the system for meeting the peak demand which results in reducing the operational benefits and increasing the costs [15]. There is no universal definition of PSF in the present context. Different groups and authors have defined it independently, and their contributions are tabulated in Table 1.

Table 1. Definitions of PSF contributed by authors and groups.

Reference	Definition of PSF
[16]	"The ability of a system to deploy its resources to respond to changes in net load, where net load is defined as the remaining system load not served by variable generation".
[17]	"Flexibility expresses the extent to which a power system can modify its electricity production and consumption in response to variability, expected or otherwise".
[18]	"The potential for capacity to be deployed within a certain time-frame".
[19]	"The ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons".
[20]	"The system's capability to respond to a set of deviations that are identified by risk management criteria through deploying available control actions within predefined time-frame and cost thresholds".
[21,22]	"Operational flexibility is defined in terms of power capacity (MW), ramp rate (MW/min), i.e., the ability to increase energy production with a certain rate, and ramp duration (min), i.e., the ability to sustain ramping for a given duration".

Table 1. *Cont.*

Reference	Definition of PSF
[23]	"The general characteristic of the ability of an aggregate set of generators to respond to variations and uncertainty in net load".
[24]	"The ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant time scales".
[25]	"Readiness of power system network for higher shares of variable RE".

The PSF is essentially needed to increase VRE penetration in the utility grid for achieving the RE targets of maintaining high efficiency and reliability of power grid. Flexibility can be increased by demand side management (DSM), energy storage systems (ESS), energy curtailment, sector coupling, and expansion of transmission grid [26]. PSF can be characterized by different indicators, and six different indicators are detailed in Table 2 [27].

Table 2. Summary of indicators utilized for characterizing the grid flexibility.

S. No.	Indicator	Characteristics of Grid Flexibility
1	Reliability of grid	How is the current grid reliable in terms of disruption?
2	Ramp of load profile	How steep is the ramp of daily load profile of a nation in the worst-case scenario?
3	Access to the electricity market	How much access to the trade of electricity does a country have to balance excess and deficit generation of electricity?
4	Forecasting system	Whether the forecasting techniques are employed to predict the expected generation from solar and wind energy or not.
5	Ratio of natural gas for generation of electricity	What is the share of natural gas in electricity generation?
6	Diversity of RE	How many RE sources of various nature are grid connected in the present scenario?

4. Drivers of Power System Flexibility

Rapid, large-scale integration of VRE to the network of utility grid is a main factor for driving the investigation related to PSF. The VRE sources are becoming cost-effective and cheaper to generate electricity due to non-requirement of fuel and available government subsidies. Hence, the thermal power plants (TPPs) with low efficiency are not capable to compete with the VRE sources. However, VRE sources generate variable output power which causes uncertainty and fluctuations in power generation. These fluctuations affect the power plant mix, sequence of power plant dispatch, and frequency. Hence, flexibility is essentially required. The fluctuating fuel prices, growth in VRE generation, choice of new technologies by consumers, and environmental regulations and policies are the main drivers of research into flexibility [28]. Important drivers of PSF are discussed in the below subsections.

4.1. Increase in Penetration of Variable RE in Power Grid

The issues of global warming and changes in climate due to environmental impacts have forced us to reduce the use of fossil fuels. This has motivated research efforts and the framing of effective policies for environment which will increase the application of VRE sources to generate electricity [29]. Wind and solar (both PV and thermal) are the emerging RE technologies used for large-scale generation of electrical power. These sources of RE power are intermittent and uncertain in nature due to the variable nature of both the solar energy and wind energy resources [30]. The changes in weather conditions are the cause of intermittent nature of RE power generation. This can reduce the power generation capacity of turbines used in the wind power plants by 100% on calm days and up to 70% on cloudy days for solar power plants. This is greatly related to the changes in power generation from the generators of conventional power plants and variability in load demand. This problem has become significant and more challenging with the increased penetration of VRE sources with the power system network [31]. This has forced the inclusion of flexibility in the network of power.

4.2. Uncertainty in Fuel Price

Fluctuating and uncertain fuel prices also drive the need for flexibility. The fuel prices of conventional energy sources such as natural gas and coal are fluctuating, and their availability is also uncertain. This causes uncertainty during generation expansion planning. The prices of coal are moderately stable and increase at an annual rate of rise equal to 2%. The price of natural gas is unpredictable, to a large extent. Natural gas is the most expensive fuel compared to other fuel sources used for electricity generation, and its prices are volatile in nature which causes a high level of uncertainty [32]. As per the United States Energy Information Administration (EIA), the projected natural gas prices in the year 2040 would range from USD 8.50/MMBtu to USD 17.50/MMBtu [33]. This high level of uncertainty will affect the generation mix, dispatch order, and frequency, resulting in requirement of flexibility.

4.3. Uncertainty in Load Demand

Load is the inherent source of variability and uncertainty and drives the need of flexibility in power system operations. Furthermore, unplanned outages of generation units, shut-down of transmission lines and transformers, and other equipment/facility components also drive the flexibility [34]. Due to development of accurate and efficient load-forecasting algorithms, it has become possible to mitigate variability and uncertainty of load during power system operations to some extent. However, with consumer movements towards use of active energy, the uncertainty in load is continuously increasing, which increases the need for flexibility. Furthermore, use of electric vehicles also increases the need for localized flexibility [35].

A critical review of the papers discussed in this section is carried out, and a comparative study is prepared for all types of drivers considering various aspects and dimensions which affect the PSF and are illustrated in Table 3. Results are expressed on a scale of 100. Higher values indicate the increased need for flexibility. Flexibility needed for increased penetration level at the distribution system operator (DSO) level is considered maximum and is taken as 100. Flexibility requirements for all other drivers is expressed relatively.

Table 3. Drivers and relative increased need for flexibility.

S. No.	Flexibility Driver	Relative Strength
1	Increased wind generation at transmission system operator (TSO) level	95
2	Increased wind generation at DSO level	86
3	Increased solar PV generation at TSO level	87
4	Increased solar PV generation at DSO level	100
5	Generation outages	68
6	Inflexibility of conventional power plants	82
7	Reduced contribution from conventional power plants	81
8	High volatile load	78
9	Load forecasting error	52
10	High volatile exchange of power between regional grids	65

Table 3. *Cont.*

S. No.	Flexibility Driver	Relative Strength
11	Changes in energy market design	77
12	Changes in system operational policies	76
13	Increased transmission system congestion	78
14	Transmission/interconnector outages	73

5. Resources of PSF

Recently, the VRE has been integrated to the utility grid in large quantum. Furthermore, energy storage systems are being deployed in utility grids. Hence, present-day power systems are complex in nature, with the form of source–grid–load–storage [36]. Resources of flexibility have different forms in view of all four components and are detailed in the below subsections.

5.1. Flexibility of Generation Source

Power generation sources include thermal power plant (TPP), nuclear power plant (NPP), hydropower plant (HPP), and renewable energy. Each of these sources provide power system flexibility limited to their design and operational constraints. The conventional power plants such as TPP and HPP have a limited role in optimization of flexibility. The startup time of TPPs is long, and energy consumption for start–stop is high. The seasonal and geographical restrictions affect the generation from many HPPs. Generation from NPPs is limited in terms of response time and economic considerations, and it is inflexible and does not participate in flexibility [37]. Hence, conventional generation sources have limited impact on optimization of PSF. The TPP and HPP power plants can participate in flexibility by modifications including capacity of TPP for deep peak load regulation, yearly regulated HPP, oil fired units, and gas fired units [25].

Large-scale grid-integrated RE influences security and stability of a power system network. Centralized wind power plants (WPPs) and solar power plants (SPPs) equipped with efficient controllable mechanisms provide good flexibility under certain conditions [38]. A detailed study on the flexibility from distributed multi-energy systems is detailed in [39].

5.2. Flexibility of Utility Grid

Interconnection of power grids of nearby regions will help to exchange power between these grids, which increases the supply demand balance, increasing the flexibility. However, improvement in transmission capacity will increase the cost and risk of faults on the power network [40]. In [41], authors introduced a method to decrease wind energy curtailment by increasing the transmission capacity between the areas in Sweden and those in Norway and Denmark.

Reliability and economy are considered for economic load dispatch, optimal power flow, reactive power dispatch, and power generation in the traditional power system without considering flexibility. However, considering interconnections of power grids and market transactions, dispatching modes can be adopted to improve PSF to some extent [42]. A flexibility-based risk-limiting dynamic economic load dispatch solution for the grid incorporated with wind power plants is described in [43], wherein unwanted wind curtailment and load shedding are reduced. In [44], authors proposed a model using a multi-objective optimization technique for layout of a transmission line in China, wherein grid stability and the flexible resources are considered for eliminating the power transmission bottleneck and improving the cross-regional consumption of RE power. It is established that power transmission capacity will increase by 265% in 2039 compared to 2018. Multiple uncertainties due to wind power fluctuations and generator failures is mitigated by controlling power flows on the HVDC and HVAC transmission lines [45]. It is established that HVAC transmission switching can assist HVDC for optimizing the power flow and provide more flexibility.

5.3. Flexibility of Load

Power supply and demand balance are managed effectively by demand side management (DSM) and demand response (DR). Both the DSM and DR are utilized for improving the flexibility of a power network on the timescales of a second, a minute, and 10 min, considering rapid regulation modes [46,47]. In [48], authors investigated demand side flexibility (DSF) of a building stock in Singapore and explored the realization of flexibility using demand-side bidding. Modeling of a building energy system and a model of relationship among occupant comfort and load with model predictive control is utilized to allow optimal load scheduling, and the objective to minimize the overall electricity cost while maintaining comfort of the occupant is achieved. Hu et al. [49] carried out a detailed survey on the technology, architecture, and methods used for neighbourhood-level coordination and negotiation in residential microgrids for DSF management. In [50], authors presented a study to analyze the energy system impacts of price-induced DSF with empirical data. Effects on the energy system for connecting consumers of household electricity with data of their consumption and price is assessed. DSF from household consumers is evaluated using data from an 18-month field trial on 1557 Austrian households. In [51], authors analyzed the impacts of DSF participation in a spot market and reserve market with respect to the German power network for the scenario of 2030, and a summary is provide in Table 4. It is observed that use of DSF decreases the impacts of reserve provision on the cost of a system, and the largest reduction is observed in the scenario of low coal/high VRE.

Table 4. Summary of impacts of DSF on a system with reserve.

S. No.	Attribute	Baseline Scenario	Low Coal Scenario	Low Coal/High VRE Scenario
1	Reduction in total operational cost of a system using reserves due to DSF	EUR 349 M (2%)	EUR 378 M (1.7%)	EUR 2814 M (11.3%)
2	Reduction in cost of reserve provision due to DSF	EUR 100 M	EUR 213 M	EUR 1658 M
3	Change in average price due to DSF (%)	−3.4	−1.9	−25.8
4	Change in variability of prices (standard deviations from average) due to DR (%)	−58	−59	−27.3
5	Change in variability of load (standard deviation of load changes between hours) due to DR (%)	+17	+8.5	+15.6
6	Change in the maximum hourly demand (%)	+12%	+7%	+9%

Use of the electric vehicles (EVs) is continuously increasing. EVs are high-capacity loads. Charging behavior of EVs has high level of uncertainty and produces a negative impact on PSF. However, if EVs are guided for charging in an order and combined with DSM or DR, these can be used as a flexibility improvement option with distributed energy storage devices [52]. Kim et al. [53] investigated a technique for utilization of EVs as flexible resources. An operation method for securing the flexible ramping products in the microgrid was also introduced. The proposed method reduced the operating cost of microgrid and stabilization of variability.

5.4. Flexibility of Storage

The commonly used storage systems for flexibility improvement in power utilities are pumped storage, flywheel storage, electrochemical storage, compressed air storage, and electromagnetic energy storage [54]. A pumped storage power station is capable of responding to load changes at a fast rate, due to which it is also considered an ideal flexibility resource. It also provides phase modulation, frequency modulation, and voltage regulation. However, installed capacity of pumped storage stations is small throughout the world [55]. In [56], authors presented a study for assessment of the flexibility provided by large-sized hydropower reservoirs installed in the western region of Africa which helped to plan grid integration of solar energy plants and wind energy plants in the region. Estimation of reservoir capacity and operations is achieved using dynamic programming. An objective to minimize the variability of residual demand is considered, which is generally met by the generation from the conventional power plants at high monetary and carbon costs.

Energy storage technologies are also used in the power system to improve flexibility at large scales. However, use of these technologies is limited due to economy and technological constraints [57]. In [58], authors presented a framework of distributed computing which is based on the novel column generation and sharing algorithm with reduced computational burden. This is effectively used for planning of RE systems incorporated with energy storage to provide flexibility options. A detailed study for techno-economic analysis of long-duration energy storage systems and technologies of flexible power generation to provide support to the grids with high VRE is presented in [59].

5.5. Flexibility of Aggregators and Multi-Energy Systems

Aggregators and multi-energy systems (MES) are two technologies pointed by industry and researchers which provide effective and key flexibility solutions to enable power systems to operate at high levels of VRE penetration. Aggregators are used to activate the full range of customers in demand response and help to aggregate the resources in an adequate technical and economical format. The aggregators provide flexibility considering constraints of network, generation, and consumers, and support security of power supply systems [60]. Various types of aggregators, depending on the source of aggregated energy and used for flexibility, are described in Figure 3 [61]. MES uses integration of multiple energy vectors which are operated optimally to realize low-carbon energy systems. These sources can provide power system flexibility by shifting across different energy vectors [39].

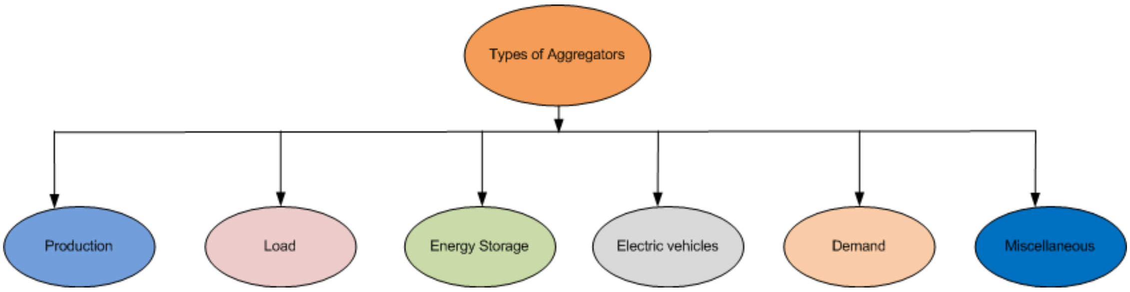

Figure 3. Types of aggregators depending on the source of aggregated energy.

A two-stage stochastic optimization model to support an aggregator of prosumers for bidding of the day-ahead energy and secondary reserve markets is proposed by authors in [62]. Prosumers' flexibility is optimized by the aggregator considering minimization of net cost of buy and sell of energy. Furthermore, secondary reserve in both day-ahead and real-time market stages are also considered for flexibility optimization. Different scenarios of uncertainties of the RE power generation, consumption of electrical power, outdoor temperature, prosumers' preferences, and house occupancy are considered for the study. It is established that proposed bidding strategy effectively reduces the costs of both aggregator and prosumers by 40% compared to existing bidding strategy used by retailers. Pakere et al. [63] proposed an in-depth system dynamics model for introduction of aggregators as a future player aimed to increase total share of the RE power in utility grids and simultaneously decrease the surplus solar and wind electricity occurrence. The hourly rates of power production and consumption at the national level for the Latvia grid are analyzed. It is established that introduction of aggregators and load shifting based on standard peak shaving effectively increases the share of surplus power. Furthermore, demand-side management using available RES power generation effectively decreases the surplus power by 5%. A study on participation of an aggregator of small prosumers in the energy and tertiary reserve markets is presented in [64]. A two-stage stochastic optimization model is designed for exploitation of load and generation flexibility of the prosumers, and energy and tertiary reserve bids to minimize the net cost of the aggregator buying and selling energy in the day-ahead and real-time markets, as well as to maximize the revenue of selling tertiary reserve during the real-time stage, are introduced.

The energy system is changing, and emerging RE power resources are accommodated in the existing power network which helps to improve power reliability and flexibility. In [65], authors introduced a method for co-optimization of a multi-energy microgrid, considering multiple services such as energy arbitrage, frequency control ancillary services, and network reliability services. In [66], authors presented a method for storing the renewables in the gas network. Modeling of power-to-gas seasonal storage flexibility in low-carbon power systems is discussed in detail. In [67], authors designed a method for integration of storage and thermal demand response to unlock flexibility in district multi-energy systems to reduce energy consumption and carbon emissions. An optimization is applied for operation of the generation units, capacity and operation of thermal storage units, and the application of demand side management to the thermal network for flexibility improvement.

After detailed review of the papers discussed in Section 5, different technologies/solutions used for the improvement of flexibility are identified for all four categories of flexibility resources and are summarized in Table 5. Furthermore, characters of various resources of PSF are evaluated and summarized in Table 6.

Table 5. Technological options and solutions for flexibility.

S. No.	Resource of Flexibility	Solutions/Technology
1.	Flexibility from storage	Pumped hydroelectric energy storage (PHES); flywheel energy storage (FES); compressed air energy storage (CAES); lithium-ion batteries (Li-ion); lead–acid batteries (PbSO4); sodium–nickel–chloride batteries (NaNiCl); nickel–cadmium batteries (Ni–Cd); zinc–bromine batteries (ZnBr); sodium–sulfur batteries (NaS); capacitor energy storage (CES); vanadium redox flow batteries (VRB); superconducting magnetic energy storage (SMES); supercapacitor energy storage (SES)
2.	Flexibility from load (demand side flexibility)	Demand response from large industrial plants; demand response from commercial and domestic sectors
3.	Flexibility from generation	Variable RE power plants; open-cycle gas turbine power plants (OCGT); combined heat and power plants (CHP); combined-cycle gas turbine power plants (CCGT); biogas power plants (BGPP)
4.	Flexibility from utility grid	Inter-regional power grid interconnections; transmission capacity addition; power to hydrogen conversion and reuse; power to heat and gas conversion and reuse

Table 6. Characters of PSF resources.

Type of PSF Source	Attribute	Flexibility	Economy	Quantity	Maturity
Generation source	Traditional generation	Not bad	Good	Less	Fully matured
	Well-controlled RE source	Good	Very good	Large	Not matured
Utility Grid	Interconnections of power grid	Not bad	Not bad	Small	Matured
	Optimal dispatch	Good	Good	Small	Matured
Load	DSM/DR	Very good	Very good	Large	Matured
	Electric vehicle	Not bad	Good	Large	Matured
Storage	Pumped storage power station	Very good	Very good	Small	Fully matured
	Additional energy storage devices	Very good	Not bad	Small	Not matured

6. PSF Requirements

PSF requirement is the measure of extent to which a system is capable to modify generation or consumption of electricity in response to variability. To ensure stable operation of a power system network, balance between the supply and the demand must be maintained at various timescales ranging from milliseconds to seasons. High VRE penetration into the utility grids triggers the challenges for power system balancing and requirement of flexibility initiatives [68]. Flexibility requirements may be assessed in terms of balancing the time horizons, flexibility requirements of net load, and flexibility requirements of VRE. Furthermore, flexibility requirements can also be assessed in terms of the flexibility of power, flexibility of energy, flexibility for transfer of capacity, and voltage flexibility.

The calculation of flexibility requirements are generally carried out on four balancing time horizons which include 15 min, one hour, 6 h, and 36 h. The 15 min time horizon is very crucial because it is evaluated in this time horizon how fast and efficiently the flexible resources are capable of responding to steeper ramps for maintaining the balance in supply and demand. Furthermore, the one-hour time horizon is also important, as the planning of generators in intraday market is performed in terms of hourly blocks. The 6 h time horizon is also effective because most of the dispatchable power plants start up or shut down within a period of 6 h [69].

Flexibility requirements of net load are assessed using the data of system load, transmission RE sources, and imports and exports of power on a same time horizon. Net load is computed using the following relation [69]:

$$\mathrm{NL} = \mathrm{SL} + \mathrm{PE} - \mathrm{TRES} - \mathrm{PI} \tag{1}$$

where NL: net load, SL: system load, TRES: transmission RE sources, PI: power import, PE: power export. The upward and downward ramps of the NL will help to assess the required load flexibility.

Flexibility requirements of VRE depend on the variability and uncertainty of RE output forecast. Variability is described in terms of the percentage of total installed capacity per minute considering the maximum ramp and ramp rate in a given time frame. Uncertainty depends largely on how far ahead of delivery the producer must commit for delivering a specific quantum of energy maximizing the error forecast on the 36 h time horizon. This is described as percentage error of total installed capacity per minute [69,70].

Flexibility requirement for power indicates the balance between supply and demand required for maintaining frequency stability for a small time period. This is caused due to the dependency of the power supply on intermittent weather conditions. Flexibility requirements of energy supply demand balance are needed for demand scenarios over medium- to long-term periods. This is due to decreased fuel storage-driven supply of energy. Requirements of flexibility for transfer capacity indicate the power transferability required to avoid bottlenecks over small to medium periods of time. This is caused due to increase in peak demands, peak supply, and consumption levels. Flexibility requirement for voltage indicates that bus voltage is required to maintain within prespecified limits over short time periods. This is due to increased level of VRE in power system networks which results in bidirectional power flow and variance in operational scenarios [71,72].

The operating reserve indicates the active power capacity that can be used for load generation balance and frequency control. Operating reserves are used to improve flexibility by managing the variability due to RE sources and forecast error [73]. Operating reserves are mainly classified in three categories, which include regulation reserve, spinning reserve, and non-spinning reserve. Regulation reserve indicates the capacity product for responding to short-term changes in electricity demand which might affect the frequency of a power system. Spinning reserve indicates the capacity provided by resources which are running (i.e., “spinning”) and supports the bulk electric system to restore the frequency after a forced outage. Non-spinning reserve is a capacity product intended to help the system to recover from unplanned contingency [74]. In [75], authors presented a method which can be utilized to determine operating reserve with increased wind energy penetration in a utility grid. It is established that dynamic allocation of reserves will reduce the capacity of reserves required in the system. In [76], authors presented a study for investigation of the impacts of modeling non-normality and stochastic dependency of variables for determination of operating reserves of the power systems during the event of high penetration of wind power into the utility grid.

Related Research

Flexibility issues related to a low carbon power system network and short-term impacts of intermittent nature of RE sources have been investigated by authors in [77]. It is established that power plants using coal-fired technology can provide flexibility to balance variations of wind power. Heggarty et al. [78] proposed a technique which used analysis of frequency spectrum-based metrics to evaluate flexibility requirements on annual, weekly, and daily time horizons. Sensitivity of the flexibility requirements to the network interconnections, penetration of wind energy, solar energy, electric heating, and cooling is also investigated. The study can be utilized for identifying future challenges, estimating market potential to provide flexibility solutions, and computing impact of policy-related decisions. In [79], authors developed a multi-timescale UC and a model of economic load dispatch for estimating the requirements of ramping. A solar power ramping product (SPRP) was also designed and used in coordination with the multi-timescale dispatch model considering the ramping capacity limits, flexible ramping requirements, active power limits and an objective function. It is established that application of SPRP will reduce the requirement of flexible ramping reserves for generators of conventional power plants. In [80], authors discussed the flexibility requirements for large-scale grid integration of VRE to the network of an Indian power system. Options of technology, policy, and modeling were discussed in detail.

7. Flexibility Metrics

The flexibility requirement of a power system network are quantified in terms of various metrics such as power magnitude (MW), frequency, ramp response of generator (MW/min), available flexible resources (MW), flexibility trinity, periods of flexibility deficit (PFD), expected unreserved ramping (EUR) (MW/min), insufficient ramp resource expectation (IRRE), flexibility wellbeing assessment, ramping capability shortage expectation (RSE) (hours/day), and expected flexibility shortfall (EPS). A brief summary of these metrics reported in literature is provided in Table 7. These metrics describe the flexibility at operational timescales. A power system network can be operated at various levels of flexibility estimated on selected timescales which vary from a few seconds to months. All time intervals require different levels of flexibility. To estimate PSF, generally, the unpredictable fast seasonal change is considered which is equal to net load, i.e., demand-VRE. PSF analysis considering the time scale is demonstrated in Figure 4 [25]. Important metrics are briefly described below.

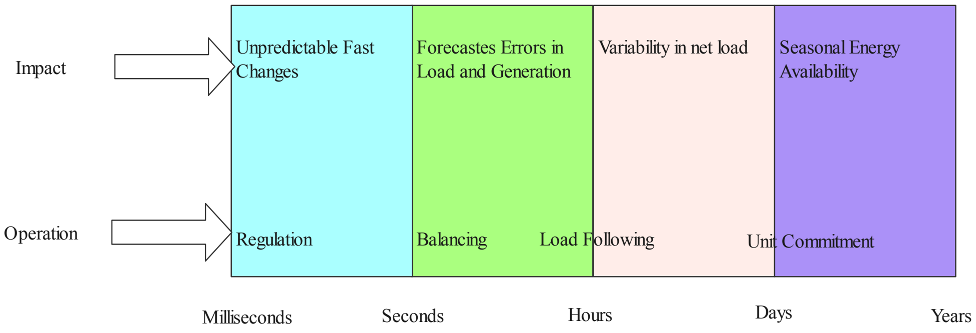

Figure 4. PSF analysis considering timescale.

Table 7. Definitions of PSF metrics.

Reference	PSF Metrics	Definition
[81]	Magnitude (MW)	"Generation capacity required to respond for a ramp event on supply side whereas on the demand side, incremental and decremental flexibility requirements is dependent on the size of net load ramp or outage".
	Ramp response	"This indicates the rate of change of net load or plant output and their predictability".
	Frequency (# occurrence)	"Number of instances for events of different sizes and responsiveness occurs are measured. Available flexible resources incur an operating cost every time they are used to balance supply and demand resulting in cost implication".
	Available flexible resources	"This estimates the capability of changing resources in response to mismatch between net load and total available generation".
[82]	Expected flexibility shortfall	"This effectively measures the conditional expectation of load loss due to right arrow insufficient flexibility".
[83]	Period of flexibility deficit (periods)	"It measures the number of instances when there is a deficit of power from available flexible resources".
	IRRE	"A probabilistic method is used to determine the likelihood of flexibility deficit over a variety of time horizons".
	Expected unreserved ramping (MW/min)	"It indicates the total magnitude of deficit of net flexibility".
	Flexibility wellbeing assessment	"It combines the information from PFD and EUR metrics to classify system states such as safe, warning, or dangerous".
[84]	Flexibility trinity	"It indicates the power ramping capability (MW/min), power capability for up/down regulation (MW) and energy storage capability (MWh)".
[85]	RSE (hours/day)	"Similar to IRRE, this metric is capable to assess the probability for which the net load variations are not covered by the system's ramping capability".

PFD metric can be computed on a convenient user-decided time horizon for a particular direction considering available flexibility. PFD also helps for identification of number of periods of flexibility shortages and corresponding time horizons. Different actions may be required to solve every flexibility issue. The improved short-term forecasting capabilities, reserve sharing between connected systems, dynamic and probabilistic reserve procurement strategies, and fast-start and high-response resources are used to mitigate deficits over shorter time periods. Long-term forecasts for scheduling of large, slow-starting generation and intertie flows are used to mitigate deficits over longer time periods. Even after adopting operational practices, if there is still a flexibility deficit, then new resources may be required. Number of PFD for different time horizons is detailed in Figure 5. It is inferred that there are large number of periods for short time horizons (e.g., 1 h in length) when a flexibility deficit would occur. However, for large time horizons (approximately 8–10 h), there are a moderate number of periods with flexibility deficits due to large magnitude of net load ramps. For other time horizons, number of flexibility deficits is relatively low. Hence, it is established that number of flexibility deficits in short duration ramps is the main concern over the course of a year [83,86].

EUR flexibility metric indicates the total magnitude of deficit of net flexibility. EUR differs from the expected unreserved energy metric with respect to the capacity adequacy planning. Operational changes effectively meet the smaller magnitude shortfalls of flexibility. This may not be required for operation of the system, depending on the risk level. Higher EUR levels are required for operational modes for existing resources or large-scale demand side, generation, or transmission resource additions to supplement the system's current capability [83].

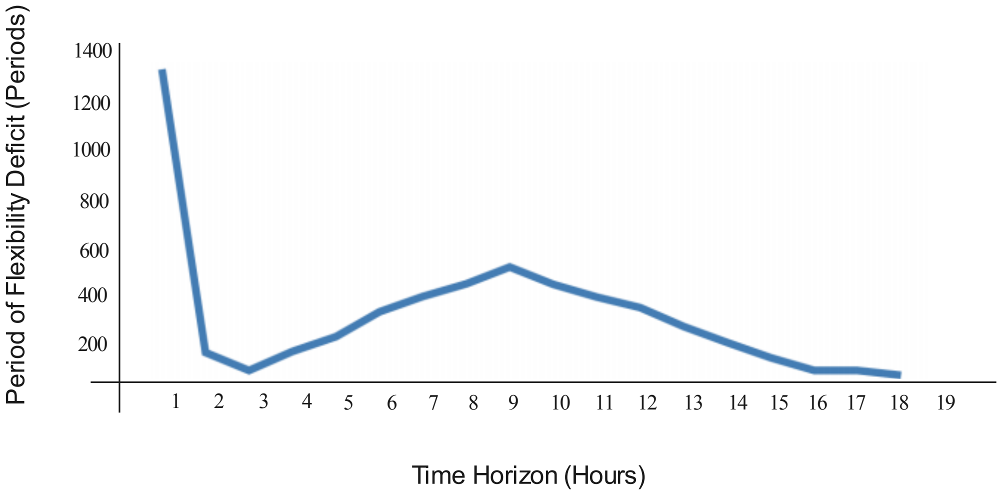

Figure 5. Number of PFD for different time horizons.

The IRRE measures frequency of shortfalls of flexibility over a time horizon using a probabilistic approach for determination of possibility of meeting every net load ramp incident on a distribution power network at every time period. IRRE helps to achieve comparison between flexibility available and net load ramps from a distribution network and computes the probability of meeting each ramp and expected magnitude over a time series. The IRRE is a more conservative approach to flexibility assessment compared to the PFD [83].

Flexibility wellbeing measurement metric combines the information of PFD and EUR metrics for determination of state of system, such as user-defined safe, warning, or dangerous state. A system which is currently operating with good reliability is further tested and verified using this metric. This metric allows users to plot the frequency and magnitude of flexibility deficits using an intuitive method based on categorization of values. Figure 6 describes the zones and data points for a test case illustrating the flexibility wellbeing assessment. It is observed that for a selected time horizon, the PDF and EUR coordinates are outside the safe and warning zones. This plot is effective to determine the combinations of frequency and cumulative magnitude of flexibility deficiencies [83,87].

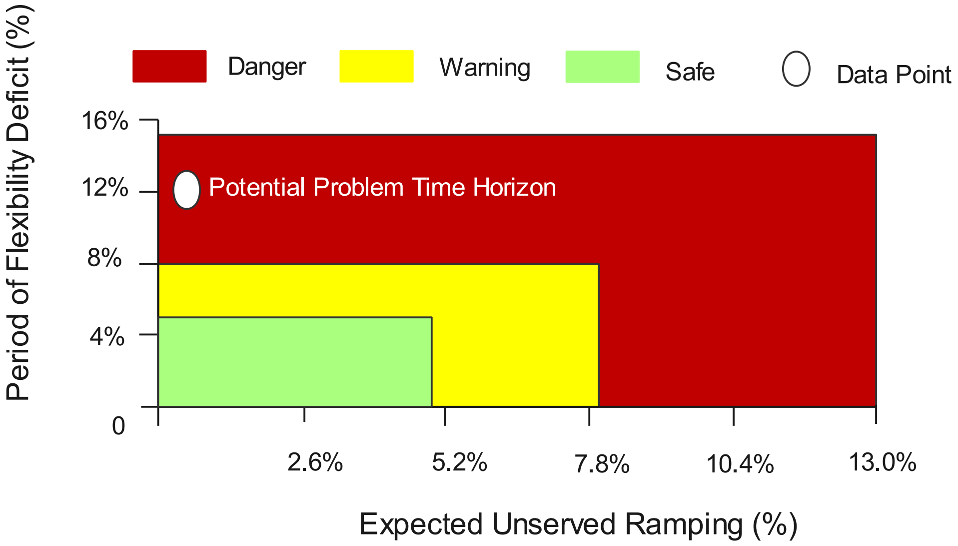

Figure 6. Number of PFD against the sum of magnitudes of the deficits over time horizon of one year, illustrating the flexibility wellbeing analysis.

Related Research

A detailed study on the utility grid-level energy storage systems and requirement for the flexibility capacity metrics is presented in [88]. The dispatch of three large energy storage technologies and a conventional generator was optimized using a mixed-integer linear program considering price-taker first in a day-ahead market. Abrantes et al. [89] designed a method for assessment of operational grid flexibility (GOF) focused on economic impacts of net load variability/uncertainty metric, and it was established that market outcomes give a good basis for assessment of GOF. In [90], authors discussed the use of flexibility metrics for analysis of challenges faced by grid operators for balancing during the scenario of high share of variable RE sources. A new metric is proposed, and advantages are combined with the existing metrics to enhance the flexibility properties and capability of utility grids in Japan and Sweden for balancing. In [91], several metrics are detailed for quantification of building-to-grid demand response flexibility using heat pump aggregations for different stakeholders. A control method for aggregations was also designed, using a multi-energy residential energy consumption tool which is effective to assess flexibility over long sustain times (e.g., reserve services). Oree et al. [92], developed a composite metric which effectively and accurately assessed the flexibility of a power system network with conventional generators using eight technical parameters of generating units as indicators. It was established that the designed composite metric is consistent in nature and adaptive to automatically add/remove the generating units.

Detailed analysis of the papers discussed in Section 7 was carried out to evaluate performance of various metrics and specific use of the metrics. A summary of metrics meant for stakeholders of the power field is included in Table 8.

Table 8. Metrics for power system stakeholders.

Name of Stakeholder	Name of Metric	Specific Content
System and network operators	Power payback ratio (PPR)	Electrical Power
	Coincidence factor	Electrical Power
	Constant to maximum ratio	Electricity
Retailer	Energy payback ratio	Electricity
	Total energy change ratio	Electricity
	Net energy transfer ratio	Gas and electricity
Aggregator	Impacted dwelling percentage	Time
	Average distribution duration	Time
	Average power contribution	Electrical Power
Consumer	Probability of comfort variations	Temperature

8. Measurement of PSF

Measurement of PSF depends on the predefined characteristics. Here, assessment of PSF is discussed, considering the technical viewpoint and analytical approach.

8.1. Technical Viewpoint to Measure PSF

There are four technical parameters which have great impacts on the PSF and are considered for measurement of flexibility. These include minimum power generation capability of power plants, capability of ramp rate, cycling rate described in terms of startup time of generation units and controllability of a generating plant/unit. These criteria used for PSF measurement changes with time depending on the generation, transmission, and distribution conditions [93,94]. Figure 7 illustrated the power system flexibility measurement technique considering technical characteristics [95]. Technical flexibility measurement characteristics are described in the below subsections.

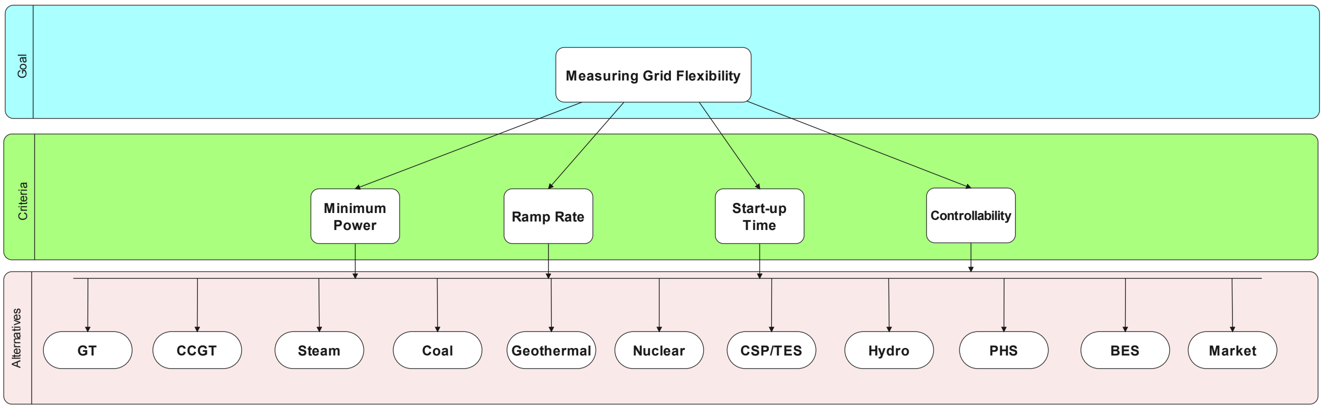

Figure 7. PSF measurement using technical characteristics (GT: gas turbine, CCGT: combined cycle gas turbines, CSP: concentrated solar power storage, TES: thermal energy storage, BES: batteries energy storage).

8.1.1. Minimum Power

The minimum generation of power by a unit which ensures that safe operation of a plant has an effective role for estimation of the flexibility. The units, for which the minimum power of the generating plant or storage unit are large, are not able to mitigate large changes that occur due to large variability of the VRE sources when the level of RE penetration into the network of power system is high. If the minimum power of the safe operation of the unit is low, then power dispatching becomes easier and the units effectively participate in the flexibility [93]. Hence, the difference between the rated capacity and the minimum percentage of rated capacity of a power-generating unit, for which safe possible operation of the unit is an important characteristic, is important for measurement of flexibility capability.

8.1.2. Ramp Rate

The capability of the reserve source which can provide positive and negative ramp rate is defined as the degree of meeting the ramp rate of the load minus RE sources. MW/min is the unit used to define ramp rate. Different variations in sources of flexibility are used to track power changes in various time frames and regulate the power in very small scales of time [96]. Hence, ramp rate is an important characteristic used to measure the PSF.

8.1.3. Startup Time

The capability of a generation cycle can be expressed in terms of startup time. This is a flexibility metric approach which can be effectively used for measurement of flexibility. The startup time provides information related to capability of a plant for how fast the unit can support the network of a power system during a time period when sudden change in the demand and large variations in uncertain VRE generation is observed [95]. Hence, small startup time will provide high flexibility, and low startup time will provide small flexibility.

8.1.4. Controllability

The controllability of the generation output indicates the ability of peripheral input to change the output from a primary situation to a final condition. The systems may have partial control capability or full control capability. The partial controllability is caused due to the constraints of an input for changing its state [97]. There are some restrictions or constraints of the power generation plants which forces one to limit the controllability of a generation plant. This can be inferred by the difficult-to-change generation from an NPP for periods of power dispatching and operation due to safety concerns. Thermal fatigue observed during the rapid change of the set point of the generation controller has a great impact on control decisions [98].

A pairwise comparison is prepared between criteria with respect to the goal of the authors in [95], which is presented in Table 9. It is observed that ramp rate is considered to be the most important criterion, followed by minimum power. The controllability and startup time have minimum impact on the power system flexibility.

Table 9. Pairwise comparison matrix with respect to goal.

	Minimum Power	**Ramp Rate**	**Startup Time**	**Controllability**
Minimum power	1	0.18	4.55	1.89
Ramp Rate	5.44	1	9	6.33
Start-up Time	0.22	0.11	1	0.27
Controllability	0.53	0.16	3.67	1

8.2. Analytic Framework to Measure PSF

Analytic frameworks help to assess that a system has sufficient flexibility for matching the generation and load over the entire time horizon. The under scenarios of projected RE growth and change of the demand profile and effectiveness of a system to improve flexibility are considered in the analytical approach of PSF measurement. There are three important steps in analytical approach which include estimates of flexibility of a system, first-cut analysis of time series data, and assessment of flexibility considering power system planning [99].

8.2.1. Getting Started: Quick Estimates

The capacity of sources of flexibility should be estimated. These sources include capacity levels of dispatchable hydropower plant, combined cycle gas turbine (CCGT) plant, combined heat and power (CHP) plant, demand response, interconnection to nearby network systems, pumped-hydro storage, battery energy storage (BES), etc. Flexibility charts are used to evaluate and summarize the capacities of various types of physical sources of flexibility which contribute to the ability of the power system network to achieve balance. Flexibility charts which indicate the types of generation-based flexibility of three countries and maximum share of wind power (indicated by red text) for demand of a period of one hour are illustrated in Figure 8. Percentage of installed capacity of each source of flexibility relative to peak demand is indicated by the color green. Large installed capacity will provide more possible flexibility. These charts only highlight potential flexibility sources [100]. Flexibility charts provide a quick comparison of relative strengths in flexibility to the policymakers, decision-makers, operators, journalists, etc.

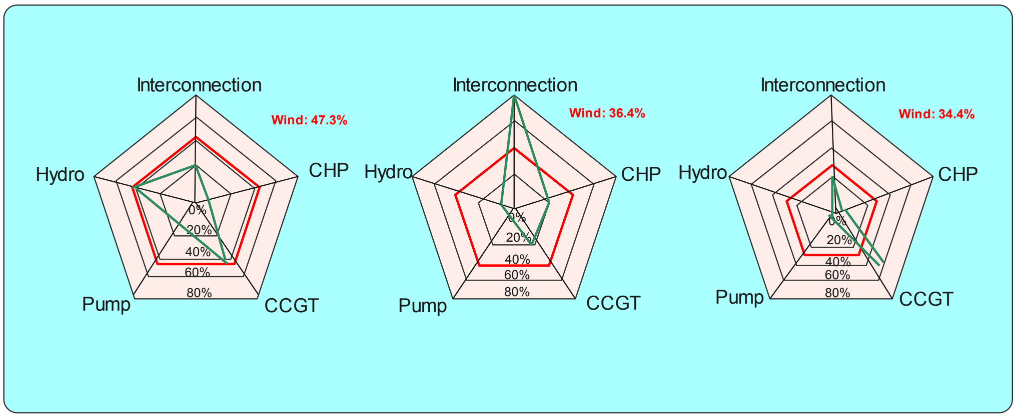

Figure 8. Frameworks and metrics charts for measuring PSF.

8.2.2. Getting Serious: First-Cut Analysis

The technical capability of the power system is assessed to meet demand for a given variability level and uncertainty level without considering RE curtailment throughout the year. Generally, PSF is a time-dependent quality of a power system and depends on the quantum of generation, shape of load curve, and seasonal and diurnal characteristics of sources of wind, solar, and hydropower. Measurements of PSF considering the time-based properties provides a strong picture to assess challenges in the system likely to be faced and possible ways to address them. This is achieved using the revised flexibility assessment tool (FAST) which is based on time-series data. FAST estimates the technical capability of a power system for integration of increased penetration levels of VRE. This is achieved by measuring the maximum magnitude of change in supply/demand balance which can be met by a network of power in a given time frame [101].

8.2.3. Getting Very Serious: Flexibility Assessment and Power System Planning

PSF is measured considering all aspects of a power system. The impact of increased VRE and dynamic loads on the operation of a power system is assessed. Furthermore, possible changes which can be applied to power systems, markets, and operations for improving the reliability are assessed. Physical characteristics such as constraints of transmission networks, size of balancing areas, and characteristics of RE resources and generators are measured. Institutional characteristics such as system operation practices (accuracy of forecasting, thermal cycling, scheduling), economic considerations, and market scenarios (incentives and costs) are assessed for providing flexibility. Combination with other systems of energy, such as transportation and CHP heat, is also assessed. Hence, flexibility measurement gives information of priorities of investment for generation and transmission capacity expansion as well as development of new methods to quantify the relationship between transmission and flexibility [102]. An analytical framework to measure flexibility is illustrated in Table 10. In this table, green, yellow, and red colors indicate the minimal, moderate, and significant impacts.

Table 10. Analytical framework to measure flexibility.

Attribute	**Getting Started**	**Getting Serious**	**Getting Very Serious**
Purpose	Simplified communication tool. Comparison across jurisdictions.	Screening tool for evaluating requirement for further flexibility analysis	Flexibility adopted resource planning
Execution complexity	Simple analytical framework	Required data may not exist. Data curation and customization may be required.	Requires advanced analysis techniques and data requirements.
Requirements of example data	Existing capacity of power system. Capacity mix and availability of interconnected systems.	Renewable resource assessment. Various time series data sets. Ramping capabilities of dispatchable sets.	Comprehensive suite of power system data. Operational rules and market and policy context.
Execution limitations	Existing capacity and interconnection data is generally available in all jurisdictions.	May be infeasible if RE resources assessments are unavailable.	May be infeasible without significant data and modeling and analytical expertise.
Limitations of results	Does not evaluate whether system is sufficiently flexible. May exclude aspects of flexibility that can not be reduced to capacity. Ramping capability of individual generators not considered.	Significant treatment of dispatchable generators. Presumes fully built-out transmission.	While analysis results are always qualified, this tier of tools and metrics provides the most robust of solutions.
Effectiveness of tool for generation and load variability	Preliminary and comparative analyses.	Systems which are evaluating need for more robust flexibility assessment (e.g., generation levels of 5–15% wind or solar).	Systems which already utilized “no regrets” sources of flexibility.
Metric	Flexibility charts.	FAST	IRRE and bulk system flexibility index.

8.3. Related Research

An integrated framework for measurement of operational flexibility of a power system network where generation has a high share of VRE is studied in [82]. Authors introduced formulation of an integrated generation expansion planning (GEP), UC model considering short-term technical constraints, use of optimization techniques to reduce computational burden, and use of appropriate metrics for assessment of operational flexibility. It is established that under high penetration of VRE, shortage level has been reduced to 50%, and load not served level reduced to 3% from 60%. Han et al. [103] proposed an improved linear formulation of the UC model by the use of unit-grouping techniques. This technique is applied for estimation of curtailment of RE and operational costs for a large-sized power network. The developed model can be used to assess long-term planning, flexibility assessment, wind curtailment analysis, and operational cost estimation. In [104], authors presented a study for estimation of potential of a network for providing flexibility using CHP systems for the year 2030. It is established that consideration of time-of-use rates as an economic incentive results in significant reduction in energy costs of consumers. Zhang et al. [105] developed a mathematical model of a wind–hydro hybrid power generation system, and flexibility indices, such as probability and expectations of upward and downward flexibility, were defined. Flexibility of various reserve ratios was assessed. It was established that with increase in reserve ratio, the flexibility (both upward and downward) was improved and independent of changes in wind speed. A review of the flexibility measurement and application to the transmission grid operational planning and electricity market is presented in [106]. Definitions of PSF, generation changes, bulk system flexibility indices, mathematical models, and calculation methodology of flexibility are discussed in detail. In [107], authors proposed a simulation-based flexibility measurement scheme to trace the effectiveness and deviations of active distribution network planning in execution. In [108], authors presented a robust optimization model considering multiple uncertainties to estimate flexible resource requirement in a Korean grid for future RE scenarios. The proposed model effectively estimated the flexibility requirements for the year 2030. Clegg et al. [109] designed a method for quantification of flexibility of an integrated gas and electrical network considering multi-RE sources and different heating scenarios. The concept of dynamic locational flexibility of a power system network was introduced in [110]. A quantitative dynamic flexibility index was designed to measure the impact of change in bus injections on the small-signal stability of the system. The applicability of the study to the Northern Regional Power Grid of India was also discussed. Capasso et al. [111] proposed a method using the technical uncertainty scenario flexibility index (T-USFI) to evaluate the local flexibility in power system network with high share of VRE.

9. Flexibility Provisions

The flexibility of all power system elements should be provided for accommodating high share of VRE and a highly responsive demand. Power plants which can ramp up/down at fast rates and efficiently are required to provide flexible generation. The transmission flexibility can be provided by the transmission networks equipped with balancing resources, capable of sharing with neighboring networks, and application of intelligent techniques for optimization. Demand-side flexibility can be achieved by demand response, storage, responsive distributed generation (DG), and application of smart network. Accurate solar and wind forecast, good collaborations between neighbors, and real-time and frequent decisions help to achieve flexible system operations. Different provisions are required for flexibility of power, voltage, transfer capacity, and energy, as illustrated in Figure 9 [112]. Flexibility of power is provided by demand-side response (DSR), short-term battery energy storage system (BESS), virtual inertia, fast frequency response, and power system stabilizer. Flexibility of voltage is provided by onload tap changers of transformers, voltage boosters, automatic voltage regulators, and coordinated voltage control. Flexibility of transfer capacity is provided by the DSR, BESS local support, topology changes, rescheduling, and phase shifting transformer (PST). Flexibility of energy is provided by back-up generation, energy storage for long term support, optimization techniques, and HVDC supergrid [113–116]. In [117], authors applied the flexible AC transmission system (FACTS) and HVDC equipment to the power network of a metropolitan area to improve power system reliability, flexibility, and controllability. In [118], authors presented a framework for efficiently characterizing the available operational flexibility in a network of multi-area power systems.

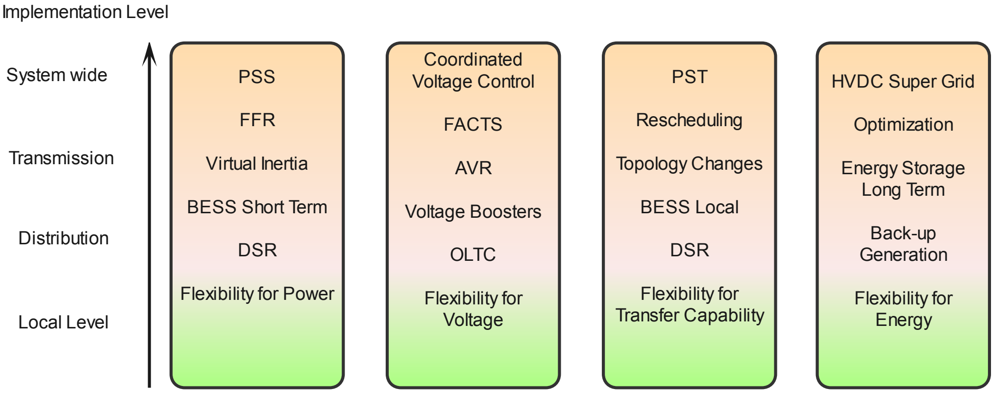

Figure 9. Flexibility provisions.

Flexibility requirements on the generation side can be fullfilled using partial load operation, load following, and fast start/stop times. The characteristics of the flexible and inflexible power plants considering minimum stable output, ramp rate, and lead time are illustrated in Table 11 [112].

Table 11. Characteristics of flexible and inflexible power plants.

S. No.	Type of Power Plant	Minimum Stable Output (%)	Ramp Rate (%/min.)	Lead Time, Warm (h)
1	Inflexible CCGT	40–50	0.8–6	2–4
2	Flexible CCGT	15–30	6–15	1–2
3	Steam turbine (gas/oil)	10–50	0.6–7	1–4
4	Inflexible coal	40–60	0.6–4	5–7
5	Flexible coal	20–40	4–8	2–5
6	Lignite	40–60	0.6–6	2–8
7	Inflexible nuclear	100	0	-
8	Flexible nuclear	40–60	0.3–5	-

10. Power System Flexibility Planning

PSF planning is a complex optimization problem and it involves different components and phases. Estimation of existing level of flexibility will help to effectively plan PSF and it also determines the present and future requirements of flexibility. Investment in the sources of flexibility needs to be increased when deficiency is observed in the system flexibility. Urgent need of flexibility might change the preference of flexible source alternatives considering the cost-effectiveness and gestation period. Alternatively, present flexibility requirements are fullfilled and then planning is carried out for future requirements of the flexibility. Flexibility planning considers the generation costs, level of over- and under-generation, curtailment level, reserve margin, and network capacity [119]. The process of power system flexibility is illustrated in Figure 10. PSF planning involves three important steps, including evaluation of present flexibility level, response to flexibility deficiency using least-cost-based approach, and assessment of future flexibility requirements [28].

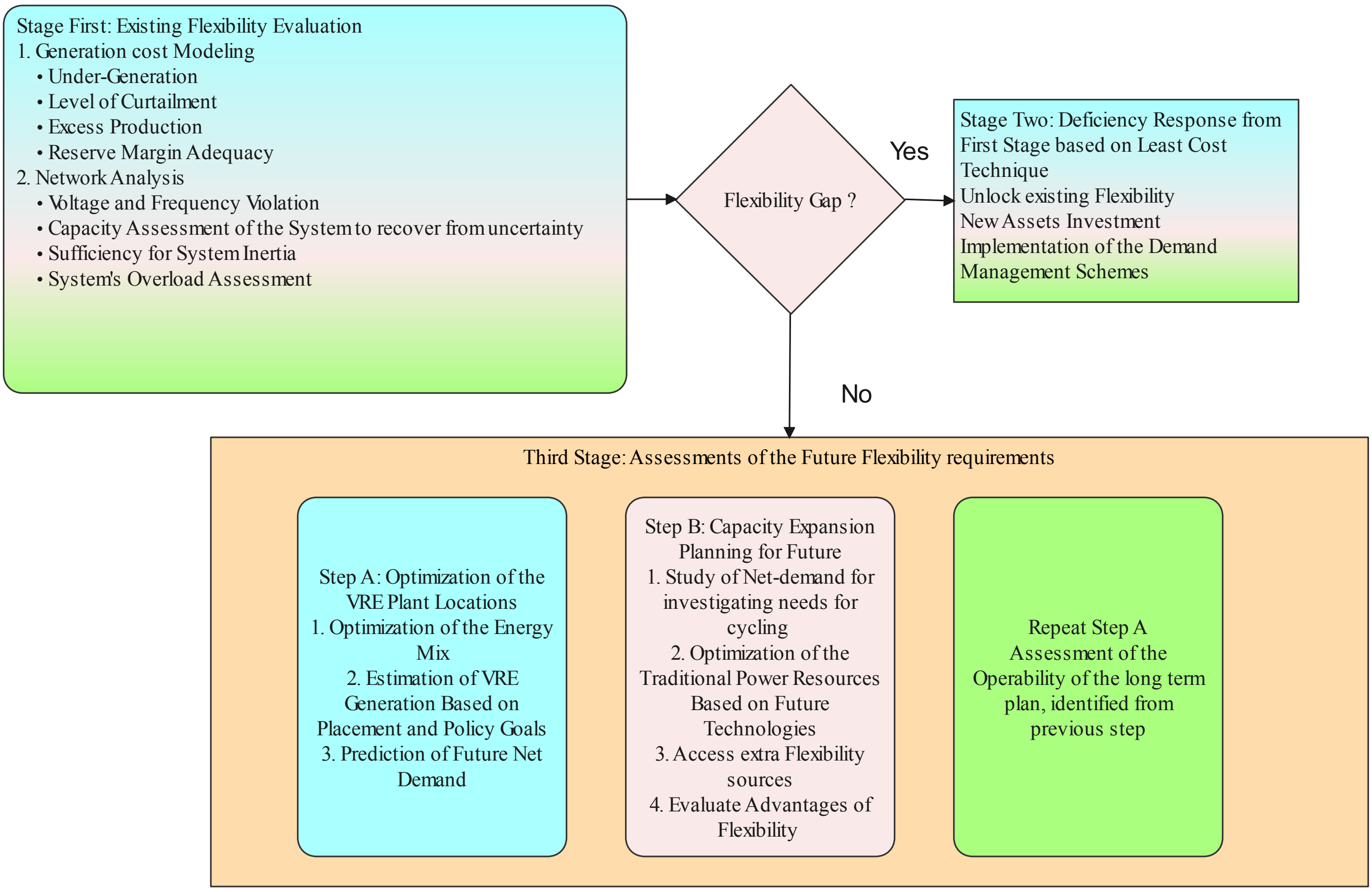

Figure 10. Power system flexibility planning.

A GEP model incorporated with UC to estimate the actual flexibility of the power system was designed by authors in [120]. This helps to make optimized investment decisions on VRE, energy storage (ES), and constraints of UC. Sun et al. [121] designed a large-scale multi-stage stochastic programming model considering an approximate dynamic programming approach for flexible expansion planning of a distribution network incorporated with multiple RE sources. This helps to reduce the investment risk and configure RE equipment to meet flexibility. A brief review related to the planning and operational considerations for the power flexibility is discussed in [122]. A study on integration of grid flexibility in the chance-constrained power system operation planning framework is discussed in [123]. A short-term operation planning effectively secured the operation during N-1 contingency for the scenario of distribution of power injection. It is established that economic efficiency and grid flexibility can lead to gains in operational reliability.

11. Conclusions

This paper reviewed the power system flexibility required to increase share of variable renewable energy sources into the network of a power system. Each aspect of the power system flexibility, such as basic concepts, drivers of the PSF, resources of PSF, requirement of the PSF, metrics used for assessment of the flexibility, methods and approaches used for measurement of level of flexibility in the network of power system, flexibility provisions, and methods used for the PSF planning have been reviewed critically.

According to developed review, it is concluded that power system flexibility has become a topic of major concern for the utilities and needs to be investigated so that the share of VRE sources may be increased to meet the future energy demand. Major drivers of PSF include the increased penetration level of VRE into the utility grids, uncertainty in fuel price, and load demand. Resources of PSF include generation sources, interconnections of power grid to the nearby regional grids, loads, and storage. Requirement of PSF for a network should be assessed on different timescales in terms of load variations and variations of the VRE sources. Flexibility requirement of a power system network is quantified in terms of various metrics, such as power magnitude, frequency, ramp response of generator, available flexible resources, flexibility trinity, PFD, EUR, IRRE, flexibility wellbeing assessment, RSE, and EPS. PSF can be assessed considering the technical aspects and analytical framework. Different provisions for PSF are required to provide flexibility of power, voltage, transfer capacity, and energy. PSF planning is a complex optimization problem and effectively estimates the present and future requirements of flexibility. It is hoped that this review will be beneficial to the users, designers, manufacturers, researchers, and engineers working in the field of power systems, and will help increase the penetration level of VRE into the utility grids.

Presently, penetration level of VRE into the utility grids is below 50%. To meet targets of reduction in the emission of greenhouse gases, utilities are continuously increasing the VRE penetration level and it is aimed to meet 80% of energy demand by VRE. This high share of VRE will affect the stability of the grid, quality of power, operation practices, load generation balance at different times of the day, etc. Hence, techniques are required to provide flexibility during the scenario of VRE penetration level higher than 80% so that stability of the utility grid may be ensured. This can be considered as future research work, and such techniques are required to be developed and implemented in the real-time scenarios of utility grids.

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Abbreviations

Abbreviations used in this article are detailed below:

AC	Alternating current
BES	Battery energy storage
BESS	Battery energy storage system
BGPP	Biogas power plant
CAES	Compressed air energy storage
CCGT	Combined cycle gas turbines
CES	Capacitor Energy Storage
CHP	Combined heat and power
CSP	Concentrated solar power storage
DC	Direct current
DG	Distributed generation
DR	Demand response
DSF	Demand side flexibility
DSM	Demand side management
DSO	Distribution system operator
DSR	Demand side response
EIA	Energy Information Administration
ESS	Energy storage systems

EPS	Expected flexibility shortfall
ES	Energy storage
EUR	Expected unreserved ramping
EV	Electrical vehicle
FAST	Flexibility assessment tool
FCEV	Fuel cell electric vehicle
FES	Flywheel energy storage
GEP	Generation expansion planning
GOF	Operational grid flexibility
GT	Gas turbine
HPP	Hydropower plant
HVAC	High voltage alternating current
HVDC	High voltage direct current
IEA	International Energy Agency
Li-ion	Lithium-ion batteries
MES	Multi-energy system
NERC	North American Reliability Corporation
NaNiCl	Sodium–nickel chloride batteries
NaS	Sodium–sulfur batteries
Ni-Cd	Nickel–cadmium batteries
NL	Net load
NPP	Nuclear power plant
OCGT	Open-cycle gas turbine power plant
PbSO4	Lead–acid batteries
PE	Power export
PFD	Periods of flexibility deficit
PHES	Pumped hydroelectric energy storage
PI	Power import
PPR	Power payback ratio
PSF	Power system flexibility
PSO	Power system operator
PST	Phase shifting transformer
RE	Renewable energy
RSE	Ramping capability shortage expectation
SES	Supercapacitor energy storage
SL	System load
SMES	Superconducting magnetic energy storage
SPP	Solar power plant
SPRP	Solar power ramping product
TES	Thermal energy storage
TRES	Transmission RE sources
TSO	Transmission system operator
TPP	Thermal power plant
T-USFI	Technical uncertainty scenario flexibility index
UC	Unit commitment
V2G	Vehicle-to-grid
VRB	Vanadium redox flow batteries
VRE	Variable renewable energy
WPP	Wind power plant
ZnBr	Zinc–bromine batteries

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