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Review

Challenges of renewable energy penetration on power system flexibility: A survey

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ABSTRACT

Flexibility in power systems is ability to provide supply-demand balance, maintain continuity in unexpected situations, and cope with uncertainty on supply-demand sides. The new method and management requirements to provide flexibility have emerged from the trend towards power systems increasing renewable energy penetration with generation uncertainty and availability. In this study, the historical development of power system flexibility concept, the flexible power system characteristics, flexibility sources, and evaluation parameters are presented as part of international literature. The impact of variable renewable energy sources penetration on power system transient stability, small-signal stability, and frequency stability are discussed; the studies are presented to the researchers for further studies. Moreover, flexibility measurement studies are investigated, and methods of providing flexibility are evaluated.

1. Introduction

Initially, the flexibility in power systems has been defined as the ability of the system generators to react to unexpected changes in load or system components [1]. Recently, it has been recognized as a concept that was introduced to the literature by organizations such as the International Energy Agency (IEA) and the North American Electric Reliability Corporation (NERC). Despite being recognized, there is not a universal definition of the power system flexibility, but authors and groups suggested their own definitions [2]. The IEA explains that a power system is flexible, if it can, within economic boundaries, respond quickly to high fluctuations in supply and demand, ramping down a generation when demand decreases, and upwards when it increases for scheduled and unpredictable events [1].

Taking into consideration the increasing penetration levels of power generation from variable and hardly predictable sources such as wind and solar energy, the flexibility of power systems has become a concept that needs to be redefined. One of the main reasons is that, besides the uncertainty on the demand side, there is also uncertainty on the supply side. In some studies, flexibility is described as the ability of a power system to use its own resources in order to be able to respond to net load changes that are not met by variable generation [3–5]. According to a similar definition, flexibility is the ability of the power system to accommodate the net load changes by adjusting the input of flexible loads or the output of generation units at various regulation intervals [6]. In the report prepared for the IEA [7], the flexibility concept is defined as the capability to balance rapid changes due to RES generation and forecast errors. In the joint report of the OECD and IEA [8], the ability of the power system to modify generation and consumption in response to expected and unexpected variability is referred to as flexibility.

The supply and demand of the power systems are kept in balance, and the planning is made without restriction of load changes. The reserve generation for balancing purposes is started up by forecasting the load behavior [9]. Flexibility needs are divided into four categories; flexibility for power, energy, transfer capacity, and voltage [10].

From an operational perspective, flexibility is the potential for capacity to be deployed within a certain period [11]. According to Bucher et al. [12], operational flexibility is defined as the ability of the power system to damp the disturbances (such as generator trippings due to forecast errors or changes in the power injection) to protect the safe operating condition. Holttinen et al. [13] highlighted that operational flexibility types are dependent on time-scale. These types are listed as increased frequency response and reserves for seconds to minutes, increased ramp capability for minutes to hours, and scheduling flexibility for hours to a day. Ma et al. [14] described technical flexibility as

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coping with variability and uncertainty in both supply and demand side while keeping reliability at a satisfactory level at a reasonable cost over various periods.

Generally, studies derived flexibility metrics from capacity requirements for power balance. In the power node framework and methodology, three quantities named power ramping, power, and energy are used to assess technical available operational flexibility. There are metrics to support long term planning of power systems. Also, metrics are available to accommodate power imbalance and dynamic limitations [15].

Today, due to the increasing share of RES in electricity generation it is necessary to redefine the flexible power system features. Also, as power systems continue to develop, the definition and necessity of flexibility will be changed, and the solutions for providing flexibility will become more complex. The large proportion of the papers that are included have publication dates later than 2010, as seen in Fig. 1. Around 50% of the included papers are identified as articles from journals, and the other 19% are categorized as conference papers. The subject areas of these journals are energy and engineering. Also, 19% of them are reports that are conducted by different agencies. International Energy Agency (IEA) is one of the most interesting agencies in this topic and collaborate with other organizations to prepare these reports. First of all, in this study, the historical development of the flexibility concept in power systems is presented in the context of international literature. The characteristics of flexible power systems, flexibility sources, and the evaluation parameters are presented. The impact of variable RES, such as wind and solar energy, penetration on power system transient stability, small-signal stability, and frequency stability are discussed; the studies conducted in this topic are examined and presented to the researchers for further studies. In addition, the studies on the flexibility measurement are investigated, and methods of providing flexibility in a power system are evaluated.

2. Power system flexibility

Flexibility in conventional power systems is ensured by providing reserves and generation planning. A reserve is also kept for unexpected generation outages or transmission line failures. In the early 1970s, nuclear power plants widely spread with the oil crisis. However, they do not have flexibility characteristics because they operate at full capacity as base-load power plants. The US has increased the installed power of Pumped-storage Hydropower Plants (PHP) to solve this flexibility problem [16]. In this method, a proportion of nuclear power plant's generation is directed to PHP when demand is reduced, and then the stored energy is used when demand is increased.

In modern power systems, besides the conventional generation units, there is Variable Generation (VG) with shares depending on the level of penetration. The load which is not met by VG can have different characteristics; hence it can be supplied from various power system sources. The features, such as increased variability and different ramping patterns, give rise to greater flexibility necessity [17,18]. Generation flexibility in power systems is based on the three main parameters, as shown in Fig. 2. These are the absolute power output range (MW), ramp rate (MW/min), and energy level continuity (MWh) [6,19,20].

- The absolute power output range is the difference between the installed power of a unit and the minimum power that it can operate in a stable condition. The largeness of this difference can provide flexibility to broader system conditions.
- The ramp rate shows how quickly the unit can change its output power within a certain period. The sources that have a high ramp rate are more flexible.
- The energy level continuity shows the duration of a certain power output level that the generation unit can provide. The sources with a long duration increase flexibility by meeting demand under long-term disturbances or outages.

Flexibility needs are divided into four categories; flexibility for power, energy, transfer capacity, and voltage [10].

- Flexibility for power: The power supply-demand balance is needed to maintain frequency stability for short-term periods (a second to an hour). It is due to an intermittent weather condition-dependent power supply in generation.
- Flexibility for energy: The energy supply-demand balance is needed for demand scenarios over medium to long term periods(hours to several years). It is due to a decrease in fuel storage-based energy supply in generation.
- Flexibility for transfer capacity: Power transferability is needed to prevent bottlenecks over short to medium term periods (minutes to several hours). It is due to increased peak demands, increased peak supply, and increased usage levels.

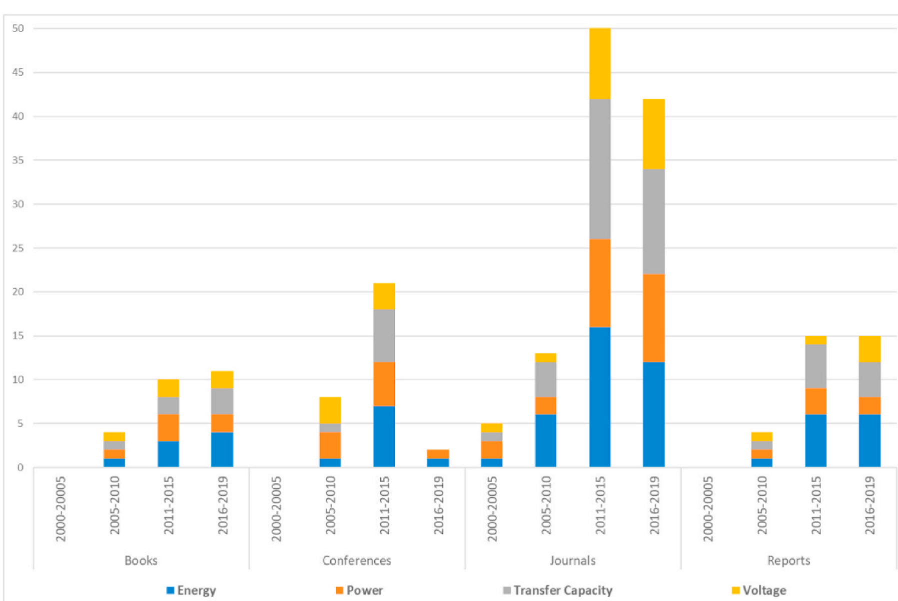

Fig. 1. The distribution of investigated references based on the power system flexibility categories.

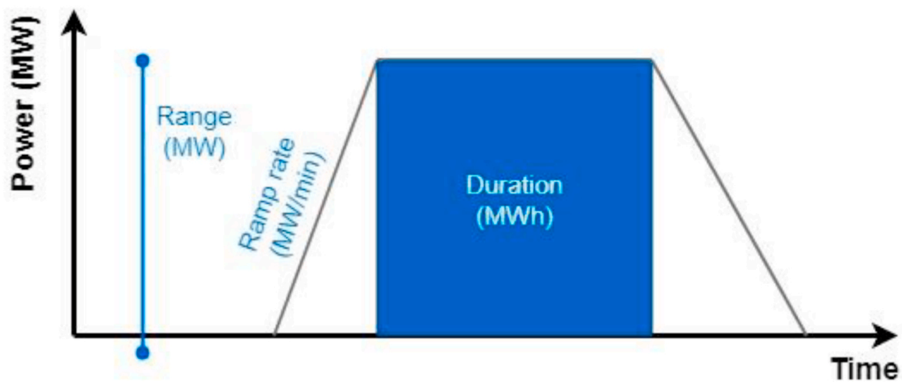

Fig. 2. Flexibility dimensions [14].

- Flexibility for voltage: The bus voltages need to be kept within predefined limits over short term periods (seconds to tens of minutes). It is due to increased distributed generation in distribution system resulting in bi-directional power flow and operation scenarios variance.

It is considered that the flexibility in a power system is "consumed" by load changes, weather forecast errors, generation units or transmission line outages, and generation from variable RES [21]. In addition, in the report of the North American Electric Reliability Corporation (NERC) 's Integration of Variable Generation Task Force (IVGTF), three key features have identified that is essential to be considered when assessing the flexibility requirements in the power system [22]. These are the magnitude of net load changes, the time interval over which these changes occur, and the frequency of ramping events. The importance of these is the ability to distinguish unpredicted ramps from periodic ramps and provide the needed flexibility using properly the available resources to balance a net load ramp over a period of time [5]. In Ulbig and Andersson's study [23], the sources of power system flexibility are divided into four categories:

- Potential flexibility sources; are physically available and usable flexibility sources. However, they are not controllable or observable.
- Actual sources of flexibility; are the usable part of potential flexibility sources because they are controllable and observable.
- Flexibility reserves; are the economically usable part of the actual flexibility sources.
- Flexibility reserves in the power market; are parts of the flexibility reserves that can be obtained from the power or ancillary services market.

3. The growing renewable penetration effects on power system

The needs for sudden, high ramping, and frequent start-ups caused by the intermittent and variable nature of the electricity generation from RES, coupled with the net load changes, cause difficulties for conventional generation units [13,14].

The variability concept is considered differently at every stage of planning and operation. While the net load changes do not play an important role in long-term resource planning, the daily cycle is a major factor in the day-ahead operation plan [13]. In the time interval (ms) that can be defined as a very short term, some control systems are required due to the instantaneous changes in the RE generation. These are control systems for Low Voltage Ride Through (LVRT) [24], active and reactive power, voltage, and ramp rate [25,26].

Modern grid codes have been extended to reduce effects of increased wind energy penetration. The LVRT requirement that necessitates wind generators to remain connected to network to cope with the voltage sag and the High Voltage Ride Through (HVRT) requirement to withstand severe overvoltage profiles are included in grid codes [27].

The operational flexibility type depends on the time scale. While more frequency control and reserves are needed in the seconds to minutes time interval, increased ramping capability for minutes to hours, and planning flexibility for hours to a day ahead is required [13]. From the system planning perspective, flexibility time interval and variable generation effects are shown in Fig. 3.

In the case of a large proportion or all of the demand is supplied by RES generation, the baseload plants must reduce or completely stop their generation. However, these plants should be re-dispatched to meet the demand with a decrease in RES generation. This constitutes a big problem since the start-up times of coal, or nuclear power plants are too long [26]. As a result of exposure of these plants to excessive cycling, especially in the components where there are high temperatures and pressure; problems such as wear and tear, metal fatigue, corrosion, and erosion are caused in the medium term [28–30]. Therefore, operating-maintenance and fuel costs increase, and there is a decrease in the expected life of power plants. Also, the plant outages for maintenance purposes are more frequent [26,28,31]. In the long term, considering carbon laws and limitations, a transition to low-carbon solutions in base-load plant technologies is expected. Another important point to mention is that they need to be more flexible than existing technologies [26].

Innovations are needed in the planning and operation of transmission networks as well. The main purpose of the existing transmission lines is to transmit the energy from the regional generation units to the load centers. However, the distance and voltage levels are increasing with the installation of RES plants far away from the load centers at the endpoints of the network. On the other hand, the RES generation, which is distributed over a broader area, decreases the variability of total generation, and this advantage can be utilized with correct planning [32]. The increase in penetration levels requires finding the optimal network topology, which has a serious impact on transmission line losses and overall system performance in the case of a disturbance [33].

A power system's stability is a key factor for secure and uninterrupted system operation. The stability of the power system is defined as the ability to restore the operating balance after being subjected to a physical disturbance [34]. One of the most important parameters in the simultaneous operation of power systems is the system inertia. The lower the inertia of the system is, the more the system is sensitive to frequency deviations [35]. RE power plants do not contribute to the system inertia, because they are connected to the network by power electronics, and they are electrically isolated from the network. In particular, photovoltaic (PV) systems do not contribute to the inertia in any way because of their structures [36], and the system inertia is decreased. As a result, besides the frequency and rotor angle stabilities of a power system, it also effects the transient stability with larger rotor oscillations [35].

In this part of the study, the effects of wind and solar power

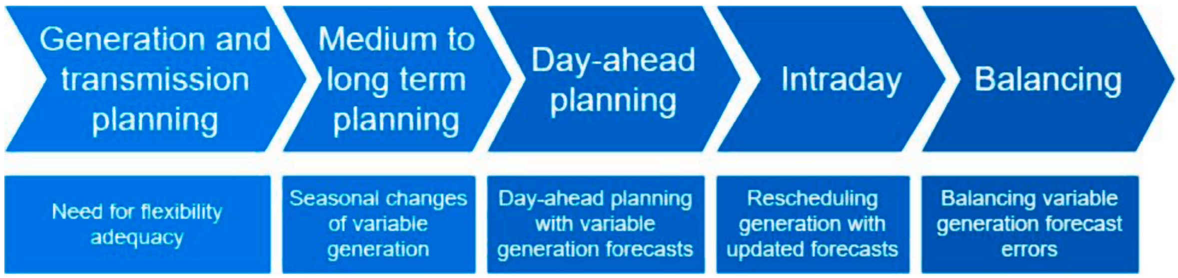

Fig. 3. Effects of variable generation on the flexibility timeline [13].

penetration on voltage, transient, small-signal, and frequency stabilities of the power system are investigated. The related literature is presented below under these titles.

3.1. Effect of wind power systems (WPS) on the power system stability

According to Holttinen's research, 10% wind power penetration for Scandinavian countries increases the reserve requirement by 1.5%–4% of the installed wind power. The lower the minimum power output of the power plants which meet the demand, the more RE penetration can be accommodated in the system without the need to shut down power plants. Therefore, besides the increased reserve requirements, the minimum power outputs of the power plants may also cause problems in the short term [37]. The impact of penetration levels (5%–35%) and the power plant location (two different locations) on voltage stability were investigated by Naser et al. [38]. It was observed that the system is better in terms of voltage stability at low penetration levels. The results show that the connection of WPS to the network at several points positively affects the voltage stability compared to the single point connection. According to Hossain et al. [39], Doubly Fed Induction Generator (DFIG) turbines cannot deliver as much reactive power as Synchronous Generators (SG) do and cannot generate large short-circuit currents. Hence, the voltage support provided by reactive power injection after a failure is worse for DFIG than in the case of an SG. Also, DFIG turbines behave as Squirrel Cage Induction Generator (SCIG) during transient events and thus can consume reactive power and reduce the system's voltage stability limit. The study summarizes that a system dominated by Wind Turbines (WT) shows worse performance in terms of voltage stability than conventional systems. On the other hand, in the study on long-term voltage stability by Londero et al. [40], it is specified that high penetration levels contribute positively to the system voltage stability. It is stated that turbines can provide more reactive power support to the system as the penetration level increases.

Meegahapola and Flynn [41] investigated the impact of very high (40%) wind power (DFIG WT) penetration on the transient and frequency stabilities of the power system in a 39-bus test system. It was observed that the transient stability is adversely affected in case of a fault close to a region with high wind penetration. The main reason for this was shown as the reduction in active power generation and an increase in reactive power absorption during the crowbar protection when the WTs are partially loaded. In the case of a fault close to SGs, it was observed that the WTs improve transient stability with their contribution to the power flow for synchronizing forces in the network. Edrah et al. [42] have implemented various scenarios into three generators 9-bus test system using an SG and a wind farm, which consists of DFIG turbines. According to the obtained results, the rotor angle stability of the system is adversely affected by the use of equivalent power DFIG WTs instead of SG. However, it was emphasized that this effect could be reduced by using the necessary control strategies.

The study on small signal stability by Ayodele et al. [43] investigated effects of parameters such as power dispatch, wind farm location, and wind power penetration level. According to the analysis performed on the 9-bus test system of the IEEE, local area modes are positively affected by the wind power, and better damping is achieved with the DFIG WTs in the inter-area mode. Although the system gets unstable when injecting power with a weak tie-line from a region with 50% RE generation, this is not valid for power absorption. Moreover, the system stability is not affected by the length of the transmission line from the connection point of the wind farm to the network. Modi et al. [44] used the 14-Generator South East Australian equivalent system to study the effect of high wind power penetration. It was observed that the damping of inter-area modes is severely affected by wind penetration, altering power flows in the network and displacing some of the SGs. The selection of the generators to be displaced has affected the system's damping performance. A decrease in damping of modes was noted as the stabilizers, which play an important role in damping of oscillations were displaced with the SGs. Mehta et al. [45] examined the effect of DFIG WTs on a two-area four generator test system. The study shows that the system becomes unstable in terms of the small-signal by replacing an SG with a DFIG WT. On the other hand, it was stated that the necessary damping torque could be obtained by equipping the remaining SGs with automatic voltage regulators and power system stabilizers. The existence of these two control systems in SGs results in improved dynamic performance and the importance of DFIG turbine location is eliminated; the is also a better performance regarding the damping of local and inter-area modes.

Meegahapola and Flynn [41] emphasized that changing the response of the DFIG turbines according to the load condition is expected to positively affect the frequency stability. The DFIG turbines have an emulated inertial response that is a short-term controlled response to transient power imbalances by utilizing their stored rotational energy [46]. Qureshi and Iqbal [47] investigated the impact of SCIG and DFIG WTs on the system frequency stability using a 9 bus 3 machine system. According to the results of the research, the contribution of SCIG WTs to the damping of frequency oscillations is less than that of SG. DFIG WTs do not response to frequency deviations as their rotor mechanical speed is decoupled from the grid frequency.

3.2. Effect of photovoltaic systems (PVS) on the power system stability

A study on PVS voltage and reactive power responses was conducted by the California Independent System Operator (CAISO) [48] for various connection types. It was indicated that overvoltage problems are inevitable due to the high share of PV connected to the sub-transmission network. It was also pointed out that in a system with PV, the Static Var Compensators (SVCs) caused higher transient overvoltages. The main reason for this was stated as the injection of reactive power into the system by the SVCs for several cycles due to their low operating speed after the clearance of the fault. According to the steady-state analysis that was performed for PV penetration by Eftekharnejad et al. [49], the most affected system parameters are voltage magnitudes. Overvoltages occurred in the transmission line busbars, especially at 20% and additional penetration levels. In a system with high PV penetration during transient events, larger voltage drops were found after a fault. Also, the disconnection of a large part of the rooftop PV systems resulted in increased voltage fluctuations and damping times as the penetration levels increased. Tamimi et al. investigated the effects of centralized and distributed PV systems on the steady-state voltage stability of the Ontario power system. Various penetration levels with an installed power of up to 2000 MW have been examined. The results showed that the distributed PV could significantly improve voltage stability compared to the centralized systems [50].

In studies performed for transient stability, the impact of penetration level was firstly investigated at 5–30% range. The results showed that improving the system stability for penetration levels above 10% of PV depends on the Fault Ride Through (FRT) capabilities of these power plants [48]. Eftekharnejad et al. [49] investigated the effects of rooftop and large-scale PV systems penetration on a large interconnected power system. For this purpose, PV penetration levels of up to 50% were examined by reducing the share of conventional generation. Analyzes showed that high PV penetration levels have positive and negative effects on the system transient stability. Also, PV penetration levels, system topology, type, and location of the fault are key factors for the nature of the effect (positive or negative).

Furthermore, the disconnection of a large proportion of rooftop PV causes deviations in the rotor angles of nearby SGs and voltage fluctuations. Tamimi et al. examined the effects of large-scale and distributed PV integration on the transient stability of the Ontario power system. Critical Clearing Time (CCT) indication was used to evaluate the system's dynamic stability performance. A 3-phase short-circuit fault for 80 ms in the 500 kV transmission line in the Toronto area has been tested. The results show that central PV power plants with voltage and reactive power control do not change the system's dynamic stability. On the other hand, an increase in distributed PV penetration levels improves transient performance [50].

Studies have also been conducted on the effects of PV penetration on small-signal stability. Liu et al. [51] examined the impact of the location and penetration level of PV generation on the two-area power system. The results show that the effect of the high PV penetration level is positive or negative, depending on the state of the SGs that are displaced. Ravichandran et al. used a 3-SG 9-bus test system, and modified the system with the real-time data of the Indian network. The impact of variables such as solar irradiation, temperature, load, and configuration have been investigated. An increase in rotor modes was noted in the integration of PV into the network and in the same way with increasing solar irradiation.

Furthermore, the damping of the modes has also increased with increasing load, while there is a decrease with increasing generation [52]. Du et al. [53] used a single-machine infinite bus power system in their study. Analyzes show that PV generation affects small signal stability by interacting with conventional generation due to the lack of rotating components. However, there are not any additional oscillation modes added to the system. This effect varies depending on the operating conditions of the system since the contribution of the damping torque of the PV power plant can be positive or negative. After a certain critical operating condition, the effect of PV generation on the system small signal stability becomes negative. Eftekharnejad et al. used large-scale PVs and rooftop PVs, which are aggregated at the voltage level of 69 kV. According to the results, there is a significant reduction in damping ratio as large conventional generators are displaced while penetration level increases from 30% to 40%. The increase in penetration level causes a decrease in the system inertia resulting in a reduced critical modes damping of the system [54].

In the studies of PV penetration regarding the frequency stability, Alquthami et al. [55] have assessed penetration levels of 5%, 10%, and 20% while keeping SGs in the system. Simulations show that the system frequency stability is adversely affected at 20% penetration level. Abdlrahem et al. used a two-area power system with a real-time simulation model of 4 × 50 MW PV generation. In this study, automatic generation control (AGC) was applied to allow the maximum penetration level by adjusting the output power of the generators since each area has two SGs. Increased penetration level in one region of the system led to positive effects in both regions, such as faster damping of frequency oscillations and lower magnitude (overshoot) of oscillations [56].

In a system where a significant amount of SGs are displaced by RES, the control systems and their coordination are affected as well. Also, fault state characteristics exhibit different features. The fault current of SGs is 5–10 times of the nominal current, while it is roughly 2 times for inverter-based systems and decreases with time. This might prevent the protective relays from detecting the fault conditions in inverter-based systems [57,58]. On the other hand, the inverters are able to avoid the thermal overloading of the network components by rapid response to network imbalances. Another advantage of inverters is that their fault currents can be programmed [57].

4. Flexibility measurement

An insufficient ramping resource expectation (IRRE) is a measure used in long-term planning, based on conventional generation sufficiency criteria. In order to assess the flexibility, demand and variable generation should be taken into account. The considered time intervals also play an important role. For IRRE, downward flexibility of each unit (1) and system flexibility time series (2) are calculated [3].

$$Flex_{t,i} = Ramp_{up}.\left(1 - \left(1 - Online_{t,i}\right).S_i\right) \tag{1}$$

$$Flex_t^{system} = \sum_{\forall i} Flex_{t,i} \tag{2}$$

In equation (1), $Ramp_{up}$ is ramp-up of generator, $online_{t,i}$ is operation stage of a generator in t time, S_i is generator start up time. IRRP is called insufficient ramping resource probability.

$$IRRP_{t,i,+/-} = AFD_{i,+/-}\left(NLR_{t,i,+/-} - 1\right) \tag{3}$$

In equation (3) t is time horizon; $NLR_{t,i,+/-}$is the net load ramp in either direction, $AFD_{i,+/-}(X)$is available flexibility distribution. IRRE is the sum of the IRRP values over entire time series.

$$IRRE_{i,+/-} = \sum_{\forall t \in T_{+/-}} IRRP_{t,i,+/-} \tag{4}$$

Another developed indication of flexibility is the Normalized Flexibility Index (NFI). The overall system flexibility is predicted by evaluating the flexibility level of each generation unit [59]. All generation units can contribute to upward reserve with their ramp-up rate and spare upward capacity, and downward reserve with their ramp-down rate and spare down capacity. For mathematical representation, range of each unit is called flex index. The index is normalized to eliminate variable size effect of each unit.

$$flex(i) = \frac{\frac{1}{2}\left[P_{max}(i) - P_{min}(i)\right] + \frac{1}{2}\left[Ramp(i)\right]}{P_{max}(i)} \tag{5}$$

In equation (5) Ramp(i): average of ramping up and ramping down of unit i; P_{max}(i): maximum capacity of unit i; P_{min}(i): minimum capacity of unit i.

Flexibility index of the whole system is represented with FLEX, and it is weighted average of each unit flex [60].

$$FLEX_A = \sum_{i \in A}\left[\frac{P_{max}(i)}{\sum_{i \in A} P_{max}(i)} x flex(i)\right] \quad \forall i \quad \in A (6)$$

The Loss of Wind Estimation (LOWE) indicator shows the system flexibility level in terms of its ability to accommodate wind power [59]. One of the methods developed for measuring flexibility is Flexibility Assessment Tool (FAST). This method identifies the available flexibility sources, then evaluates the flexibility needs and compares the needs with the sources [8].

Inflexibility indicators are also used since they are more apparent than flexibility criteria. These indicators are the difficulty of maintaining supply-demand balance, a significant amount of curtailment, and imbalances of Renewable Energy (RE) generation in certain regions. Also, in the power market, inflexibility leads to negative prices or volatility in electricity prices [61].

Flexibility charts are used to reflect generation-based flexibility in a more understandable way [62]. Five parameters are used in the graphs: penetration levels (as a ratio of peak load) of gas turbine combined gas cycle (CCGT), combined heat and power (CHP), pumped hydropower, hydroelectric power plants (Hydro), and interconnections. Besides, wind power penetration is shown by the red polygon in the graphs. The graphs show potential sources of flexibility, such as the amount of installed capacity [63]. Fig. 4 shows the flexibility graphs arranged for central Europe.

One of the important points in the graphs (Fig. 4) obtained by Yasuda et al. [62], is that the countries with high RE penetration have high transfer capacities with neighboring systems. The interconnections, which are previously used to maintain the system's reliability, began to be regarded as a flexibility source. The use of these connections helps growing the balancing areas, and the unique flexibility mechanisms of each power system become available to neighboring systems. Also, considering interconnected countries as a whole, the reserve capacity increases, and variability of sources such as solar and wind decreases since the generation is distributed to a larger area [63,64].

5. Flexibility provision

The flexibility of all elements in a power system should be provided to accommodate more renewable energy and a highly responsive demand. For a flexible generation, power plants that can be ramped up-down quickly and efficiently, and operate at low output levels are required. For flexible transmission, transmission networks capable of using various balancing resources, including sharing between neighboring power systems, and use of intelligent network technologies for optimization, are required. The flexibility of demand-side resources can be achieved through demand response, storage, responsive distributed generation, and use of smart networks. Flexible system operations can be realized with near real-time and frequent decisions, more accurate wind and solar forecasts, and better collaboration between neighbors [61]. In Fig. 5, implementation examples used to provide these flexibility solutions are presented in detail with regard to flexibility need and implementation level [10].

Increased wind power penetration in power systems directly affects the system behavior. Fluctuations in wind power can affect the small-signal, transient, and voltage stability of power systems and frequency control [65]. The use of high-performance excitation systems is essential to maintain steady-state and transient stability of synchronous generators and provides rapid voltage control [66]. For this purpose, Automatic Voltage Regulators (AVR) containing Power System Stabilizer (PSS) are used [67]. Fast Frequency Response (FFR) is the most innovative method used to eliminate sudden supply and demand imbalances in short and very short time periods. It requires proper power electronics and batteries. The challenge of system is to define how much inertia can be changed [68]. Virtual inertia increases robustness of system against oscillations in high RES penetration and provides flexibility to power system in droop selection [69]. Battery Energy Storage System (BESS) provides flexibility in power system by allowing more grid connections in existing network capacity, reducing need to provide a spinning reserve with reduction of effect of prediction errors, reducing load on the consumer side with use of higher network capacity, reducing curtailment, and network restrictions [70].

Coordinated voltage control manages the power factor, on-load tap changer, and generation curtailment. Its main purpose is to improve stability by dealing with voltage rise issue [71]. On-Load Tap Changer (OLTC) s are widely used in HV/MV transformer applications due to their low current levels. While line voltage regulators help locally improve voltage profile and reduce losses in distribution line, OLTC has a wider effect [72]. Flexible AC Transmission System (FACTS) controllers are preferred in modern power systems due to their fast controllability, better utilization of existing transmission systems, increasing the reliability and availability of transmission lines, increasing dynamic and transient network stability. Static VAR Compensator (SVC) is the first generation FACTS device used to improve voltage profile of a particular busbar with reactive power compensation. Static Synchronous Compensator (STATCOM) is a solid-state voltage source converter from FACTS family, which injects a variable-size almost sinusoidal current into the system, connected to transmission line. Unified Power Flow Control (UPFC) is the most powerful FACTS method, which is a combination of Static Synchronous Series Compensator (SSSC) and STATCOM, and improves power system transient stability [73]. Phase-Shifting Transformer (PST) is an element of transmission expansion, which increases utilization of conventional components. It can be considered as an option of FACTS. HVDC lines contribute to power system flexibility by providing transmission to longer distances with less power loss and increasing controllability of power grid. There are

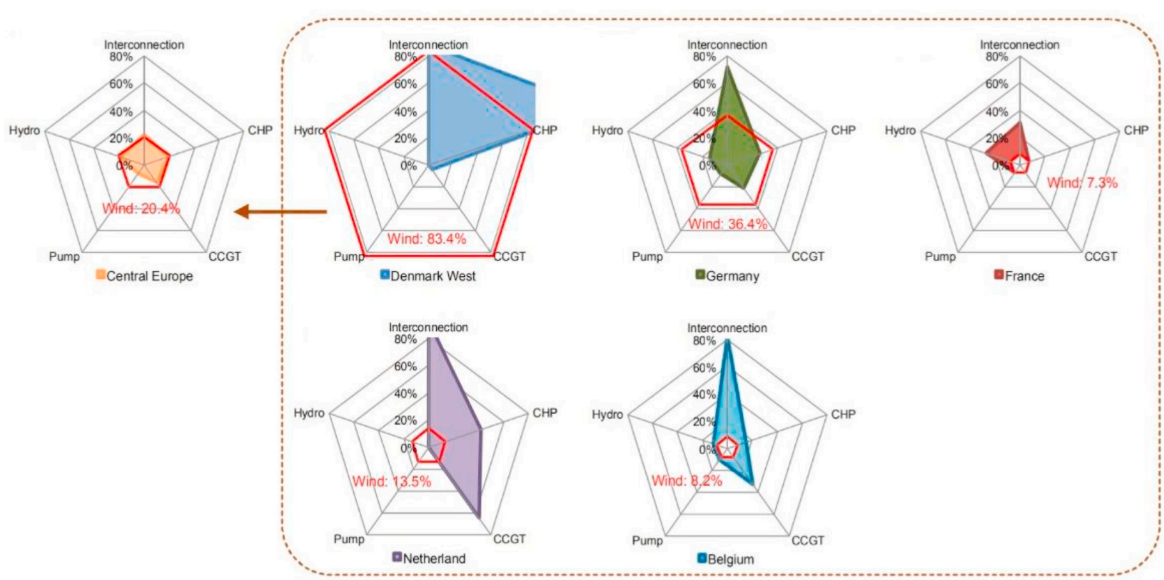

Fig. 4. Flexibility graphs of the central European region with wind penetration level [62].

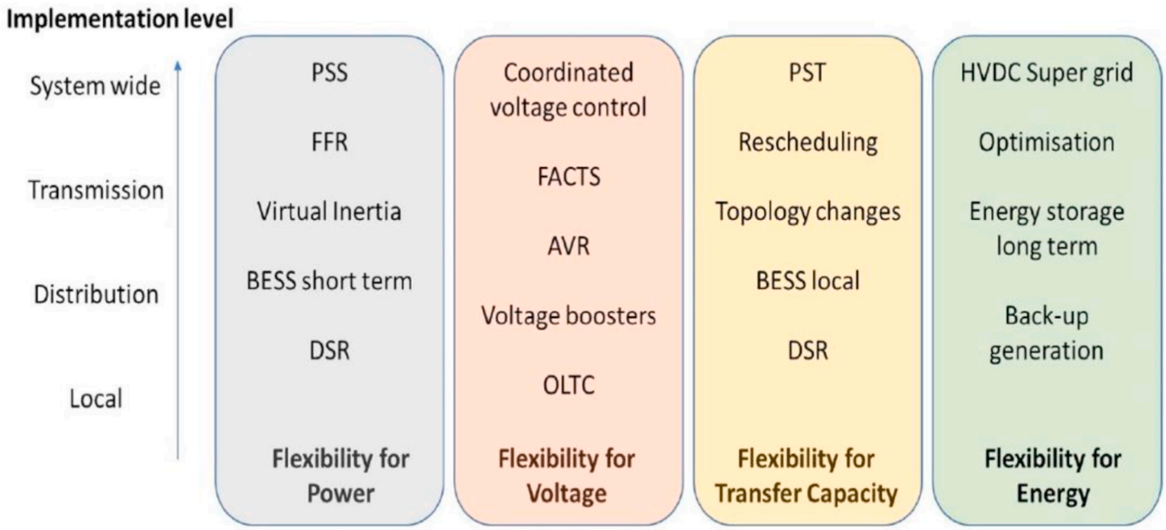

Fig. 5. Examples of flexibility solutions for each category with implementation levels from local to system wide [10].

basically two types; line commutated HVDC (LCC-HVDC) and voltage source converter based HVDC (VSC-HVDC) [74]. Solutions showed in Fig. 5 Such as Demand Side Response (DSR), are detailed in following titles.

Flexibility needs on the supply side of the power system can be met with partial load operation of the power plants connected to the system, load following, and fast start/stop times [14]. According to the IEA report [75], the characteristics of the flexible and inflexible power plants, in line with the aforementioned variables, are shown in Table 1. In this table, the dispatchable non-renewable energy generation technologies are evaluated with their flexibility dimensions, and power plants show large differences in their technical flexibility. Hence, they are identified as flexible and inflexible generation technologies. Flexible generation technologies comprise flexible CCGT and flexible coal. These power plants are designed to operate as load following plants that can adjust their generation level to cope with load variations and start at fairly short notice. The coal plants will be shut down before the end of their lifecycle. Nevertheless, the ability of other coal plant operators to apply the existing flexibility options to their system will be instrumental in valuing coal in an increasingly low-carbon energy system.

5.1. Demand side management

Demand-side management is a source of power system flexibility. However, this study focused on requirements due to increased RE penetration. For this reason, although this title is briefly mentioned, it is a wide area to be studied. While there are many factors in a power system that will increase flexibility on the supply side, the demand side can also contribute to flexibility [76]. Demand response, which is a more specific way of demand-side management, is the ability to control end-user devices by rescheduling their operation [77]. It can be divided into categories such as electrical demand increase (load growth, valley filling), decrease (peak shaving, conservation), or re-planning (load shifting) (Fig. 6) [78].

Table 1
Characteristics of flexible and inflexible power plants according to the IEA report [75].

Power plant type	Minimum stable output (%)	Ramp rate (%/min)	Lead time, warm (h)
Inflexible CCGT	40–50	0,8-6	2–4
Flexible CCGT	15–30	6–15	1–2
Steam türbine (gas/oil)	10–50	0,6-7	1–4
Inflexible coal	40–60	0,6-4	5–7
Flexible coal	20–40	4–8	2–5
Lignite	40–60	0,6-6	2–8
Inflexible nuclear	100	0	–
Flexible nuclear	40–60	0,3-5	–

System operators attempt to match high demand periods with high RES generation. With this method, electricity consumption does not decrease, but consumption is shifted to a more convenient time in terms of network operation [77]. Thus, demand-side management acts as a reserve. This is more evident when the periods of low demand and high RES generation are similar [79].

In cases where peak load and wind generation is high, the decrease in wind power is a significant problem for the system. In this case, the system can be balanced by decreasing the consumption using demand-side management [80]. However, in the Strbac's study [79] stated that demand-side management could only compete with conventional methods for providing reserves in a system that contains only inflexible generation with a high amount of unpredictable wind energy. The contribution of demand-side management is lower in a system with flexible power plants.

5.2. Flexible coal, natural gas, and nuclear power plants

Coal-fired power plants generally are designed as baseload plants that will operate for maximum time with constant output power. While the level of existing power plants' flexibility can be increased by renewing the used technology, new power plants can be designed more flexibly [63]. It is possible to design new coal or lignite-fired power plants with a ramp rate of 7%/min from 40% to 100% power output. A ramp rate of 10%/min is also targeted [81,82]. However, a typical once-through boiler design has a 7%/min ramp rate in the 50–90% load range. It has been observed that this ramp rate can be achieved in a 550 MW bituminous coal-fired power plant in Germany [29]. In addition, two lignite-coal burning units, each with a capacity of 1100 MW installed in Germany in 2012, can ramp up or down by 500 MW in 15 min [83]. The undesirable effects of gained flexibility are low efficiency due to the continuous start-stops and ramping, cost increases, shorter equipment life, and more maintenance requirement. On account of this, solutions to reduce these effects are investigated by manufacturers [29].

Nuclear power plants are baseload plants and considered the most inflexible plants. The majority of them are designed to be operated at full power and to be stopped only for fuel change or periodic maintenance. However, flexibility can be provided to these plants with the necessary

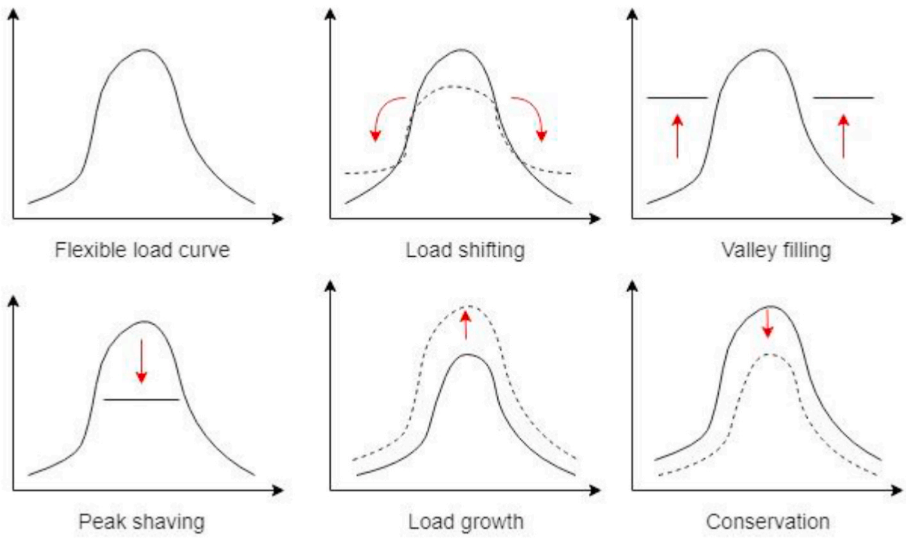

Fig. 6. Demand-side management categories [78].

design and operation [8,84]. According to the International Atomic Energy Agency (IAEA), most of the existing nuclear power plants have a power output range between 50% and 100% of the reactor thermal power and ramp rates of up to 5%/min. However, these features are not a part of the daily operation [84]. Only certain countries have the experience of operating and designing nuclear power plants in a wide range of flexibility. In France, some nuclear power plants are able to ramp their power output from 30% to 100% in 1 h and from 60% to 100% in 30 min in load-following mode [8]. However, the Nuclear Energy Agency (NEA) [85] stated that nuclear power plants require careful operation and maintenance since the partial load operation causes unplanned outages. In some technologies, flexible operation is not possible for up to 30 days at the end of the fuel lifetime, depending on the core design [84]. The United States has increased the installed power of pumped hydropower plants to solve this flexibility problem of nuclear power plants. While demand is low, some of the nuclear power plants' generation is directed to these power plants, and the stored energy is used when the demand is high [64].

Natural gas power plants, which are used as baseload or intermediate load power plants, can provide flexibility to the system. The most common are Combined Cycle Gas Turbines (CCGT) because of their capacity diversity, high efficiencies, and low energy costs. New generation high-performance CCGTs are much faster than conventional ones with 40-min start-up times [86]. One of the best examples is the Sloe Centrale power plant in the Netherlands. 30-minute start-up time was recorded, while achieving 59% efficiency in the acceptance test of the plant containing two 430 MW units [87]. However, the disadvantages of gained flexibility also apply to these plants. This type of operation causes wear in mechanical components, requires more frequent maintenance, and increases operating costs [86].

5.3. Flexible combined heat and power plants

Combined heat and power (CHP) plants are important to reach efficiently high RES penetration levels. Proper heating and cooling applications can be a source of flexibility. However, the generation of CHP plants in many countries is not flexible enough as it is adjusted according to the heat load [75]. Flexibility in these plants can be gained with changes in operation and equipment [88,89].

Denmark is one of the countries with the largest cogeneration system in Europe, with a 50% cogeneration share in electricity generation [90]. Also, CHP plants can be operated flexibly in countries with high wind power penetration. These operation modes are shown in Fig. 7. CHP plants use fossil fuels to meet demand during periods of high heat demand and medium/low RES generation (Mode 1). In the case of high RES generation and low heat demand, the output of the plant can be reduced, and if necessary, a proportion of the demand can be met by heat storage (Mode 2). In the case of RES generation exceeds demand, the excess power can be used in an electric boiler to meet heat demand, heat storage or can be used for both (Mode 3) [75].

5.4. Curtailment of RE generation

The curtailment of RE generation is presented under flexibility provision title, and this method is used as flexibility source in the existing power systems. However, curtailment of RE generation is not generally acceptable solution for the public. There is loss of green energy and economical cost due to curtailment.

When wind power and PV systems cause transmission or operational constraints, the system operator may be forced to accept less wind and solar power than what is available. This event is called curtailment [91]. The integration of wind power plants that have low capacity factors affects the transmission system design. In long-term grid integration studies, wind power plants' operation time considered short due to the variability of wind power [92]. Moreover, it is uneconomic to design transmission network for all of the available wind energy. In some cases, curtailment of generation can be a more economical solution [91,92]. Other reasons for renewable curtailment are the minimum output power of thermal and hydroelectric power plants, avoiding back-feeding in distribution systems, and the requirement to limit nonsynchronous generation on small grids for system frequency stability [91].

As of the end of 2017, China's installed renewable energy power is 619 GW. It consists of 341 GW hydroelectric, 164 GW wind, and 131 GW solar power [93]. China, the leader in renewable energy, is the country that faces the most serious problem of renewable curtailment [94]. Its infrastructural reasons are weak grid structure, concentrated wind sources in remote areas far away from load centers, a large proportion of coal-fired power plants, and lack of adequate market mechanisms. Unfavorable feed-in tariffs, unreasonable dispatch priorities, lack of grid codes for wind integration, and low wind forecast accuracy are the operational difficulties [95]. The curtailment problem in China has started in 2009 in the Inner Mongolia region and spread throughout the country in 2010. The curtailment of PV generation arrised in 2013. Between 2013 and 2016, the national average curtailment of PV was 15%. Between 2011 and 2015, the national average curtailment of wind power was 15%. In 2016, this rate was up to 43% in the northern regions

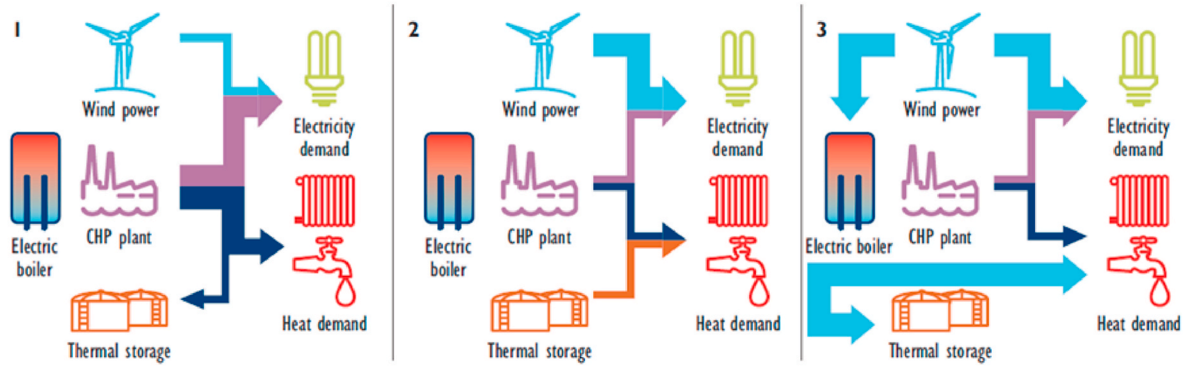

Fig. 7. Operating modes of wind energy and CHP plants in Denmark [75].

of China [96]. According to the National Energy Administration in China in 2016, the average curtailment of wind power was 17% (49.7 TWh) [94]. Another example is Ireland and Norther Ireland, where in 2016, only 227 GWh of wind power generation (7620 GWh) was curtailed. This number is 215 GWh lower than the previous year. The 52% of the curtailments were due to system-wide reasons, and 48% were due to local network reasons. In Ireland, the limit of the System Non-Synchronous Penetration (SNSP) for the power system was increased from 50% to 55% in March 2016 and to 60% in November 2016 [97]. Significant developments about curtailment have been achieved between 2009 and 2014 in Italy as well. The curtailment of wind power was decreased from 10.7% in 2009 to 0.8% in 2014, while curtailment of PV generation has not occurred in these years. This decrease is the result of investments for overcoming the inadequacy of the transmission network between south and north, one of the main reasons for the outages. On the other hand, no significant curtailment was observed in Denmark and Portugal, which have high wind penetration. Regulations in Portugal does not allow the curtailment of RE generation except technical problems. In 2016 in Denmark, during 317 h where RE generation exceeded the demand, there was not any curtailment since they used the interconnections with neighboring countries [91]. In Germany, the amount of energy not used due to the curtailment increased by three times in 2014 and 2015 compared to the previous year. The compensation costs of curtailments in 2015 was estimated at 478 million euros [98].

5.5. *Strengthening and expanding the transmission network*

Strengthening the transmission network with flexibility enhancements such as balancing electricity generation over a wide area, facilitating exchanges with neighboring countries, and linking the international power markets is a key factor in the RES grid integration [63]. In the planning and operation of transmission networks, reserves and load varieties help to balance the variable renewable generation. As the balancing area grows, a decrease in the variability of renewable energy can increase the flexibility of the power system [99].

There are also some difficulties with the grid integration of RES [100]. Natural problems are caused by the spread of the RES in a wide geographical area. Serious increase in generation or demand in a region causes uncertainties in transmission network planning. Moreover, a wind power project in a remote area can not be financed without access to the transmission network. On the other hand, the plan, permit, and construction time of a transmission line can last for 5–10 years, and the transmission line can not be built without proving the necessity of the line. Paying for the transmission line by the generator in advance is a disadvantage, and the involvement of the new generators in this cost is a controversial issue [100,101]. From an economic perspective, the connection of RESs in remote areas of the network is more costly than conventional systems [100]. In order to operate the transmission line economically, the price gap between the high-priced area and the low-priced area needs to be greater than the annual investment and operating costs. To be able to do this, it is required to carry a large amount of energy with low-cost transmission [101].

Technically, there are problems caused by network topologies and connection schemes. An inefficient and uneconomical "spaghetti" network connection is structured to allow each power plant in the remote area to connect to the network on its own (Fig. 8a). The SENE (scale-efficient network extension) scheme (Fig. 8b), where an area is connected to the load center through high voltage line, is more useful when considered the power plants that can be built in the future. Another option is to add a hub to the SENE approach (Fig. 8c). In case of a large amount of generation, such as thousands of MW, in a certain area, an additional HVDC line may be needed [100].

In Germany, while the wind power generation is concentrated in the north, the load centers are in the south. This high amount of long-distance transmission causes bottlenecks in the network. To overcome this difficulty, the power is transmitted to the south via the transmission networks of neighboring countries (Poland, Czech Republic, Netherlands, and Belgium) instead of the domestic transmission network [102]. Pointing to this problem, Malek et al. [103] stated that congestion would be observed with the increase in wind power and PV particularly in Germany, Austria, and Poland networks. Considering the phase-out of nuclear (8386 MW until 2022) and conventional power plants, the generation in the south will decrease considerably. For the security of supply in this area, additional transmission capacity will be required to the areas where conventional power plants, RES, and storage (e.g., Scandinavian countries) are located. As a consequence, Germany is planning to commission two long-distance HVDC transmission lines in 2025 [102]. The routes that need to be strengthened in Germany are shown in Fig. 9.

The European Network of Transmission System Operators for Electricity (ENTSO-E) launched a European-wide project in 2010 with national and regional investment plans called a 10-year network development plan (TYNDP). It aims to provide a more economical RE integration, especially in line with RE targets set by the European Union. In the report of the project for 2016, regional investment plans were presented by dividing the European continent into 6 regions [104].

Public opposition to the construction of new transmission lines also causes delays [105]. An alternative option is using more efficiently the existing transmission networks with evaluating the transmission capacity and better dynamical control of the power flow. Power flow control equipments such as phase changers, HVDC transmission lines, and Flexible Alternating Current Transmission Systems (FACTS) make it possible to use almost the entire transmission capacity. As a result, it is inevitable to strengthen the transmission network at higher penetration levels [106].

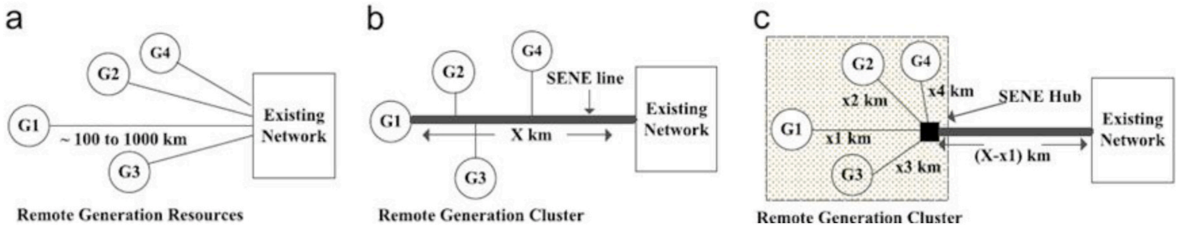

Fig. 8. Transmission network topologies for connection of the generation in remote areas [100].

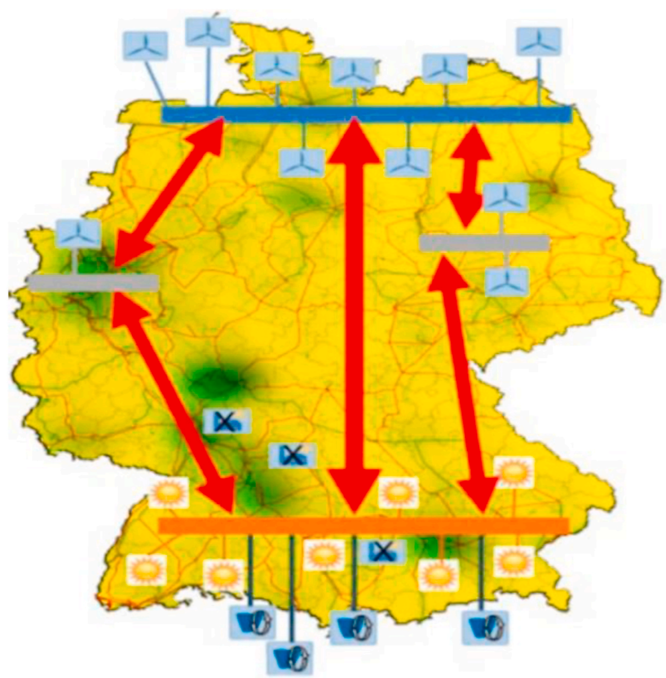

Fig. 9. The routes that need to be strengthened in the German transmission network [104].

6. Conclusions

Flexibility in power systems is the ability to provide supply-demand balance, to maintain continuity in unexpected situations, and to cope with supply-demand uncertainty. In conventional power systems, flexibility was ensured by providing reserves and generation planning. However, it has gained a new dimension in the modern power systems where renewable energy penetration has increased steadily, due to the difficulties brought by generation uncertainty and availability concepts. Thus, generation management became more imporatnt with absolute power output range, ramp rate, and energy level duration being the key parameters.

The sudden and high ramping rate and frequent start-up needs arise as a result of uncertainty in electricity generation, due to the variable and intermittent nature of the renewable energy sources, and the load variations. Meeting these needs is challenging for conventional power plants. In modern power systems where renewable energy penetration level is high, renewable energy sources have dispatch priority, and during high generation periods, the demand is largely supplied by them. Therefore, the generation of baseload plants should be reduced or stopped when renewable energy based generation is sufficient; however, when the renewable energy based generation is interrupted or halts, the baseload plants must be re-commissioned.

Stability is crucial for the reliable and continuous operation of a power system. The wind and solar penetration levels, their connection topologies, and the wind turbine types have an influence on voltage stability, transient stability, small-signal stability and frequency stability of power systems containing renewable energy source generation.

Voltage levels are increasing with large-scale renewable energy sources being often remote from load centers. This wide geographical area diversity can reduce the variability of total generation; hence this advantage can be exploited with the correct planning. Moreover, with increasing renewable energy penetration, the network topology, which affects the transmission losses and the system's performance against failures, should be selected optimally. The method of providing flexibility with the demand-side management of distributed schemes with medium and small-scale renewable energy sources should also be considered. While supply-side flexibility in a power system can be achieved through generation management, demand-side management, the correct planning, and operation of transmission networks have also gained importance. The methods of meeting the flexibility needs arising from increased renewable energy penetration in a power system can be summarized as follows:

- Demand-side management can contribute to flexibility with demand planning, unlike methods that increase supply-side flexibility in a power system. In this context, demand management should be based on the share of renewable energy generation.
- Flexible operation of fossil-fueled power plants can be achieved by operating these plants, which are generally used as baseload plants, at a high ramp rate, and low output power. These operating characteristics negatively affect the life cycle.
- Combined heat and power plants can be a flexibility source with accurate heating and cooling timings in the case of a power system containing renewable energy generation.
- The curtailment of renewable energy generation is not considered as a solution. But it comes forward as a solution method due to reasons such as weak network, wind power aggregated in remote areas, high coal-fired power plant share, lack of adequate market mechanisms.
- Strengthening and expanding the transmission network is the best technical solution for network integration of increased renewable energy sources penetration with flexibility enhancement such as balancing distributed generation, facilitating interconnections with neighboring countries, and linking international power markets. On the other hand, infrastructure and financing may reduce its applicability.

Flexibility needs arising from increased renewable energy penetration in a power system are discussed in this study regarding the definition, criteria, and methods. The development of the aforementioned substances with increasing renewable penetration requires the role of electricity markets to be addressed in further studies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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