Celal Bayar University Journal of Science

Evaluation of Various Flexibility Resources in Power Systems

Emir Kaan Tutus[1*], Nevzat Onat[1]

[1]Manisa Celal Bayar University, Faculty of Engineering, Department of Electrical and Electronics Engineering, Yunusemre, Manisa, Türkiye
[*]emir.tutus@cbu.edu.tr
[*]Orcid No: 0000-0001-5119-8174

Received: 10 April 2023
Accepted: 27 September 2023
DOI: 10.18466/cbayarfbe.1280545

Abstract

Variable Renewable Energy Resources (VRES), especially wind and solar power, are known for their intermittent, uncertain, and low-energy-density nature. The increasing adoption of these stochastic sources presents irregularity in the net load in the power system network; therefore, it poses a challenge to the reliable operation of power systems. Consequently, there's an increasing need for power system flexibility to cope with VRES-related challenges. Flexibility planning will therefore be a crucial aspect for power system management, particularly as the penetration of VRES continues to rise. To reach this objective, the diversification of flexibility options emerges as a promising solution. Various strategies are prominent in the literature for enhancing power system flexibility to adapt to VRES variability. These include the utilization of flexible generators, adjusting load profiles through demand-side management, integrating energy storage systems and electric vehicle batteries, developing grid infrastructure, using surplus energy for various daily applications (e.g., heating), and the implementing of curtailment practices. Demand-side management and energy storage, for example, offer valuable flexibility by allowing consumers to adjust their consumption patterns to electricity supply and demand fluctuations. Additionally, flexible generation technologies like gas turbines and combined heat and power systems provide rapid responses, aiding grid balance during high VRES output variability periods. Overall, this paper provides an overview of power system flexibility, exploring the various flexibility resources available to VRES-related challenges. Finally, this paper emphasizes the importance of continued innovation in developing new flexibility solutions to meet the growing demand for sustainable and reliable power systems.

Keywords: Power system flexibility, assessment of flexibility, variable renewable energy resources, demand-side management, electric vehicle.

List of Abbreviations

Variable Renewable Energy Resources	VRES
Renewable Energy Resources	RES
Microgrids	MG
Variable Renewable Generation	VRG
Energy Storage System	ESS
Demand Response	DR
European Union	EU
United States	US
Demand-Side Management	DSM
Electric Vehicles	EV
Vehicle-to-Home	V2H
Vehicle-to-Vehicle	V2V
Vehicle-to-Building	V2B
Vehicle-to-Grid	V2G
National Renewable Energy Laboratory	NREL

1. Introduction

The Earth is experiencing a noticeable change due to the global warming. It has been changing significantly in recent years, and temperatures are rising at an unprecedented rate. This is largely due to human activities such as the burning of fossil fuels, deforestation, and industrial processes that release greenhouse gases into the atmosphere and trap heat from the sun. On the other hand, the increasing energy demand is causing a parallel increase in installed power that will lead to the installation of new power plants. The installation of new facilities constantly does not make economic sense. Hence, such environmental and economic issues pushed into societies to adopt new practices and technologies, leading among them is the increasing use of Renewable Energy Resources (RES).

This offers new opportunities for power systems and one of the opportunities that RES is taking in place of emission-emitting sources. Thus, the governments have implemented policies and incentives to encourage the use of renewable energy, and as technology has progressed, the cost of these sources has decreased year by year [1], making them increasingly viable. Also, thanks to natural disasters, which are defined as high-impact low-probability events, network outages can occur, leaving sufferers without power for extended periods of time. However, Microgrids (MG) equipped with RES are capable of operating in island mode, ensuring that critical facilities and infrastructure can continue to operate independently from the main grid. As a result, the penetration of RES has increased substantially in most parts of the world [2, 3].

These types of sources, mainly solar and wind, are considered as clean and sustainable energy sources contribute to decarbonization and reduction of greenhouse gases, however, they are also known as VRES [4] due to the *inherent variability and unpredictability of their generation profiles*, which depend on meteorological conditions. Their characteristics pose a significant challenge to the reliable and stable operation of the power system, as they can make difficult to maintain a stable supply-demand balance, especially when their penetration levels are high, which can lead to blackouts and other issues [5]. To address this challenge, maintaining the flexibility of the power system is essential [6, 7]. *Flexibility is the ability to deploy system resources in a way that responds to changes in net load. Here the net load is called as remaining system load that cannot be met by variable renewable generation (VRG) (e.g., solar and wind)* as seen in eq. (1.1) [8].

$$Net\ Load = Load - VRG \qquad \textbf{(1.1)}$$

As flexibility could be provided through power plants with constant voltage/frequency output in the past, (i.e., dispatchable power plants) there were no problems with the concept of flexibility. Moreover, in conventional power plants, the reserve capacities of generation plants were also considered system flexibility [5, 6]. However, as the VRG installed capacity increases, existing power system flexibility is insufficient. Therefore, it is required to re-model the system's flexibility or create new flexibility options *(i.e., diversification in the flexibility resources.)*. Flexibility might be achieved through several means such as Energy Storage Systems (ESS), Demand Response (DR), and flexible generation. These flexible resources can cope with the inherent variability and unpredictability of VRES and ensure the continuity of power system stability.
In this paper, a comprehensive review of resources contributing to the flexible framework of power systems is carried out, accompanied by evaluation of their present merits and drawbacks. The main contribution of the study is a detailed review and evaluation of the options that can be integrated into the system to ensure power system flexibility by coping with the challenges posed by the increasing penetration of VRES.

This paper is organized as follows. Section 2 gives what flexibility is. In Section 3, sources of flexibility in each part of the power system are reviewed. A brief of power system flexibility assessment and assessment indices are presented in Section 4. And lastly, the conclusion is outlined in section 5.

2. Power System Flexibility

The increasing spread of greenhouse gases resulting from the burning of fossil fuels, particularly in the electricity and transportation sectors, has led to environmental pollution and contributed to global warming, leading to climate change. To meet the emission reduction targets established by the European Commission and the White House, the European Union (EU) and United States (US) power sectors are required to cut CO2 emissions from 2005 levels by 58% and 42% by 2030, with the potential for reductions of up to 79% and 83% by 2050 respectively [9]. On the other hand, to ensure that the world remains habitable, it is essential to limit the increase in global temperatures and reduce the risks and effects of climate change. As a response, the Paris Agreement was signed in 2015 to reduce carbon emissions by increasing the decarbonization policies of the states and limiting the average global temperature rise to below 2 degrees [10]. To achieve this goal, the penetration of RES into the power system network has increased. RES such as solar and wind are called VRES, due to their intermittent nature, their output is dependent on meteorological conditions, resulting in fluctuations in supply and demand that cause a mismatch between of two. The imbalance can compromise the operational reliability of the power system, making flexibility an inevitable concept for the secure and reliable operation of power systems with a high share of VRES penetration. To fulfill the flexibility requirements, three different types of flexibility have been identified:

1) Short-Term Flexibility: It is based on estimated fluctuations in the balance of supply and demand, short-term is in the form of hour-to-hour.
2) Mid-Term Flexibility: It depends on the number of thermal power plants that must remain connected and operate in the system. Mid-term is in the form of hour-to-day.
3) Long-Term Flexibility: This type of flexibility is based on the annual and seasonal availability of VRG and electricity demand. Long-term is in the form of days, weeks, months, and years.

Celal Bayar University Journal of Science
Volume 19, Issue 3, 2023, p 243-252
Doi: 10.18466/cbayarfbe.1280545

3. Sources of Power System Flexibility

Conventional generation in power systems is gradually being replaced by power systems based on VRG. It is not enough to provide the flexibility of such a system with a single source of flexibility multiple options are required [6, 8, 10]. In order to be able to say that a power system is flexible, it must always be able to ensure supply-demand balance, be able to cover changes in the amount of production caused by variable renewable energy sources, and reconfigure quickly in case of possible outages [12]. For this purpose, the resources given in the list below are defined as a source of flexibility and depicted in Figure 1.

1) Flexible Generators
2) Demand-Side Management (DSM)
3) Energy Storage Systems (ESSs)
4) Grid Infrastructure
5) Operational Procedures
6) Convert Excessive Electricity into Thermal Energy
7) Electric Vehicles (EVs)
8) Curtailment of Surplus Renewable Generation

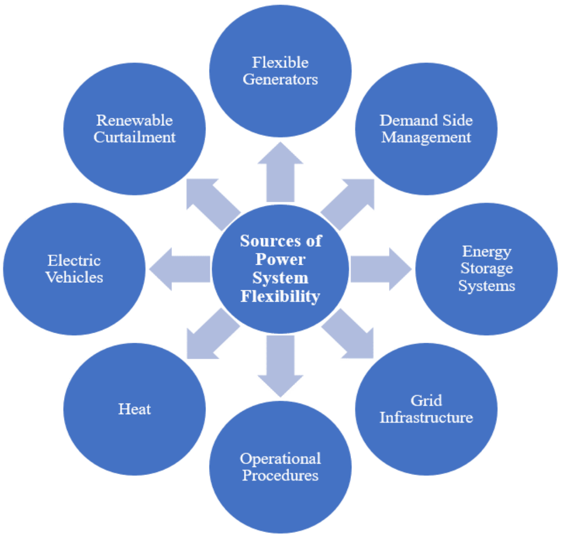

Figure 1. Sources of power system flexibility.

3.1 Flexible Generators

Flexible generators are one of the key resources of power system flexibility that can respond reliably and quickly to changes in supply and demand. These types of generators have the ability to ramp up and down their output quickly, making it convenient to balance the intermittent output of VRES [8]. Flexible generation resources can include gas-fired power plants and some types of renewable energy sources that have controllable output such as hydropower [13]. Generation plants are divided into three different groups according to their economic and technical attributes as follows:

1) Base Load Power Plants: These power plants are operated at the rated power level. Due to their characteristics, they are used to supply the base load and continuously operated plants (e.g., hydropower plants, and nuclear power plants). These plants have a slow start-up time which reaches an hour to one day.
2) Intermediate (Load Following/Mid-Merit) Power Plants: In these plants, the generation of electricity is adjusted according to fluctuation in demand. They are located between peak and base load power plants to factors such as efficiency, cost, capacity, etc.
3) Peak Load Power Plants: These plants such as solar power plants, are used at high-demand times. They are fast start-up power plants with the ability to reach full capacity within a few minutes after a cold start. These plants are crucial for the system's reliability since they ensure reserve generation.

3.2 Demand-Side Management (DSM)

This term, known as load management before, was first used by Clark Gellings in 1984 [14], is an initiative by electrical services to encourage consumers to change their load patterns through different techniques -either horizontal axis (time) or vertical axis (magnitude)- for the benefit of the grid. It has a key place in terms of flexibility by trying to provide a balance between supply and demand both on the consumer side and on the grid side.

DSM aims to extend the consumption of peak hours throughout the day, to reduce technical losses in networks, provide energy efficiency, and benefit both sides of the grid by reducing the bills of end-users [15]. Since the majority of global consumption occurs in the residential sector [16], DSM techniques, including peak clipping, valley filling, strategic protection, strategic load growth, load shifting, and flexible load shape, involve optimizing the operation of household appliances to match the existing generation value to demand. Scheduling operations of washing machines and dishwashers during off-peak hours instead of peak hours can be said as an example [17]. The six techniques defined below, are shown in Figure 2 respectively from a) to f).

1) Peak Clipping: It refers to the reduction of demand on-peak period.
2) Valley Filling: Related to its incentives for energy consumption during off-peak hours, when the cost of generation is lower than during on-peak hours.
3) Load Shifting: This technique identifies shifting some part of a demand from the on-peak period to the off-peak period. In load shifting, total energy consumption does not change i.e., the average power is the same but peak power is reduced. This is why, the load factor which is a ratio of average power over peak power will increase in this method, and the efficiency of energy use will increase as well. Moreover, it is possible to say that load

shifting is a combination of peak clipping and valley filling.
4) Strategic Conservation: Directs at reducing energy consumption by reducing energy waste to improve energy consumption efficiency.
5) Strategic Load Growth: Refers to an increase in electrical energy.
6) Flexible Load Shape: The last technique of DSM describes limiting energy use of the consumer at certain times thanks to load-limiting devices. This technique does not affect the security conditions.

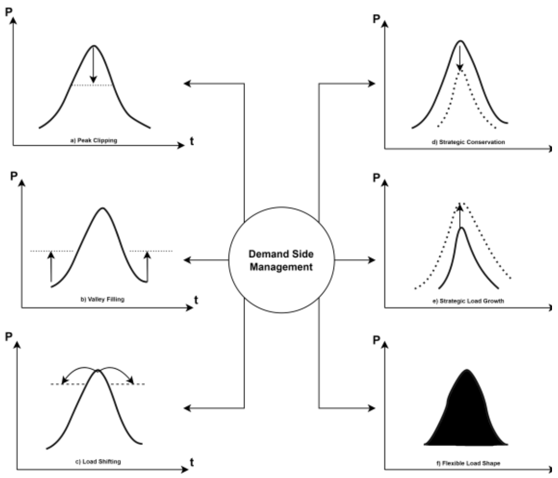

Figure 2. Demand-side management techniques (x-axis represents time, y-axis represents load.).

3.3 Energy Storage Systems (ESSs)

Energy storage systems (ESSs) have a vital role in increasing the flexibility of the power system when there is a high share of VRES penetration. ESSs are charged during hours of low demand, while base load power plants can operate at high efficiency. Also, when VRG has excess power generation, they store the surplus energy. The stored energy can be used instead of peak load power plants during high demand-insufficient generation periods which can help supply-demand balance and stabilize the power system.

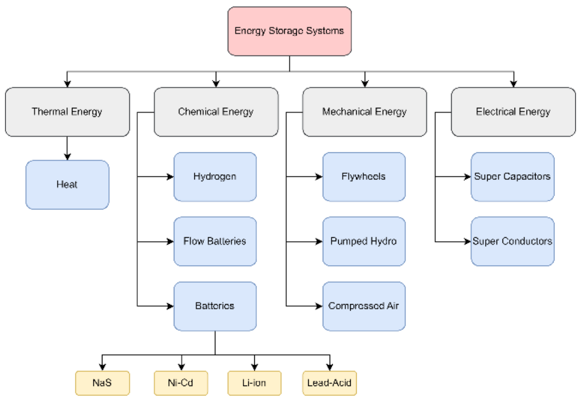

Figure 3. Types of energy storage systems [11].

Additionally, ESSs can provide backup power in case of power outages due to catastrophic events like earthquakes or malfunction of equipment. It can be therefore said as a flexible source and contributes to power system flexibility and reliable operation.

ESSs can be used as three different support services: load shifting service, short-term balancing service, and quick-acting instantaneous service [18]. According to their energy types, ESSs are classified into four types that are thermal, chemical, mechanical, and electrical. ESSs types are given in Figure 3.

3.4 Grid Infrastructure

Grid infrastructure involves all transmission lines, distribution lines, communication tools, and control equipment. Since the large-scale integration of VRES

into the power system and high-level supply security is required, more flexibility is needed [19]. Grid flexibility acts as a hyperlink between supply and demand side flexibilities. It is essential for the power system that the line capacities are sufficient [20]. If there is sufficient infrastructure, then supply can always reach demand everywhere in the power system with minimum cost [21].

3.5 Operational Procedures

It relies on how elements of the system are operated. The reason those operational procedures are considered a source of flexibility, they include methods for regulating the output of generating units to maintain the stability in the grid. The operational flexibility of the system refers to the ability to modify its generation or consumption regarding variability [22]. A large share of VRG in the power systems means that the energy generated from these sources will be excessive. This indicates that the operation of power systems will also become more difficult. Therefore, the flexibility requirements must be greater than before. Herein, choosing the proper operational procedure assists in providing reliable electricity to the customer at the lowest cost as much as possible. System operator needs accurate information which is related to balancing supply and demand because of changes in variable renewable generation from hour to hour.

Due to the high cost of ESSs, lower-cost flexibility options such as accurate forecasting also need to be identified [23]. Accurate forecasting of VRG output is important to manage its variability and thanks to forecasting, dispatchable generation output can be adjusted precisely. Therefore, advanced forecasting techniques must be used. On the other hand, it is especially important to balance changes on the demand side. At the same time, one of the important factors is to have coordination with neighboring regions for the import and export of electricity [11].

Celal Bayar University Journal of Science
Volume 19, Issue 3, 2023, p 243-252
Doi: 10.18466/cbayarfbe.1280545

3.6 Convert Excessive Electricity into Thermal Energy

Surplus generation of renewables converted into thermal energy adds a flexibility option to the power system because of the fact that it is easier to store thermal energy than electrical energy [11]. It is both economical and efficient to convert the surplus amount of renewable energy into thermal energy to use for heating and cooling objectives [24]. Besides, this contributes to reducing carbon emissions from heating power plants by replacing fossil fuels with electricity.

3.7 Electric Vehicles (EVs)

The development of electric vehicle technologies is considered a solution for the energy and environmental crisis today and especially in the future. In terms of energy, EVs, are emerging as a promising technology for providing mobile power source during contingencies [25]. EVs can serve as a reliable backup power source to ensure energy availability for critical demands such as hospitals, communication networks, etc. during power outages caused by natural disasters or other unforeseen events.

Additionally, EVs just as the ESSs, equipped with bidirectional chargers, can provide energy storage to balance grid fluctuations, and reduce the impact of intermittency of VRES. In terms of flexibility option, EVs have some modes such as Vehicle-to-Home (V2H), Vehicle-to-Vehicle (V2V), Vehicle-to-Building (V2B), and Vehicle-to-Grid (V2G) through bidirectional inverters. V2G mode, shown in Figure 4, is called the situation in which the EV discharges the energy stored from the grid as a result of optimizations depending on the conditions in which it is located. When EV is charged, energy flows grid to the vehicle. When demand is high at on-peak hours, EV is discharged and energy flows from vehicle to grid through a unit that has bidirectional converter like the battery energy storage systems.

Figure 4. V2G technology flow diagram.

The bidirectional V2G (and the other technologies too) offers the option of flexibility to enhance the power system operations such as supporting the network, power factor control, load balancing, voltage regulation, etc. [26]. Furthermore, EVs can effectively support grid services such as DR, peak clipping, and contributing to a more sustainable and resilient power system.

By providing this flexibility to the power system, EVs can also help to improve the reliability and resiliency of the power system during normal and emergency conditions. Five EV types are defined in terms of technologies [27].

1) EV: This type of EV's called a pure electric vehicle. They include electric motors, supercapacitors, and batteries.
2) Hybrid EV: It is comprised of supercapacitors, batteries, and an electric motor, and they also have a combustion engine. To move the wheels of the car, both an electric motor and a combustion engine are used.
3) Plug-in Hybrid EV: Plug-in hybrid EV involves supercapacitors, batteries, an electric motor, and a combustion engine the same as Hybrid EVs. But unlike them, the battery must be charged for using the electric motor. Also, they have bigger electric motors and larger capacity batteries than Hybrid EVs.
4) Range Extended EV: They are just like the Hybrid EV and Plug-in hybrid EV, i.e., comprise of a combustion engine. But this combustion engine is not provided power to the vehicle but is used as a generator when the batteries run out of charge.
5) Fuel Cell EV: Fuel cell EV includes electric motors and fuel cells. Fuel cells provide energy to the motor not batteries. It cannot be pluggable.

However, it should also be taken into account that EVs can have a negative impact on the power system as of now. One of the most significant challenges is that as the number of EVs on the network increases, particularly during peak charging periods [28], it can result in grid congestion and necessitate significant and costly grid upgrades. This not only entails considerable costs but also potential disruptions and delays in implementation.

3.8 Curtailment of Surplus Renewable Generation

One of the main challenges of VRG is, in some cases it is not feasible to store or use it. Therefore, it must be curtailed. If we are looking at curtailment on the side of generation, in this situation we need to use existing RES as a primary priority and curtail the generation of emission emitting sources. According to the report published by National Renewable Energy Laboratory (NREL), it is more valid for system operators to curtail generation from wind and solar power plants when minimum generation levels are reached at some fossil fuel plants. Because these plants take a long time to be started up and shut down. Thus, they may be more costly compared to curtailing short-term renewable generation [29]. Although this situation is helpful on the one hand because the supply-demand balance is maintained, nevertheless, since there is a curtailment on RES, we cannot benefit from them i.e., this is called loss technically. This disadvantage can be coped with by using storage systems [30].

Celal Bayar University Journal of Science
Volume 19, Issue 3, 2023, p 243-252
Doi: 10.18466/cbayarfbe.1280545

In Figure 5, the curtailment event in California on 13 May 2018 is given. As seen in the figure, solar system had been online at nearly 6 a.m. From here, some flexible generators have been shut down to make room for the generated solar energy. However, as some of the non-variable renewable generations (dispatchable generation) ensure reliability of the power system cannot be ramped up or shut down for temporarily. Hence, supply exceeded the system load, and the condition called **overgeneration** occurred. In order to maintain the supply-demand balance, the system curtailed by approximately 12 GWh of solar output [31]. It is also seen in Figure 5, drawn in red.

VRG is curtailed when the following situations occur [10, 29].

→ Limited transmission line capacity,
→ Over supply of VRG when demand is low,
→ Absence of neighboring areas or even if there is, they have sufficient generation,
→ In cases such as high share of base load power plants which are inflexible in the power system.

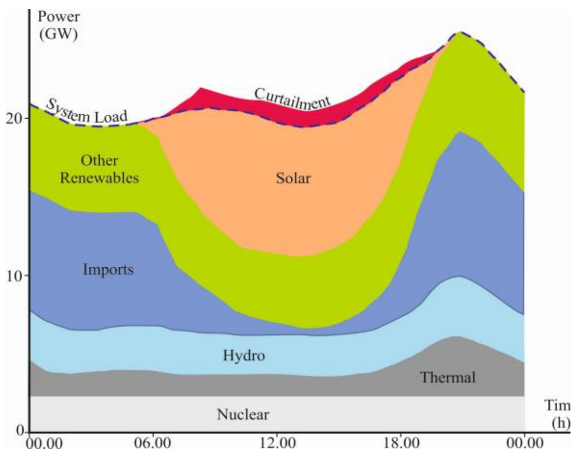

Figure 5. PV curtailment event in California on 13 May 2018 [31].

Table 1 provides a comprehensive overview of the various publications that address the aforementioned sources of flexibility. The objectives of the studies, the use of flexibility options and the research objectives aimed to achieve can be found in this table.

4. Assessment of Power System Flexibility

The existing flexibility of the system must be assessed and determined which part of the system will be improved before optimization. After the optimization process is completed, flexibility of the system is re-evaluated. Following then, the optimization process is repeated if requires. As a result, this is a cycling process. Appropriate indices are needed to evaluate the flexibility. Today experts are determined three different index categories which are device-level flexibility quantitative index, network-level flexibility quantitative index, and system-level flexibility quantitative index [33].

1) Device-level flexibility quantitative index: This index relates to flexibility of power supplies, energy storage systems and more devices. Today in most literatures for this index ramp rate, operational limits etc. are considered.
2) Network-level flexibility quantitative index: Topology of the network and capacity of each branch affect capacity of transmission lines of the network. Also, economic limitations should be considered.
3) System-level flexibility quantitative index: By considering time scale, economic cost, and response amplitude this index is used to measure the flexibility regulation ability of the entire system.

5. Conclusion

With the developing technology, both sources and producers (e.g., share of VRES increases in the power system), which are different from traditional network structures, have diversified undoubtedly. In this structure, the flexibility advantages provided by the large powerful units, the base load power plant, which have a good ability to respond to disruptive effects, are gradually decreasing. To continue in reliable operating conditions in power systems, the development of flexibility requirements is one of the key options. Due to the stochastic nature of these sources (i.e., the energy they give to the system can be varied from hour-to-hour.) and diversified loads, flexibility gap that will occur in the system should be covered by other options/sources of flexibility.

The scientific aim of the review study is to provide an overview and assessment of power system flexibility and sources of flexibility that can be on the generation side, on the end-user side, etc. in many parts of the network. The options to enhance power system flexibility are examined in Section 3. These are:

→ Flexible generators,
→ Rearrangement of the load curve with DSM on the end-user side without affecting user's comfort,
→ Storing a surplus of VRG with ESSs or EVs to use during on-peak hours,
→ The status of grid infrastructure,
→ Converting this surplus VRG into thermal energy so that it can be used for heating and cooling purposes,
→ The inflexible power plants cannot be taken off the system, so to prevent overgeneration and maintain supply-demand balance, curtailment of surplus VRG is necessary (This situation is being worked to reduce.).

With the help of the resources mentioned above, problems can be avoided by having a more flexible structure of the power system against the intermittent situation of VRES, whose installed capacity will increase even more in the future. Therefore, this research will be helped to the studies by contributing to the formation of ideas about how measures can be taken already before such a problem occurs in the future.

Acknowledgement

No particular funding grant was received by this research from agencies in the public, commercial, or not-for-profit sectors.

Author's Contributions

Emir Kaan TUTUS: Conceptualization, investigation-literature survey, visualization, writing-original draft
Nevzat ONAT: Supervision-the researching process, helped in manuscript preparation, visualization, writing-review&editing.

Ethics

There are no ethical issues after the publication of this manuscript.

Table 1. Highlights of the studies oriented on flexibility in the power systems.

Ref. No.	Aim of the paper	Results	Which flexibility options were used
[34]	Reviewing on the flexibility quantification methods, which are divided into 2 as deterministic and probabilistic approaches. The formulas and shortcomings of several of them are examined.	As a result of the research, deterministic flexibility quantification approaches yield inaccurate results in the high renewable energy penetration and the integration of demand-side resources into the system. Hence, a probabilistic approach is the preferred method for addressing intermittent net load changes within operational timeframes.	-
[17]	Optimizing the operation of household appliances in a smart home setting using renewable energy sources. The study seeks to achieve this by utilizing power forecasts and electricity tariffs to ensure the most economic operation of appliances while maintaining a desired level of comfort in the home. The ultimate goal is to ensure that the smart home can run on renewable energy sources for the longest possible time while minimizing costs and maintaining the expected level of comfort.	The reduction of electricity cost for selected two months and the year are 4.23% 2.93% respectively, In addition to cost reduction, shifting operations are decreased 32.65% and 52.99% for dishwasher and washing machine respectively. This demonstrates that comfort level is increased.	DSM
[25]	The study aims to develop a smart home energy management system that ensures uninterrupted energy supply in post-disaster by utilizing renewable energy sources and electric vehicles. The proposed algorithm prioritizing critical appliances and ensuring their operation during power outages, while optimizing the use of available energy sources.	The simulation studies showed that the proposed algorithm resulted in a 25% to 471% increase in energy supply time compared to the conventional algorithm in the worst and best scenarios, respectively. Based on these results, the remaining energy values of the electric vehicle battery (EVB) ranged from 5.08 kWh to 2.67 kWh with the proposed algorithm, while the conventional algorithm consumed all the EVB energy. Therefore, it can be concluded that the proposed algorithm prevented the battery from running out.	DSM, EVs

[35]	Minimization of generation and investment cost.	In comparison with the base case, integration both wind and DSM reduced generation and investment cost about 20%.	DSM
[36]	Investigation of the effects of DSM, which is seen as a source of flexibility in power systems, on the angular stability of the system under different conditions.	It is seen that the effect of DSM on angular stability depends on the operating conditions of the power system, The location and capacity of the DSM applied also play a role in angular stability.	DSM
[37]	Investigation of the potential impact of demand-side flexibility (provided by DR) on the market performance of a European-wide daily electricity market under the high share of RES by 2030.	It is seen that the DR reduced the cost by 8-9% for cost minimization, also the total curtailment in Europe decreased by more than 90% thanks to the DR, Another result is, increasing demand-side flexibility in integrated electricity markets with high level of VRES does not have to improve the load factor, even reduce it, it has been seen in the simulation results.	Demand-side flexibility (with DR)
[38]	Planning the long-term energy transition of electric power systems from fossil fuel to the of high share of renewable energy (75%, even 90%).	Depending on penetration of RESs in Chilean power system (minimum 75% in 2050), CO2 emission will only reduce 40% in pessimistic scenario. However, this ratio will be almost 94% in optimistic scenario according to data obtained in 2016 (36MtCO_2).	BESS, transmission lines, and curtailment
[39]	Mixing existing and new generating plants (with a high level of RES) with the lowest cost to meet South Africa's predicted annual energy of 382 TWh for 2050.	If prices fall as much as the determined values, solar and wind energy are installed 50% and 20% more, respectively. Also, 17 GW/48 GWh batteries will be able to be deployed by 2050 in these circumstances. This indicates that the battery will account for 35% of the flexibility resources.	Pumped storage, peaking open cycle gas turbines, BESS with Li-Ion
[40]	Ensuring the generation of more renewable energy (with wind) in an isolated energy system by 2030, also ensuring the regulations with Vehicle-to-Grid and heat pumps instead of thermal generators.	Compared to the reference case, the heat pump and V2G technology with different battery capacities (4-10-16 MW) is used in the other cases. As a result, a wind energy penetration of 25-30-36 MW was achieved, respectively, In addition, thanks to V2G technology, the frequency remained in the acceptable operating range of 49.9-50.1 Hz during times of overgeneration.	EV based ESS
[41]	Analyzing the role of electrolyzer in increasing power system flexibility by	This study shows that, despite the impact of restrictions caused by the	Electrolyzers

	considering hydrogen injection constraints.	connection to the gas network, the conversion of excess renewable energy into hydrogen with electrolyzers and ensuring its use in the gas network can be an important potential for increasing power system flexibility.	
[42]	Investigating the link between smart grids, network flexibility, and optimization models, considering short and long-term flexibility with a focus on renewable energy. It's relevant for entities planning renewable integration to enhance energy stability and reduce costs.	The addition of wind turbines, even with forecast errors, reduces the need for power plants as fossil fuel generators are replaced by wind turbines. Some scenarios are inducted, and it is seen that in order to achieve greater flexibility, more power plants are needed in scenarios where wind energy with fluctuation is demonstrated.	Flexible generators and wind turbines

References

[1]. M. T. Irena, *Renewable Power Generation Costs in 2022*. 2022.

[2]. Sancar, S, Erenoğlu, AK, Şengör, İ, Erdinç, O. 2020. Güneş Kollektörlü ve Elektrikli Şofbenli Bir Akıllı Evin Talep Cevabı Programı Kapsamında Enerji Yönetimi. *Avrupa Bilim ve Teknoloji Dergisi*; (19): 92–104.

[3]. Papayiannis, I, Asprou, M, Tziovani, L, Kyriakides, E. Enhancement of power system flexibility and operating cost reduction using a BESS, IEEE PES Innovative Smart Grid Technologies Conference Europe, Delft, Netherlands, 2020, pp 784–788.

[4]. IRENA (2018). 2018. Power System Flexibility for the Energy Transition, Part 1: Overview for policy makers. *International Renewable Energy Agency;* 1-48.

[5]. Akrami, A, Doostizadeh, M, Aminifar, F. 2019. Power system flexibility: an overview of emergence to evolution. *Journal of Modern Power Systems and Clean Energy*; 7(5): 987–1007.

[6]. Babatunde, O M, Munda, JL, Hamam, Y. 2020. Power system flexibility: A review. *Energy Reports*; 6: 101–106.

[7]. Saygin, D, Tör, O B, Cebeci, ME, Teimourzadeh, S, Godron, P. 2021. Increasing Turkey's power system flexibility for grid integration of 50% renewable energy share. *Energy Strategy Reviews*; 34: 100625.

[8]. Jakhar, A. A comprehensive review of power system flexibility, IEEE International Conference on Power, Control, Signals and Instrumentation Engineering, ICPCSI 2017, Chennai, India, 2018, pp. 1747–1752

[9]. Brouwer, A. S., Van Den Broek, M., Seebregts, A., Faaij, A., 2014. Impacts of large-scale Intermittent Renewable Energy Sources on electricity systems, and how these can be modeled, *Renewable Sustainable Energy Reviews;* 33: 443–466.

[10]. Horowitz, C. A. 2016. Paris Agreement. *International Legal Materials*; 55(4): 740–755.

[11]. Eltohamy, MS, Moteleb, MSA, Talaat, H, Mekhemer, SF, Omran, W. Overview of Power System Flexibility Options with Increasing Variable Renewable Generations, ACCS/PEIT 2019 - 2019 6th International Conference on Advanced Control Circuits and Systems and 2019 5th International Conference on New Paradigms in Electronics and Information Technology, Hurgada, Egypt, 2019, pp 280–292.

[12]. Langevin, J., Harris, C. B., Satre-Meloy, A., Chandra-Putra, H., Speake, A., Present, E., Adhikari, R., Wilson, E.J.H., Satchwell, A. J. 2021. US building energy efficiency and flexibility as an electric grid resource. *Joule;* 5(8): 2102–2128.

[13]. Gjorgievski, V. Z., Markovska, N., Abazi, A., Duić N. 2021. The potential of power-to-heat demand response to improve the flexibility of the energy system: An empirical review, *Renewable Sustainable Energy Reviews;* 138: 110489.

[14]. P. Warren, "A review of demand-side management policy in the UK," Renew. Sustain. Energy Rev., vol. 29, pp. 941–951, 2014, doi: 10.1016/j.rser.2013.09.009.

[15]. Gaur, G, Mehta, N, Khanna, R, Kaur, S. Demand side management in smart grid environment, 2017 IEEE International Conference on Smart Grid and Smart Cities Demand, Singapore, 2017, pp 227–231.

[16]. Taşcıkaraoğlu, A, Erdinç, O. 2019. Paylaşımlı Elektrik Enerjisi Depolama Sisteminin Kullanımına Dayanan Bir Enerji Yönetimi Yaklaşımı. *European Journal of Science and Technology*; 16; 589–604.

[17]. Tascikaraoglu, A, Boynuegri, AR, Uzunoglu, M. 2014. A demand side management strategy based on forecasting of residential renewable sources: A smart home system in Turkey. *Energy and Buildings*; 80: 309–320.

[18]. Flexibility Requirements and Potential Metrics for Variable Generation: Implications for System Planning Studies. *North American Electric Reliability Corperation;* 1-55, 2010.

[19]. Lund, PD, Lindgren, J, Mikkola J, Salpakari J. 2015. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renewable Sustainable Energy Reviews*; 45: 785–807.

[20]. Haidl, P, Buchroithner, A, Schweighofer, B, Bader, M, Wegleiter, H. 2019. Lifetime analysis of energy storage systems for sustainable transportation. *Sustainability;* 11(23): 1–21.

[21]. Schreiner, L, Madlener, R. 2022. Investing in power grid infrastructure as a flexibility option: A DSGE assessment for Germany. *Energy Economics*; 107: 105843.

[22]. Vargas-Ferrer, P, Álvarez-Miranda, E, Tenreiro, C, Jalil-Vega, F. 2022. Assessing flexibility for integrating renewable energies into carbon neutral multi-regional systems: The case of the Chilean power system. *Energy for Sustainable Development;* 70: 442–455.

[23]. Denholm, P, Margolis, R. 2016. Energy Storage Requirements for Achieving 50 % Solar Photovoltaic Energy Penetration in California. *National Renewable Energy Laboratory*; 1-37, https://www.nrel.gov/docs/fy16osti/66595.pdf. (accessed at 10.08.2022).

[24]. Mathiesen, BV, Lund, H. 2009. Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources. *IET Renewable Power Generation;* 3(2): 190–204.

[25]. Candan, AK, Boynuegri, AR, Onat N. 2023. Home energy management system for enhancing grid resiliency in post-disaster recovery period using Electric Vehicle. *Sustainable Energy, Grids and Networks*; 34: 101015, 2023.

[26]. Sami, I, Ullah, Z, Salman, K, Hussain, I, Ali, SM, Khan, B, Mehmood C A, Farid, U. A bidirectional interactive electric vehicles operation modes: Vehicle-to-grid (V2G) and grid-to-vehicle (G2V) variations within smart grid, 2019 International Conference on Engineering and Emerging Technologies, ICEET 2019, Lahore, Pakistan, 2019, pp 1-6.

[27]. Ricardo, M, Contreras, F, Alexander, B, Beltran, V, Armando, D, Ramírez, G. 2021. Electric Vehicles within the Distributed Generation. *International Journal of Engineering Research and Technology*; 14(9): 887–894.

[28]. Zhang, B., Kezunovic, M., 2016. Impact on Power System Flexibility by Electric Vehicle Participation in Ramp Market. *IEEE Transaction on Smart Grid;* 7(3): 1285–1294.

[29]. Bird, L, Cochran, J, Wang, X. 2014. Wind and Solar Energy Curtailment: Experience and Practices in the United States. *National Renewable Energy Laboratory*; 1-58, http://www.osti.gov/servlets/purl/1126842/. (accessed at 15.09.2022).

[30]. Riaz, S, Chapman, AC, Verbic, G. Comparing utility and residential battery storage for increasing flexibility of power systems, 2015 Australasian Universities Power Engineering Conference: Challenges for Future Grids, AUPEC 2015, North Wollongong, Australia, 2015, pp 1-6.

[31]. O'Shaughnessy, E, Cruce, JR, Xu, K. 2020. Too much of a good thing? Global trends in the curtailment of solar PV. *Solar Energy*; 208: 1068–1077.

[32]. Fink, S, Mudd, C, Porter, K, Morgenstern, B. 2009. Wind Energy Curtailment Case Studies. *National Renewable Energy Laboratory*; 1-48, http://www.nrel.gov/docs/fy10osti/48737.pdf. (accessed at 26.12.2022).

[33]. Xing, T, Caijuan, Q, Liang, Z, Pengjiang, G, Jianfeng, G, Panlong, J. A comprehensive flexibility optimization strategy on power system with high-percentage renewable energy, 2017 2nd International Conference on Power and Renewable Energy, ICPRE 2017, Chengdu, China, 2018, pp 553–558

[34]. Jain, AP, Yamujala S, Bhakar R. Quantification of Power System Flexibility: A Review, 2022 OPJU Int. Technol. Conf. Emerg. Technol. Sustain. Dev. OTCON 2022, Raigarh, Chhattisgarh, India, pp. 1–6, 2023

[35]. Rosso, A, Ma, J, Kirschen, DS, Ochoa, LF. Assessing the contribution of demand side management to power system flexibility, Proceedings of the IEEE Conference on Decision and Control, Orlando, Florida, USA, 2011, pp 4361–4365

[36]. Wang, M, Milanovic, JV. Contribution of Advanced Demand Side Management to Angular Stability of Interconnected Transmission Networks, Proceedings of 2019 IEEE PES Innovative Smart Grid Technologies Europe, ISGT-Europe 2019, Bucharest, Romania, 2019, pp 1–5.

[37]. Zalzar, S, Bompard, EF. Assessing the Impacts of Demand-Side Flexibility on the Performance of the Europe-Wide Integrated Day-Ahead Electricity Market, SEST 2019 - 2nd International Conference on Smart Energy Systems and Technologies, Porto, Portugal, 2019, pp 1-6.

[38]. Seshu Kumar, R, Phani Raghav, L, Koteswara Raju, D, Singh, AR. 2021. Impact of multiple demand side management programs on the optimal operation of gridconnected microgrids. Applied Energy; 301: 117466.

[39]. Klein, P, Carter-Brown, C, Wright, JG, Calitz, JR. 2019. Supply and demand side flexibility options for high renewable energy penetration levels in south africa. *SAIEE Africa Research Journal*; 110(3): 111–124.

[40]. Pillai, JR, Heussen, K, Østergaard, PA. 2011. Comparative analysis of hourly and dynamic power balancing models for validating future energy scenarios. *Energy;* 36(5): 3233–3243.

[41]. De Corato, AM, Riaz, S, Mancarella, P. Assessing the Flexibility of Electricity-Gas-Hydrogen Distribution Systems with P2G Units, 2021 IEEE PES Innovative Smart Grid Technologies - Asia, ISGT Asia 2021, Brisbane, Australia, 2021, pp 1–4.

[42]. Coban, H. H., Lewicki, W., 2023. Flexibility in Power Systems of Integrating Variable Renewable Energy Sources *Journal of Advanced Research in Natural and Applied Sciences;* 9(1): 190–204.