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REVIEW

Recent developments of demand-side management towards flexible DER-rich power systems: A systematic review

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Abstract

Recently, various distributed energy resources are significantly integrated into the modern power systems. This introduction of distributed energy resource-rich systems can cause various power quality issues, due to their uncertainties and capacity variations. Therefore, it is crucial to establish energy balance between generation and demand to improve power system's reliability and stability and to minimize energy costs without sacrificing customers' comfort or utility. In this regard, power system flexibility concept is highlighted as a robust and cost-effective energy management system, especially on the demand side, to provide consumers' demands with an acceptable level of power quality. Accordingly, here, a comprehensive review of recent developments in the power system flexibility and demand-side management strategies and demand response programs are provided to include mainly classifications, estimation methods, distributed energy resource modelling approaches, infrastructure requirements, and applications. In addition, current research topics for applying power system flexibility solutions and demand-side management strategies based on modern power system operation are deliberated. Also, prominent challenges, research trends, and future perspectives are discussed. Finally, this review article aims to be an appropriate reference for comprehensive research trends in the power system flexibility concept in general and in demand-side management strategies and demand response programs, specifically.

1 | INTRODUCTION

1.1 | Background

Nowadays, the global demand for electrical energy has increased [1]. Hence, it is crucial to utilize new alternative energy resources to cut off the adverse environmental impacts that are caused by conventional energy sources such as fossil fuels. Thus, the integration of various sorts of distributed energy resources (DERs), for instance, renewable energy sources (RESs) is expanded in the modern power systems (MPSs) [2, 3]. By looking specifically at global energy consumption in 2022, it represents about 160.8 petawatt hour (PWh) in which fossil fuels such as oil, coal, and gas participate with large percentages of this amount are 32.95%, 27.90%, and 24.52%, respectively, as depicted in Figure 1a; while other clean energy resources record the remaining percentage. Various industrial countries have implemented urgent procedures to decline this global energy consumption which varies per year as shown in Figure 1b. As shown, the energy consumption in 2021 recorded an incremental variation of 5.46% but it declined to around 1.11% in 2022. It is clear that energy consumption decreased to small amounts (lower than energy production) as a result of economic crises, and the coronavirus pandemic in 2009, and 2020, respectively. In Figure 2a, the upward trend of global electricity generation is presented which was recorded in 2022 at about 28.5 PWh considered 17.7% of the global energy consumption. Conventional energy sources, such as coal, gas, and oil still contribute with large generation amounts (60.94%), while the other renewable and sustainable energy resources provide only 39.06% of total electricity production, as depicted in Figure 2b. Although the procedures implemented for energy transition towards low carbon energy sources, as presented in Figure 2c, their share is slightly increasing every year.

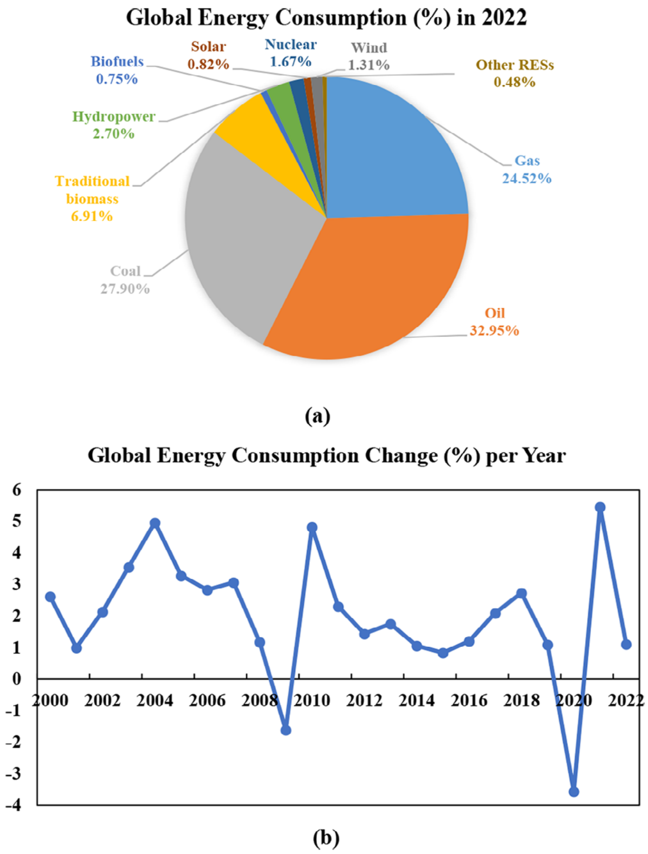


FIGURE 1 Global direct primary energy consumption [1].

1.2 | Literature review

Towards a sustainable and clean environment, several RESs such as wind energy, are being installed to eradicate the adverse impacts of conventional energy sources [4, 5]. However, RES characteristics with their variation in uncertainties and availability are associated with the climate conditions which are challenging factors [6–8]. So, the importance of integrating various types of DERs, electric vehicles (EVs), and energy storage systems (ESSs) is highlighted as a convenient solution to these challenges [9–11]. By increasing the energy demands, not only the electrical demands but also cooling and thermal demands, the multi-carrier energy systems (MESs) are utilized in cooperation with the energy hubs (EHs) framework [12]. All these advanced technologies have adverse influences on the power system operation causing several power quality issues due to the insufficient requirements of grid infrastructure [4]. Thus, the power system operators use several concepts to study the operational performance of the electrical systems such as energy supply security which determines the power system's ability to provide the required energy and withstand urgent disturbances [13]; while resilience and robustness measure the power system's capability to restore normal operation conditions after disturbances and interruptions [14]. Therefore, it is critical to achieve the energy balance between generations and demands to provide the load consumptions with different patterns, and to minimize the energy costs, which contribute to enhancing power system reliability and stability and protection from disturbance [15]. To accomplish these objectives, the power system flexibility (PSF) concept is applied to describe the ability of power systems to manage the generation and energy demands over any timescale without being influenced by the uncertainties and availabilities of RESs, in the presence of new industrial technologies and various load patterns [16]. Numerous studies have been conducted on the PSF concept in several aspects such as its resources, services, estimation methods, performance indices, and so on. In Table 1, a literature review of the most prominent review articles related to the PSF concept is investigated regarding various research objectives. To assess the various references against our work, the authors have compared them considering eight research objectives (R1 to R8), as described in the table. As noticed, most of these existing review papers either partly considered certain research objective(s) or totally ignore other ones. In turn, the proposed review paper covers the various research objectives, which is essential towards accomplishing flexible DER-rich MPS.

1.3 | Motivation and contributions

As illustrated in the literature review, there are a lot of PSF classifications and requirements which depend on their applications; so, there is not a general definition of the PSF for MPSs in the presence of DERs. This argument can be justified since the PSF can be applied to several levels such as grid, generation, demand, storage, and energy market. In this regard, the DSF is considered an important connecting node between generations and consumptions associated with the energy markets which plays a role in improving the PSF at various levels and applications in the presence of various flexibility sources and

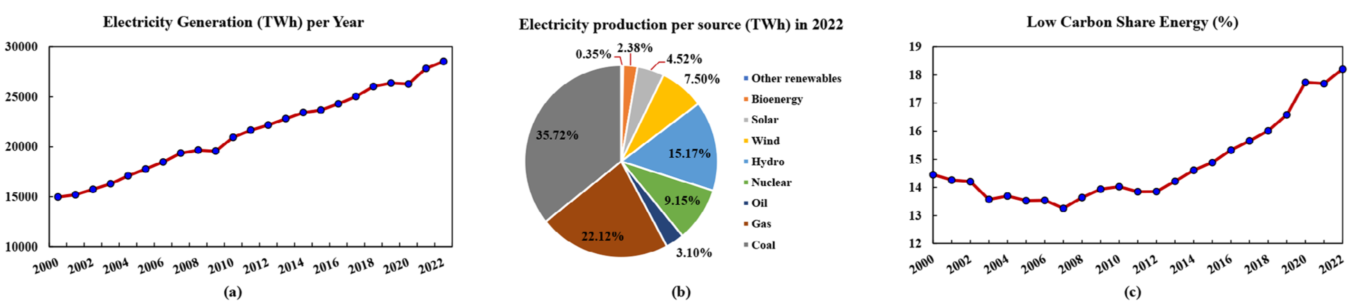


FIGURE 2 Global electricity generation [1].

TABLE 1 Literature review of the most prominent review articles related to energy flexibility management (Timeline: 2017 to 2023).

Ref.	Year	Research objectives R1	R2	R3	R4	R5	R6	R7	R8	Article contribution
[17]	2017	P	✓	✗	P	✓	✗	✓	✓	Presents a comprehensive investigation of demand response (DR) programs concerning their classification, methodologies, challenges, and practical evidence. Besides, a general overview of the demand-side management (DSM) tools and strategies was given in reference [18].
[19]	2018	✓	P	✗	P	✓	P	✓	P	Reviews the most available solutions for PSF and their sources.
[20]	2021	✓	P	✗	P	✗	✗	✓	✓	Gives a comprehensive study of the power flexibility resources in terms of definitions, classifications, and other aspects. The same content is presented in reference [21].
[22]	2022	P	P	P	✗	✗	✗	✓	✓	Investigates the demand-side flexibility (DSF) management based on residential aggregators in terms of energy flexibility definitions, sources, forecasting and quantification approaches, and energy market perspectives. That is supported by current challenges and an overview of future technologies. The same content is presented in references [23–25].
[26]	2022	P	P	✗	✗	P	✓	✓	✗	Represents a comprehensive review of the power system's flexibility regarding its definitions, sources, indices, and products. However, the target objective was considered briefly with restricted information. The same content is presented in reference [27].
[28]	2022	P	✗	✓	✗	✗	✓	✗	P	Elaborates on the applications of machine learning approaches on smart distribution systems in order to estimate and predict both power system flexibility and planning.
[29]	2022	✗	✓	✓	P	✓	P	✗	✓	Highlights the DR program requirements for smart metres and sensors, estimation methods, and communication technologies. Further, it presents the various challenges and solutions of the DR program followed by techno-economic benefits for distributed system operators (DSOs) and end-users in the future.
[30]	2023	P	P	✓	✓	✓	P	✓	✓	Involves comprehensively the DSM control schemes, indices, enhancement approaches, and other aspects. The same investigation is implemented in references [31] and [32] in the presence of EVs and residential demands, respectively.
[33]	2023	P	✗	✓	P	✓	P	✗	✗	Discusses the forecasting models of DR-based applied algorithms and factors.
[34]	2023	P	✓	✓	P	✗	P	✗	✗	Several modelling formulations and strategies with various objectives are investigated based on energy resource flexibility.
[16]	2023	✓	✓	✓	P	✓	P	P	✓	Both power system flexibility and DSM are considered in terms of definitions, modelling, classifications, and future directions.
This work	2024	✓	✓	✓	✓	✓	✓	✓	✓	An overview of the PSF in terms of various aspects, such as classifications, is presented followed by an extensive study of the DSF in terms of DSM strategies and DR programs based on technological developments and economic factors. Further, the MPS operation is discussed in the existence of new technologies and energy management systems. Then the energy market operation is investigated by mentioning the challenges and future research topics.

- R1: Overview of energy flexibility management: classifications, quantifications, solutions, and applications.
- R2: Classifications, modelling, objectives, and sources of demand-side flexibility.
- R3: Estimation and forecasting approaches for demand-side flexibility.
- R4: Enhancement techniques for demand-side flexibility.
- R5: Developments of demand response program or energy efficiency management.
- R6: Modern power operation based on demand-side flexibility management.
- R7: Economic solutions and energy market.
- R8: Prominent challenges, current status, and future opportunities.

Notes: Cross (✗) sign indicates 'no', tick (✓) sign indicates 'yes'.
Abbreviation: P, partially.

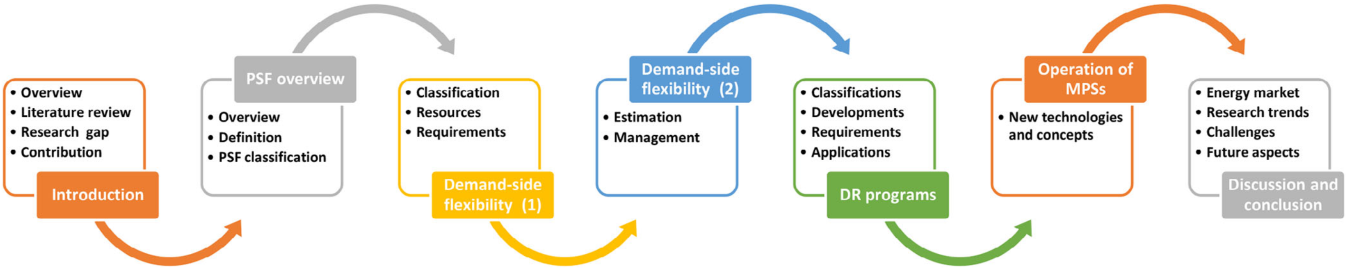


FIGURE 3 Article layout.

services. So, it is essential to investigate both the PSF and DSF concepts in terms of their classification, solutions, resources, and applications while fulfilling with the shortages of various recent review articles. Besides, this work aids in highlighting the role of PSF and DSF in DER-rich MPSs to achieve the objective of the energy transition in parallel with the satisfaction rate of consumers for power system reliability.

To cover the above-mentioned research gaps and recent energy technologies, this article presents a comprehensive survey of the PSF and DSF research trends in DER-rich MPSs concerning various objectives and contributions which can be summarized as follows:

- Overview of the PSF is given based on definitions, classification, quantification, characteristics and functions, estimation and forecasting methods, solutions, and applications supported by recent studies.
- The new PSF definition is stated in terms of various significant factors and elements found in MPSs.
- Comprehensive review of recent developments of DSF and recent DSM strategies is involved in terms of mathematical modelling, sorts, requirements, applications, etc.
- The developments of DR programs are highlighted based on classifications, requirements, and applications.
- The state of the art of the new integrated technologies in the MPSs which directly affects the operation conditions, is also considered. The role of various energy management systems is highlighted.
- The energy market perspectives are briefly described.
- The research trends, challenges, and future aspects are investigated.

1.4 | Article organization

After the introduction section, Section 2 provides an overview of energy flexibility management and its solutions to enrich the PSF and reliability. Sections 3 and 4 include an extensive study of DSF based on modelling, resources, estimation, classification, and requirements. In addition, the developments of the DR programs are elaborated in Section 5. The new technologies and research directions applied in the MPSs to increase their sensitivity, flexibility and reliability based on DSM are considered in Section 6. This is followed by a discussion about the energy markets, challenges, and future aspects associated with DSM, and PSF in Section 7. Finally, the work conclusion is provided in Section 8. Moreover, Figure 3 illustrates the article's outlines and the main contributions.

2 | OVERVIEW OF ENERGY FLEXIBILITY MANAGEMENT

2.1 | PSF definition

It is challenging to find a unique definition of PSF for describing the MPS operation. Several articles have stated their definition of PSF based on their work implementations as concluded in references [16, 20, 22, 26, 27]. As discussed in reference [20], there are three critical criteria for defining the PSF based on the type of PSF resource (generation, storage, etc.), time duration (seconds, minutes, etc.), and incentive services (external control signals, etc.). Hence, the most vital definitions of PSF are summarized in Table 2. However, these definitions did not reflect some aspects of new technologies applied to MPSs. First, new generation units are implemented along with the conventional ones such as new integrated DERs and RESs with their uncertainties besides the improvements of current techniques in transmission and distribution (T&D) management. Also, the widespread interactions of several types of new ESSs (hydrogen based), which can be fixed or portable, into the MPSs with new strategies of energy management, should be highlighted. Further, the MESs in EHs to support the electrical, cooling, and thermal demands, need more specification especially the high penetration of EVs in the residential sector. For accomplishing flexible and reliable power systems, robust infrastructure should be implemented based on advanced smart meters, communication technologies, and policies or standards with advanced control strategies.

The two-stage scheduling framework was used to optimize the integration of advanced distributed flexible resources in the EHs [39]. Another advanced energy management strategy to enhance the PSF involves using sensitivity analysis while considering future energy markets and flexibility services amid high penetration of DERs [40]. In reference [41], thermal ESSs, supercapacitors, and RESs are involved in the planning framework under a novel storage charge DR program for sustaining flexibility in the islanding mode of the microgrid. Other articles

TABLE 2 Most important power system flexibility definitions from 2018 to the present.

Ref.	Year	Definition	Remarks
[35]	2018	'Flexibility is defined as the modification of generation injection and/or consumption patterns, on an individual or aggregated level, often in reaction to an external signal, in order to provide a service within the energy system or maintain stable grid operation'.	Only the generation and demand resources of PSF were mentioned without specifying the time duration.
[36]	2018	'the capability of a power system to cope with the variability and uncertainty that VRE (variable renewable energy) generation introduces into the system in different timescales, from the very short to the long term, avoiding curtailment of VRE and reliably supplying all the demanded energy to customers'.	Definition based on generations from RESs only without mentioning the incentive control variables.
[37]	2019	'the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply'.	Other PSF resources were not involved with the general specification for the time period.
[38]	2019	'Power system flexibility relates to the ability of the power system to manage changes'.	Very general definitions without specifying the three criteria.
[20]	2021	'The ability of power system operation, power system assets, loads, energy storage assets and generators, to change or modify their routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions'.	The comprehensive definition, however, did not consider the recent technologies and solutions for supporting the PSF.
[26]	2022	'system's ability to remain functional amid rapid fluctuations and manage all system components so as not to surpass their operational constraints, while employing all of its infrastructure's potential in all time perspectives, such as from seconds to multiple years, without accruing additional costs to the system's owner(s)'.	Comprehensive definition without specifying resources and recent technologies.

considered new ESSs deployed in the MPS with the expansion of the EV charging stations at the distribution level to deal with the urgent requirements of PSF accomplishment in references [42, 43]. To cover the shortage in the existing PSF definitions, the authors suggest a revised inclusive PSF definition as follows,

> 'The modern power system's capability to reliably and cost-effectively regulate any capacity variations, and uncertainties of various DERs, including ESSs, EVs, and MESs, in generation, transmission, and distribution levels over different time horizons, in the presence of robust monitoring, convenient infrastructure, and communication technologies with advanced control strategies based on the international standard and protocols of energy markets'.

2.2 | Power system flexibility classifications

There are various classifications of the PSF based on the scientific research directions. So, the authors have merged all available classifications into several main categories as shown in Figure 4, which aid in highlighting the important research topics of the PSF in the MPSs with regards to:

- its applications which can be in generation, network, storage, and distribution levels to supply residential, commercial, industrial, and other energy demands.
- its characteristics and functions such as flexibility indices, and services besides the flexibility analysis depended on the applied timescale and techno-economic factors.
- available solutions in terms of enabling operators or technologies, and flexibility resources.
- various utilized estimation and prediction approaches.
- quantification strategies.

2.3 | Flexibility quantification

It is essential to measure the ability of power systems to adapt to any capacity variation and stochastic nature of any included components at an acceptable level of reliability using advanced technologies of meters and control systems, which present complicated procedures [22]. So, various approaches have been developed to accurately quantify and evaluate the PSF which may be not applicable for all systems efficiently due to the potential dynamics and various energy resources in the power systems. These methods can be dependent on power systems parameters or planning aspects [44].

2.3.1 | Quantification parameters

To quantify the PSF, main factors can be utilized which are dependent on the flexibility type, and system uncertainties as summarized in references [16, 22], like this:

- **Power (kW)**: it is considered the main factor to quantify the PSF as it specifies the power capacity of flexible loads based on several metrics, for example, mean, maximum, minimum, instantaneous powers, charging and curtailed powers, and power capacity. In reference [45], average reduction quantification of lighting demand annually during power curtailment was estimated using various flexibility indicators. The

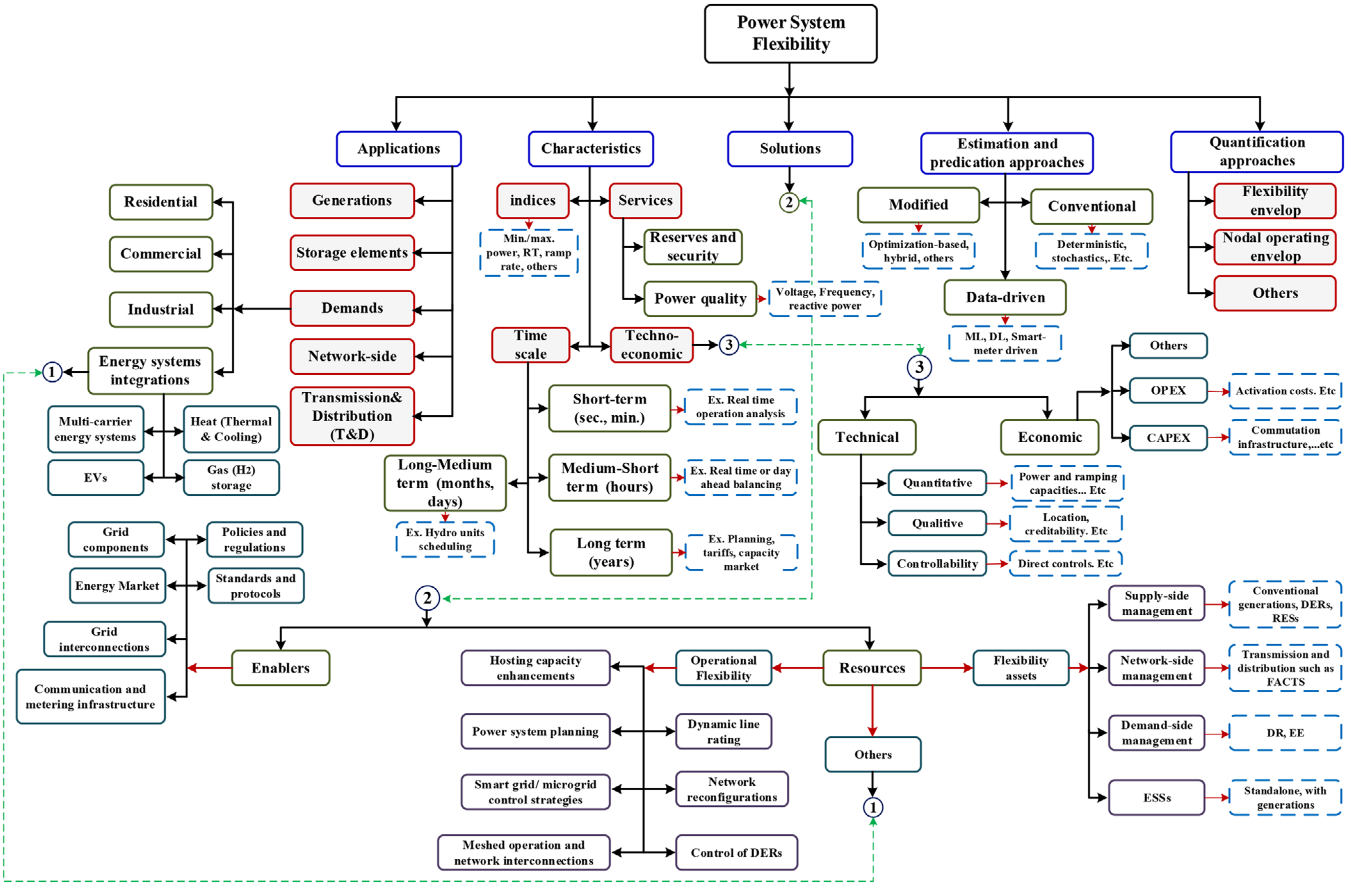


FIGURE 4 General classifications of power system flexibility.

maximum charging power of EVs was quantified in the United States and Germany based on various aspects of flexibility markets in reference [46]. Regarding the energy transition vision in Colombia by 2030, the expected power capacity of RESs was determined under the flexibility requirements [46].

- **Energy (kWh)**: it is applied to quantify the PSF of storage elements and shiftable flexible loads in terms of their energy or storage capacities, shiftable energy, and energy reduction. In reference [47], the dynamic operations of ESSs in residential buildings were regulated to increase energy flexibility using hierarchical EMS considering flexible loads and resources. In the existence of electrical and energy resources in residential buildings, a unified framework was proposed to calculate the daily energy flexibility based on peak shiftable and storage energy indicators [48].
- **Time (h)**: it is crucial for scheduling the flexible loads with shiftable demand profiles to increase the PSF which is specified by duration, available time, comfort capacity, and curtailment duration. In reference [49], the demand flexibility was scheduled in different climate conditions for commercial buildings based on the dispatch of flexible sources and the duration before comfort dynamic constraints were attained. For optimizing peer-to-peer (P2P) energy trading for thermal loads in residential buildings, virtual ESSs are modelled based on real-time variations to quantify the PSF [50].
- **Other parameters**: various parameters can be merged to quantify the PSF such as power capacity and shiftable energy considering the duration and prices [51]. Other factors depend on the relative relationship towards other variables, for instance, the PSF is determined relative to the percentage of storage efficiency or consumption. Other factors are developed based on the nature of power system modelling and its components such as power variation coefficient, ramping rate, frequency, and peak time operation. In reference [52], both cost and power consumption indicators were utilized to quantify and optimize the PSF in residential buildings during the presence of various flexible resources. Another implementation of PSF for a nearly zero-energy building with climate prediction used different metrics such as power and energy shifting, cost, and comfort level [53].

2.3.2 | Power system operational planning

Other quantification approaches are associated with the operational planning of power systems that describe their flexibility potential dynamics and individual flexible resources with the specification of operation boundaries such as bus voltages.

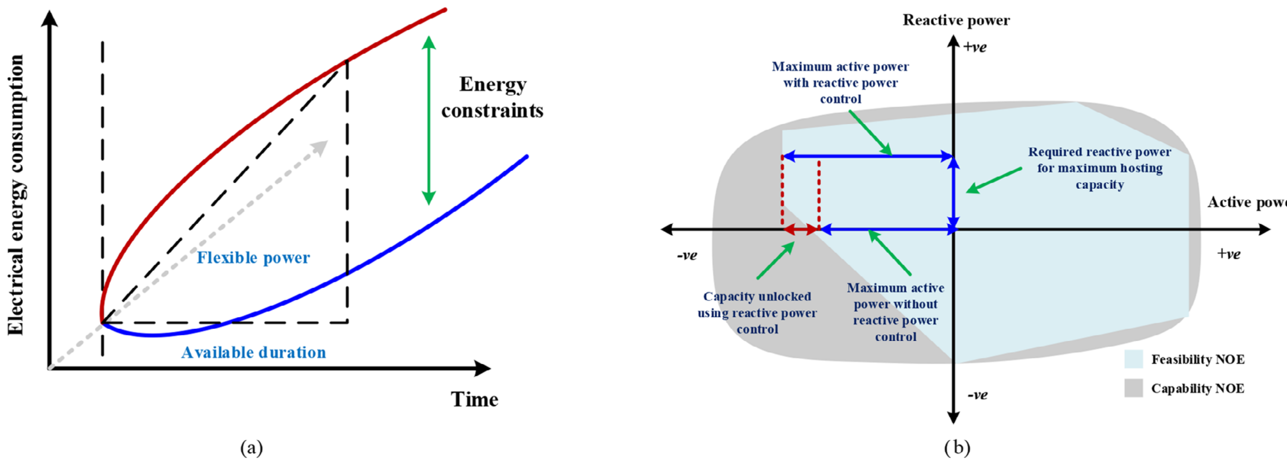


FIGURE 5 Flexibility quantification based on power system operational planning. (a) Flexibility envelope concept [56]. (b) NOE example [62].

- **Flexibility envelope**:

The concept of flexibility envelope is developed to specify the flexible power consumption restricted by maximum and minimum power limits that quantified energy flexibility found between them without violating operation limits over the available duration, as depicted in Figure 5a [54]. It is a powerful tool to assess the flexibility and potential dynamics of MPSs, aggregators, and individual resources as well as planning the penetration of RESs, DERs, ESSs, EVs, and MESs. The approach is applied to several power system planning studies in references [55–57].

- **Nodal operating envelope**:

The nodal operating envelope (NOE) concept is applied to power system operational planning which provides the operational constraints of buses or feeders such as bus voltages, so it is used to evaluate the PSF using various flexibility metrics such as capacity, ramp, duration, and cost [55, 56]. The NOE approach is utilized to calculate the maximum integration level of RESs, DERs, ESSs, EVs, and MESs which can be accommodated without violation of any operational performance indices. Therefore, it can be used for long-term planning and specifying the available hosting capacity (HC) at each time interval on the MPSs, as shown, for example, in Figure 5b. Various articles applied the NOE concept to assess the PSF during integrating DERs in unbalanced distribution networks [58, 59], and others studied the DER services in energy markets [60, 61].

2.4 | Characteristics and functions

Other articles studied and classified the PSF based on its characteristics and governed functions as depicted in Figure 4.

2.4.1 | Flexibility indices

The PSF can be evaluated mainly using ramping rate capability, energy, and power capacity, however these indices are not sensitive to rapid or delay variations in demands. Other flexibility indices depend on the technical characteristics of the MPSs which are calculated based on seven technical parameters such as 'generating units with a minimum stable generation level, ramp up/down capabilities, operating range, minimum up/down time, and start-up time' [63]. However, some limitations appeared due to the random behaviour of DERs and other power system components. Therefore, new indices are developed to cope with their restrictions and improve their operation, as follows.

- The response time (RT) index is used to quantify the PSF as investigated in reference [22].
- Another index called insufficient ramping resource expectation (IRRE), is applied to investigate the network outages or failures as a result of variations in various power system components especially on generation and distribution levels [64].
- The lack of ramp probability (LORP) index measures the inter-temporal ramping flexibility at the real timescale [65].
- Another important index used in reference [66], called system capability ramp (SCR) is based on investigations of system capability shortages considering the various system uncertainties. Moreover, the risk indices are applied to evaluate the shortage of ramping capability in power systems [67].
- Other indices were developed to deal with the techno-economic factors which influenced PSF evaluations at real operation time [68, 69]. In terms of calculating the optimal cost for improving and providing flexibility services, the cost indices are used in references [70, 71].
- In reference [72], a new index was used for assessing the PSF to apply to power system planning. Which considers the capacity availability of supply resources and ESSs.
- Other various indices are mentioned in references [21, 26, 27, 73] for special purposes of PSF evaluations and have their merits and demerits such as ramping capability shortage expectation (RCSE), flexibility area index (FIA), and building energy flexibility index (BEFI).

2.4.2 | Flexibility services

The PSF services should be declared to aid the system operators in providing complete energy management during the variability and uncertainty of various generation units and demands [74]. Also, it helps in optimizing and control coordinating the operation of flexible resources, and DERs in MPSs such as smart grids, and microgrids enabling prosumers' and aggregators' participation in the electricity market [75, 76]. Hence, the PSF services can be provided by various PSF solutions regarding specific timescales that can be divided into:

- Grid services: offer energy management and balancing to enhance the power quality provided to consumers. Besides increasing system reliability and security.
- Prosumers and demand services: give the ability to prosumers to manage their energy consumption and production based on energy costs and resilience in addition to voluntary demand reductions as responding to variations in generation and demand sides and energy markets.
- Market participant services: exhibit maximization of the profits of both end-users and system operators.

Another classification can be made related to the power system security which depends on the available power capacity and provides power reliability and quality to end-users [26]. It involves main items which are labelled as power quality, reserves, and security services.

a. Power quality: the PSF services provide continuous energy management of flexibility resources and loads to offer acceptable operation levels of power quality which focuses mainly on voltage regulation and frequency response stability at any time period or urgent disturbances on generations or demands.
b. Reserves and security: reserve services ensure the provision of additional energy resources for rapid actions to any power disturbances, especially in peak demands such as ESSs or small generation units. While security services exhibit acceptable power system reliability and cost-effective operation for consumers without any supply interruptions.

2.4.3 | Flexibility timescales

For evaluating the PSF under the variations and uncertainties of various power system components over generation, transmission, distribution, and energy market levels, the various timescales should be integrated as a prominent variable during power system operation and planning [26]. Also, these timescale classifications provide a vital vision of transmission system operators (TSOs) and distribution system operators (DSOs) for making decisions about the deployment of flexible resources to ensure power system stability and security. These timescales can be classified into:

- Short term (subcycle): the timescale acts for milliseconds, seconds, or minutes and is used to define the capability of power systems to respond to variations in power exchange stages such as voltage regulations and frequency response services with real-time operation analysis. Hence some energy management systems are applied for regulating and forecasting the short-term operation of various RESs in references [77–79], frequency stability investigations [80], and referring to the influence of virtual power plants on power system transient response [81].
- Medium–short term (interday, daily): it is applied to examine the power system's capability to respond to various characteristics and alterations of power system components within hours, such as ramping up or down generation or dispatching flexible resources [82]. Moreover, it is used for scheduling day-ahead balancing between supply and demand associated with energy markets [83, 84].
- Long–medium term (weekly or seasonal): it refers to the ability of power systems to respond to changes in demand and supply within a week or over a season which can be used in hydro units, thermal units or RESs scheduling [85, 86].
- Long term (years): for planning the power system generation and consumption for years regarding the energy costs, a long-term timescale is applied [87, 88].

2.4.4 | Flexibility techno-economic factors

Another classification of PSF characteristics is dependent on both technical and economic aspects, as depicted in Figure 4 [20]. The technical characteristics can be classified as follows,

- Quantitatively: it expresses the capability of flexibility resources numerically.
- Qualitatively: it expresses the degree of quality as a response to flexible resources.
- Controllability: it investigated the PSF through the control strategies of flexibility resources.

On the other hand, the PSF characteristics can be classified according to the economic factors into two types. The capital economic characteristics (CAPEX) are used to justify the investment costs of applied technologies to activate the PSF in addition to capital costs of flexibility sources, other implemented equipment, and communication infrastructures. Further, the operational economic characteristics involve several types of costs that may be variable (salaries and wages), costs for re-installed flexibility technologies and updated power system infrastructure or equipment. Also, other costs are specified by DSO and customers to support the PSF. Other costs may be involved besides the main types to complete an overview of the economic characteristics.

In reference [39], the energy management strategy is applied for operation scheduling and the distribution flexibility resources in order to reduce the carbon emission cost and boost the system efficiency and reliability. The cost benefits are analysed through a flexible energy management strategy to

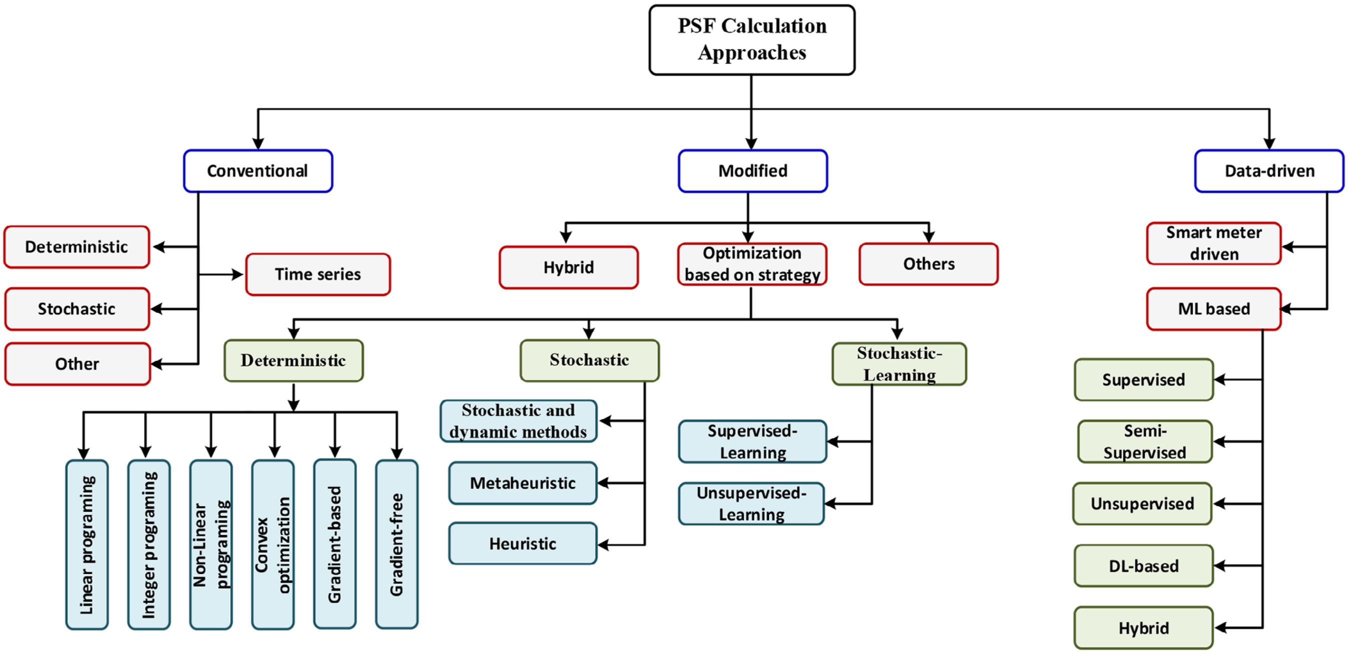


FIGURE 6 Calculation approaches of the power system flexibility.

minimize the installation's energy cost and predict the over-run costs using optimization algorithms [40]. Other articles investigate the PSF through the technical characteristics in terms of maximizing generations and control systems to sustain acceptable power quality [42, 43].

2.5 | Estimation and prediction approaches

Several calculation approaches are applied for estimating and predicting the PSF which can be based on various flexibility indices especially the grid flexibility index that confirms the ability of the utility grid to manage the power flow among various energy levels and power system components regarding its infrastructure and typical operation scenarios. These methods can evaluate the PSF based on both technical and economic flexibility indices, operational measuring data, timescales, and communication infrastructure, which also help to provide a meaningful picture of the challenges that the power system operators and planners might face and how to address them [29]. Hence these approaches can be categorized into conventional, modified, and data-driven approaches, as depicted in Figure 6. The selection of a suitable approach is associated with several factors such as applied flexibility indices, timescale, power system structure, available data from measurement devices, control strategy, required performance and accuracy, energy market data, and other applied factors from operators. Despite the simplicity and compact performance of conventional approaches, nowadays both modified and data-driven approaches are extremely expanding [28, 89]. As these approaches are important towards both system operators and end-users, the authors will discuss the approaches from the point of view of the various applications based on the DSF which ensures the reliability, stability, and security of MPSs with high shares of modern technologies.

2.5.1 | Conventional approaches

The conventional approaches may be classified into deterministic, stochastic, time series, and other approaches. In deterministic approaches, the prior knowledge data of both technical and economic flexibility metrics are required [90]. Despite their simplicity with low computational time, these methods do not reflect the uncertainties and availability of various power system components [91]. By considering the uncertainties of generation units and load demand, stochastic approaches are developed to reflect realistic system conditions. However, by increasing the uncertainties and scenarios, the simulation complexity, computational time, and memory usage are increased [92]. Based on the time-varying generations and demands from measurement devices, and historical data, the time series methods are applied easily in short-term timescales to avoid increasing complexity or computational times [93]. Various recent articles applied these approaches for estimating the DSF [94–101].

2.5.2 | Modified approaches

To deal with the shortcomings of conventional approaches, modified approaches are applied extensively which can be classified into optimization-based, hybrid, and other approaches [102]. These approaches can operate with any number of

TABLE 3 Comparative study of power system flexibility estimation methods concluded from references [112–114].

	Conventional			Modified			
Item	**Deterministic**	**Stochastic**	**Time series**	**Optimization based**	**Hybrid**	**Others**	**Data driven**
Data requirement	Small	Moderate	Large	Large	Depends	Depends	Large
Considering uncertainties?	No	Yes	Yes	Yes	Depends	Depends	Yes
No. of applied scenarios	Few	Large	Moderate	Large	Moderate	Moderate	Extreme
Complexity	Simple	Complex	Complex	Complex	Moderate	Depends	Complex
Computational time	Small	Large	Large	Large	Moderate	Depends	Large
Scalability	Easy	Complex	Complex	Complex	Moderate	Moderate	Easy
Results' accuracy	Approximate	Accurate	Accurate	Exact	Accurate	Accurate	Exact

uncertainties and constraints of variables and their demand scenarios to specify various objective functions at the same time. However, the selection of a suitable approach it is based on depends on the user's judgment and performing a high number of iterations to attain accurate results increases the complexity and computational time compared to conventional approaches. Various recent articles applied these approaches for estimating the DSF [103–107].

2.5.3 | Data-driven approaches

Recently, the data-driven methods based on artificial intelligence (AI) algorithms have been extensively used not only in estimating the PSF but also in predicting system failures, measurement error detection, prices in energy markets, and other special applications [28, 89]. Moreover, handling big data from energy markets, supervisory control and data acquisition (SCADA) systems, and smart meters in distribution systems is beneficial for power system planning. However, advanced infrastructure (monitoring, measurements, control systems, communication systems, and advanced generation units) of the power system is required which is very complex and expensive especially to upgrade in old distribution systems. Recent articles applied these approaches for estimating the DSF [108, 111]. Table 3 compares applied approaches in terms of data requirement of variables, number of uncertainties and scenarios, computational time, accuracy, and scalability.

2.5.4 | PSF simulation tools

To apply previous approaches for solving the mathematical models of different power systems, it is essential to use convenient simulation software as discussed in reference [115]. Several software are mainly used for conventional and modified approaches to investigate various power system aspects (planning, optimization, and analysis) such as DIgSILENT Power Factory [116], GAMS [117], OpenDSS [118], MATLAB [119], Etab [120], Synergi Electric [121], NEPLAN [122], CYME [123], PSS Sincal ICA [124], EDSA Paladin Toolkit [125], HYPERSIM/ ePOWERgrid [126], EasyPower [127], DSA Tools [128], and HOMER [129]. Also, some previous software can be utilized for data-driven methods such as CYME, OpenDSS, or DIgSILENT Power Factor. Other specified tools for data-driven methods are developed such as Tensorflow, Typhoon, Theano, Caffe, Torch, and PyTorch which can be programmed using C, C++, Python, Lua, MATLAB, etc., as stated in reference [113, 130]. Table 4 gives a summary of various articles that applied previous approaches for estimating DSF in terms of system configuration, consumer type, available technologies, applied approach with objective functions, and simulation software.

2.6 | PSF solutions

Another classification can be made associated with the available PSF solutions or resources, as discussed in references [19, 20, 26, 27]. The authors classify the PSF solutions into main groups, namely, flexibility enablers and flexibility resources as depicted in Figure 4.

2.6.1 | Flexibility enablers

The classification of flexibility enablers is used to define the various enabling technologies or products considering PSF solutions. Moreover, it describes the ancillary services and requirements for supporting the PSF by grid services, system or network operators, and prosumers [20]. The grid interconnection specifies the structure of connecting systems between generations and demands for all areas in different power system levels besides the type of transmission lines. While the grid components classification gives a list of various grid elements such as DERs, loads, ESSs, RESs, meters, and so on. Hence, the energy market depicts the energy investments and their dynamic pricing locally or internationally, and the benefits of consumers and system operators. These previous enablers will be discussed in detail in upcoming sections. Other critical

TABLE 4 Some recent articles applied estimation and prediction approaches based on demand-side flexibility.

Ref.	Year	System configuration	Consumer types	Technologies	Objective functions	Approach type	Simulation tool
[100]	2021	33-bus LVDS with 6-node heat network	Residential, commercial	PV, various components of IEGHS	• Optimal planning • Minimize the operating cost	Deterministic	MATLAB and CPLEX solver
[97]		DUTH, located in Greece	Residential, commercial	PV, wind, DERs	• Optimal planning • Minimize the power losses	Time series	MATPOWER
[96]	2022	128 real LV feeders in the United Kingdom		PV, ESSs	• Optimal planning • Minimize the operating cost	Stochastic	–
[108]	2023	33-node and 152-node ADNs	Residential, commercial	PV, ESSs, flexible loads, thermal DGs, Wind	• Optimal planning • Minimize the operating cost	Data driven	Dec-POMDP framework
[109]		Testbed house	Residential	PV, ESSs, EV, smart meters	Building energy management		MATLAB
[110]				PV, ESSs, various components of IEGHS			Python 3.7, the Tensorflow 2.8.0 open-source framework
[101]		EPRI Ckt5 test model	Residential, commercial	PV, RESs	Optimal planning	Time series	OpenDSS
[95]		IEEE-33-bus, IEEE-69-bus radial LVDSs		PV, EV, DGs	• Optimal planning • Minimize the power losses	Deterministic	–
[103]		EH (IEEE 118-bus, 9-bus test systems)		Wind, various components of IEGHS	• Optimal planning • Minimize the operating cost	Optimization based	MATLAB
[104]		IEEE 33-bus distribution system		Wind, EVs, ESSs	• Optimal planning • Minimize the operating cost • optimal allocation of EV charging stations		–
[106]		Microgrid	Residential	RESs (wind, PV), ESSs, EVs	MG sizing applications		MATLAB
[105]				RESs (wind, PV), ESSs	• Optimal day-ahead planning • Minimize the operating cost		–
[107]	2024	Rwandan electricity infrastructure		RESs (wind, PV), ESSs, DERs, hydro	• Optimal planning • Minimize the operating cost		Gurobi version 9.1.0
[99]		Korea and Ireland outperforming		Various types	• Optimizing electrical demands of low aggregation levels • Improve energy sharing with cost-effective aspects	Stochastic	–
[111]		NEST building		ESSs, various components of IEGHS	Energy saving and optimal operation	Data driven	MATLAB

Abbreviation: IEGHS, integrated electricity–gas–heat systems.

enables for the PSF should be considered, for instance, communication and metering infrastructure, regulations, standards, and protocols [17, 29]. Regarding the metering infrastructure, the most common types may be used such as accumulation meters, interval meters, and smart meters, as investigated in reference [131]. To provide complete controllability in the MPS, these meters should be connected to the energy providers using robust communication infrastructure involving advanced instruments as summarized based on communication technologies, standards, and characteristics in Table 5. For the residential sector, several communication protocols are utilized especially in smart homes such as user datagram protocol (UDP) sockets, message queuing telemetry transport (MQTT), and constrained application protocol (CoAP), as presented in reference [131]. Other communication protocols are applied extensively in the EV ecosystem such as Open Charge Point Protocol (OCPP), Open Automated Demand Response (OpenADR), Open Smart Charging Protocol (OSCP), IEEE 2030.5, and ISO/IEC 15118.

TABLE 5 Selective communication technologies, standards, and characteristics [29, 131].

Technology	Standard	Data transfer rate	Typical coverage range	Response time	Frequency band	Power consumption	Application area
Bluetooth	IEEE802.15.1	24 Mbps (v3.0)	10 m typical	10 ms to 1 s	2.4 GHz	Low	HAN
WiFi	EEE802.11x	1154 to 300 Mbps	Up to 100 m		2.4 GHz, 5 GHz	Very high	
Z-Wave	802.11	100 Kbps	30 to 100 m		2.4 GHz, 868.42 MHz (EU)	Low	HAN, NAN
ZigBee	IEEE802.15.4	256 Kbps	10 to 100 m		2.4 GHz	Very low	
LPWAN	SigFox LoRaWAN NB-IoT	0.3 to 50 kbit/s per channel	10 km in open space	10 μs to 20 ms	915 MHz	Low	NAN, WAN
GSM/GPRS	ETSI GSM EN 301349 EN 301347	14.4 Kbps (GSM), 114 Kbps (GPRS)	Several km	10 μs to 1 s	935 MHz Europe, 1800 MHz		HAN, NAN, WAN
WLAN	IEEE 802.11	150 Mbps	250 m	10 ms to 1 s	2.4 GHz Europe		HAN, WAN
Ethernet, PLC, Wimax, WLAN	Depends	100 kbps to 1 Mbps	Up to 1 km	10 ms to 2 s	–	Depends	BAN, IAN
Ethernet, PLC, DSL, Fibre Optics, WiMax, NB-IoT, LoRa		100 kbps to 10 Mbps	0.1 to 10 km	10 to 50 ms	–		NAN
PLC, Ethernet, Fibre Optics, LoRa, WiMax		10 Mbps to 1 Gbps	10 to 100 km	10 μs to 20 ms	–		WAN
6LoWPAN	IEEE802.15.4	250 Kbps	Up to 200 m	10 ms to 1 s	2.4 GHz	Low	HAN, NAN
3G/4G	UMTS	14.4 Mbps	Up to 100 m		450,800 MHz to 1.9 GHz		HAN, WAN
5G	5G Tech Tracker	20 Gbps	46 to 92 m		3400 to 3800 MHz awarding trial licenses (EU)	Very low	

Abbreviations: BAN, building area network; HAN, home area network; IAN, industrial area network; NAN, neighbour area network; WAN, wide area network.

2.6.2 | Flexibility resources

The PSF can be provided using several resources based on power system components, operational conditions, and other advanced technologies. So, the authors divide them into three groups namely, flexibility assets, operational flexibility, and other flexibility options.

Flexibility assets

Several power system components can be used to support the PSF through energy flow levels labelled as supply-side, ESSs, demand-side, network-side, and market products [26].

Supply side. The supply-side flexibility considers the power system components associated with the generation sector to provide flexibility services; however, their response depends on their characteristics and scale [26]. Regarding conventional generation stations, gas turbines are the most flexible generators while on large scales, the nuclear, and hydropower plant turbines are efficient in providing the required flexibility [132]. Moreover, other thermal and electrical generators can be used for the same target in old power systems. Regarding the energy demands in the MPSs, it is noticeable that various types of DERs, RESs, thermal DGs, MESs, EVs, and ESSs, are significantly integrated and their availability and uncertainty are continuously varied [133]. So, the energy management of the supply side requires robust control schemes to deal with these challenges and support the PSF. Hence, data-driven approaches are employed to schedule generation maintenance periods and manage the energy flow based on the developments in the grid infrastructure [108].

Energy storage systems. ESSs are implemented as PSF resources because of their ability to provide the power system with additional active or reactive powers based on control schemes of their charging and discharging modes [134]. Therefore the technical development of the ESSs is investigated in several articles in terms of their topologies, control schemes, technical characteristics, cost-effectiveness, and others, at both network and demand sides in references [10, 135]. Several types are commonly used such as 'pumped storage, fuel cell, flywheel storage, electrochemical storage, compressed air storage, and electromagnetic energy storage' due to their various features [27]. Other advanced ESSs are employed in the MPSs such as thermal storage, thermochemical storage, and domestic space and water heating tanks [120, 121]. To support the network-side flexibility, the virtual ESSs are implemented regarding their rapid response reserves and economic aspects based on the available transmission system operator (TSO)-DSO coordination schemes [136, 137]. The virtual ESSs represent a pivotal tool in modernizing power systems and advancing the transition towards a more sustainable and resilient energy future. By integrating virtual ESSs into MPSs, various system utilities can better accommodate fluctuations in energy demand and supply, optimize grid operations, and enhance system reliability. Additionally, virtual ESSs facilitate the integration of DERs by providing backup power during periods of low generation. Moreover, empowering consumers to participate in demand response initiatives by enabling them to store excess energy during off-peak hours and utilize it when demand is high or grid conditions are strained [81].

Various articles investigated the optimal operation of virtual ESSs and other types such as thermal ESSs, hydrogen ESSs, and battery ESSs, in the presence of EVs and MESs for energy management of EHs to feed the electrical, thermal, and cooling demands [138–141]. In reference [142], a stochastic risk assessment strategy to assess the distribution systems' performance in the presence of high penetration of DERs, MESs, and ESSs. By considering various technical risks such as branch power flows and bus voltage limits, as well as economic opportunities from gas networks, this strategy effectively reduces the operational risks and costs while enhancing system strength and robustness levels. Further, the authors in reference [143] address the critical concern of distribution companies regarding security requirements and real-time contingencies by proposing a flexibility-oriented decision-making strategy involving virtual ESSs. Through the stochastic model, the energy flexibility is enhanced by locally integrating virtual ESSs into market participation plans, while each virtual ESS optimizes power and reserve bidding in various markets to support the distribution companies' flexibility services.

Demand-side management. The DSF is discussed in depth based on DSM technologies, classifications, and developments in the remaining article sections.

Grid facilities (network side). The grid facilities are implemented to sustain the power balance between generation and demand and to increase the power system's reliability and flexibility through various instruments and strategies. Also, supporting the power system's ability to host high levels of DERs without any violations of power quality along with the energy market. Several studies concentrated on increasing the power transfer capacity of transmission systems by employing series or shunt compensation devices or using flexible alternating current transmission systems (FACTS) [134, 144, 145]. Other enhancement techniques are applied to enhance the power quality (voltage, frequency, etc.) such as ESSs, network reconfiguration, and active power curtailment [112]. Other techniques can be used to provide reactive power support, enhance controllability, and control power flow, as discussed in references [19, 146].

Market products. To support the PSF, several technologies of DSF are used such as DSM systems DR program, and energy efficiency strategy, which mainly depend on the exchange of information among the DSO, end-users, energy markets (dynamic pricing system), and smart meters through efficient communication systems, to achieve the required power balance between available energy and demand [17, 19]. Other tools are utilized such as small, distributed generators (DGs) and ESSs alongside activating the load management strategies such as load shifting. Other market products are developed to deal with the various flexibility obstacles such as flexible ramping products (FRP) which can be ramped up or down, mid-continent independent system operators (MISO), regional transmission enhancement planners (RTEP), and other ancillary service market products, as discussed in references [20, 26]. In reference [16], the flexibility markets are investigated as a platform for trading flexibility among generation, demand, and market operators based on location and energy prices. These markets are influenced by various time frames which can be day-ahead, intra-day, and balancing power markets that are associated directly with the provided flexibility services and characteristics associated directly with the provided flexibility services and characteristics.

Operational flexibility

Operational flexibility is classified as the various flexibility sources and techniques applied for specific objectives over different energy flow levels to support the PSF. With increased penetration levels of DERs, ESSs, etc. into the power systems, various HC enhancement techniques are employed to improve the power quality and support the power system reliability and flexibility, as investigated in reference [5]. while the power system planning strategies are also used with specific control strategies in smart grids or microgrids. Further, the network reconfiguration and interconnections contribute to improving the PSF besides robust control strategies for energy management of various power system components such as DERs [147].

Other flexibility options

Recently, various advanced energy systems have been significantly integrated into the MPSs for sustaining optimal energy management and achieving power system reliability and flexibility. These advanced technologies come into the picture as several countries applied strategies to accomplish energy transition toward clean and sustainable energy resources. Therefore, several studies discussed their influences on the MPSs with their merits and demerits [148–151]. These technologies involve MESs, EV aggregators, hydrogen storage, and other heat systems, which can efficiently support the PSF. However, they still require more developments to increase their efficiency and reduce implementation costs.

2.7 | PSF applications

The PSF is applied for flexibility resources, as previously discussed, and management and schedule of various sorts of loads. The demand sectors can be divided into four groups, that is, residential, commercial, industrial, and others. In Figure 7a, the global electricity consumption per demand sector is depicted which shows that the demand growth of the industrial sector in 2019, for example, recorded the first rank (9.6 PWh) followed by the residential (6.07 PWh), commercial (4.85 PWh), transport (0.42 PWh), and other services (1.94 PWh), respectively. According to the electricity trade, the residential sector exhibits great demand flexibility (51.11%) while both the

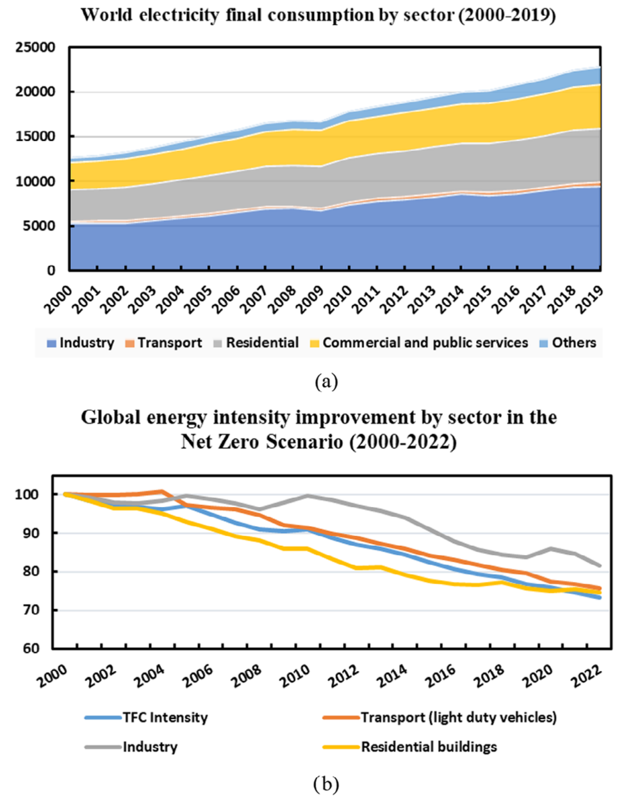


FIGURE 7 Global energy consumption per sector. (a) World electricity final consumption by sector (2000–2019) [152]. (b) Global energy intensity improvement by sector in the net-zero emissions scenario (2000–2022) [153].

industrial and transportation sectors recorded 9.04%, and 13.07% of total demand flexibility, respectively [115]. As shown previously, the energy demand globally increases which is mainly dependent on fossil fuels, so it is crucial to reduce the carbon emission to reach the net-zero emission (NZE) scenario by 2025. Another energy efficiency index is called total final energy consumption (TFC) intensity which is used to measure the global energy intensity by demand sector to achieve a lower percentage of carbon emissions per year based on the clean energy transition concept, as depicted in Figure 7b. Applying the low carbon emission sources to produce the energy demand, the energy bills are dropped along with enhancement in power system reliability. It is obvious that the global energy intensity has declined by around 4% per year on average this decade in the NZE scenario, which compares with 1.7% over the last 10 years. Therefore, the developments of DSF are conducted in several studies, as concluded in reference [115]. Various flexibility opportunities are exhibited in different demand sectors based on the implemented appliances, as summarized in Table 6.

Due to the increased flexibility opportunities in different demand sectors, it is critical to optimize the PSF in real time with the dynamic pricing of energy markets. So, the power exchange balance between generation and demand is accomplished. Moreover, it is applicable for P2P energy trading among prosumers and energy producers to sustain a stable and reliable energy supply. The concept of flexibility in real time with P2P energy trading is comprehensively discussed in reference [16].

TABLE 6 Examples of appliances in different demand sectors and related research studies.

Demand sector	Appliances' examples	Review articles (2018 to present)
Industrial	Aluminium electrolysis, steel production, pulp production, cement production, oil refinery plants, and other metal, food, and drink industries	[115, 154–158]
Residential	Refrigerators, water heaters, vacuum cleaners, hairdryers, washing machines, plug-in EVs, heat pumps, and others	[15, 154, 159–165]
Commercial	Heat ventilation and air conditioning (HVAC), lighting systems, parking lot aggregators (PLA), supermarket refrigerators, and others	[155, 166–170]
Transportation	EVs, light rail, electric trains, metro, and others	[171–176]
Other	Such as agriculture applications	[177, 178]

In Table 7, various examples of P2P energy trading projects are depicted. As discussed previously, DSF is the most prominent research direction compared to other flexibility options. So, the research directions of DSF will be only considered in detail in the upcoming sections.

3 | DEMAND-SIDE FLEXIBILITY: CLASSIFICATIONS, RESOURCES, AND REQUIREMENTS

The DSM strategies can be classified into many groups as depicted in Figure 8. Hence, these groups investigate the DSM from several research topics and applications as follows:

- Various categories: which involve DSM strategies such as DR program, on backup or spinning reserve such as ESSs and DERs, strategic load growth and planning, and energy efficiency.
- DSM enablers or implementers: these may be distributed aggregators, DSO, end-users or customers, and the utility which have the ability to activate the DSM strategies.
- Strategies of load demand management: that present the various methods for load scheduling and management to deal with the DSM.
- Other methods factors or parameters that influence the applied DSM strategy may be implementers' decisions, the applied estimation method, and the operational timescale.
- Another classification specifies the DSM requirements in terms of policies, infrastructure, energy market, etc.

Here, the DSM categories, implementers, resources, and requirements are discussed in detail as follows.

3.1 | DSM categories

The DSM strategies play a crucial role in regulating the power exchange between the generation units and the consumers

TABLE 7 Examples of peer-to-peer energy trading projects based on flexibility [16, 179, 180].

Ref.	Start year	End year	Project name	Country	Application
[179]	2011	Finished	iPower project	Denmark	Regional
[180]	2012	Finished	PeerEnergyCloud	Germany	Microgrid
[181]	2013	Finished	ECO-Grid project	Denmark	Regional
[182]	2014	Ongoing	Piclo	UK	National
[183]	2015	Ongoing	Horizon 2020-project EMPOWER	Europe	Regional
[184]	2015	Ongoing	P2P-SmartTest	Europe	Regional
[185]	2016	Ongoing	P2P3M	Europe and Asia	Consumer/prosumer
[186]	2017	Ongoing	EnerChain	Europe	Wholesale market
[187]	2018	Ongoing	American PowerNet HQ	USA	Wholesale market
[188]	2018	Ongoing	BCPG Apartment Microgrid	Thailand	Microgrid
[189]	2019	Ongoing	Brixton Energy	UK	Consumer/prosumer
[190]	2019	Ongoing	Wongan-Ballidu P2P	Australia	Wholesale market

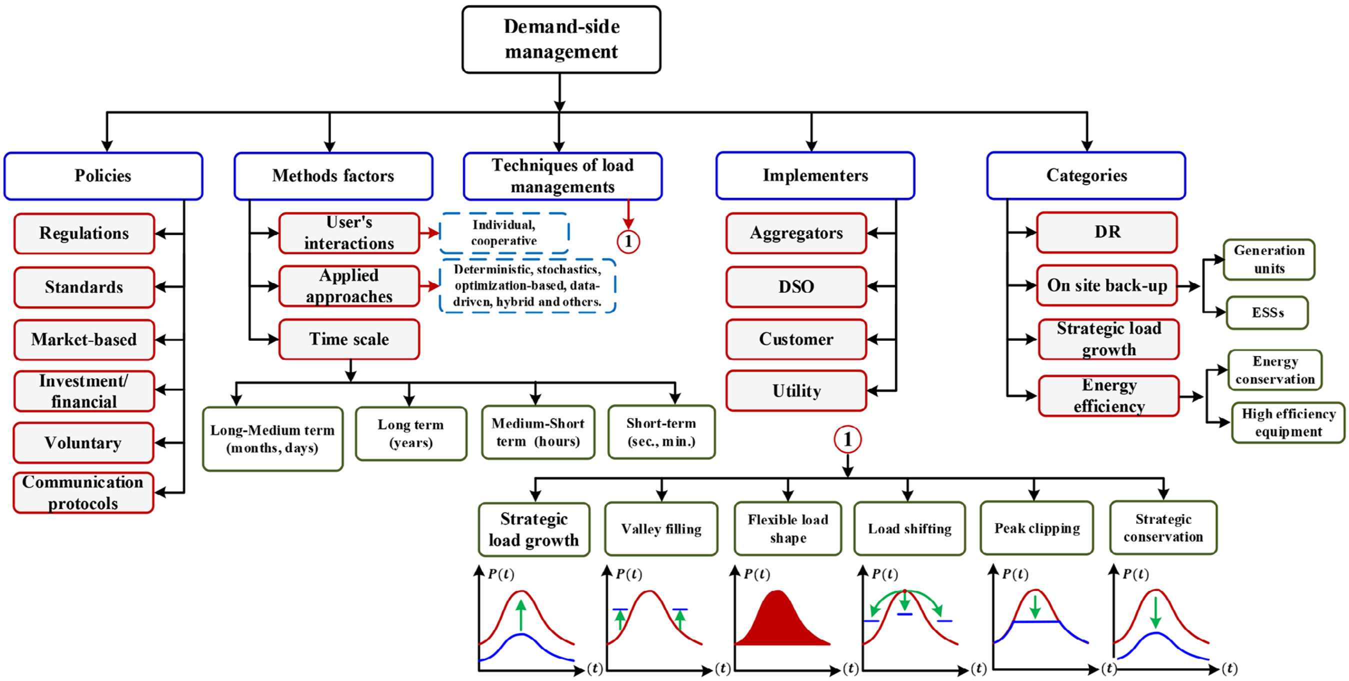


FIGURE 8 Classifications of demand-side management strategies.

on the demand side to achieve power system reliability and reduce the consumers' electricity bills, operational cost of electrical power generation, transmission, and distribution, and the peak hours' demands [191]. Further, they contribute to reducing carbon emissions and energy consumption and delaying the investments in upgrading the electrical grids by optimizing the energy use [16]. Several objective functions of the DSM strategies will be discussed below with an explanation of the implementation of power system components and required infrastructure. The DSM strategies aim for loss reduction and scheduling (direct or indirect), which can be classified into four categories as follows:

- **DR**: can be physical DR or market programs which contribute to adjusting the load consummation for short-term periods by the demand-side resources or implementers in response to the variations of the energy prices(tariff), as will be discussed in detail below.
- **On-site back-up (spinning reserve:)**: In response to any power delivery disturbances or other power quality issues, the spinning reserve equipment is considered as a backup power that can provide quick support to ancillary services of the distribution network operators [32]. It can be classified into primary and secondary stages. In the primary stage, the power exchange is regulated using frequency or voltage regulation

tools, while the secondary stage uses the power supplementary units. Regarding the power supplementary units, they can be DERs, small DGs, ESSs, or EV charging stations [24]. Furthermore, the loads and virtual power plants can regulate their power consumption whereas power quality issues occur until sustaining the normal power system operation.

- **Strategic load growth**: this strategy encourages the consumers to increase their load consumption whereas the power system stability and reliability are required to be maintained to sustain normal operation.
- **Energy efficiency**: it is considered the cheapest option to regulate or schedule the load consumption by motivating the end-users to modify their load demand level and usage patterns in response to energy markets and utility measures [192, 193]. The end-users can use energy conservation strategies which aim to reduce the use of unnecessary equipment to save energy without influencing a better level of service or life. Also, the high-efficiency equipment can be implemented for the same purpose.

Various implementers have the responsibility to establish and regulate the DSM strategies. Consumers are considered important contributors through regulating and scheduling their load consumption level or patterns to achieve the required power quality. The utilities and DSOs are considered primary implementers of DSM strategies who regulate the operation of power systems in terms of DR programs, protocols, and policies. All implementers of DSM strategies are crucial for ensuring the reliable and efficient operation of MPSs.

3.2 | Flexible DSM resources

Besides the previous PSF resources, there are some essential resources that are extensively implemented in DSM strategies which can be grouped into DSO's flexibility resource and end-users' flexibility resource. Hence, the end-users' group involves various flexibility resources such as flexible loads, distributed ESSs, EVs, pre-cooling and thermal systems, DERs, and active consumers or prosumers.

3.2.1 | Flexible loads

The load types for the residential, commercial, and industrial applications can be classified into elastic, and non-elastic types [192]. The non-elastic loads (inflexible) cannot be adjusted and controlled by the utilities or DSOs without causing service interruption for the end-users such as lighting, whose usage is based on request at specific times. In contrast, the elastic loads (flexible) can be controlled or scheduled by smart grids or utilities in response to energy market signals or the utility operation community. They can be shifted from peak demand periods to off-peak periods such as washing machines which cannot effect on the customer demand level pattern and can reduce the utility stress. Hence, the flexible loads can be regulated based on the consumption patterns, and energy market signals which can be classified into main groups: time shiftable loads, power shiftable loads, thermal loads, and critical loads or urgent. These groups are important for applying for DR programs as a sort of DSM strategies, as will be discussed below.

There are different techniques for load profile management and modifications which are essential to reduce the consumption bills and peak demands to achieve the power system reliability and stability, as summarized in Table 8.

3.2.2 | Distributed energy storage systems

As previously discussed in Section 2.6.2, the ESSs play an important role in supporting the DSM strategies with the availability of various types and innovation control techniques. The ESSs can be classified as follows:

- Fixed ESSs: involve electrical ESSs (such as supercapacitors and superconductors), mechanical ESSs (such as flywheel and compressed air), electromechanical ESSs (such as battery ESSs and fuel cells), and others.
- Movable ESSs: such as EVs (battery EV, plug-in hybrid EV, and hybrid EV).

Nowadays hydrogen ESSs are used extremely as the countries' directions towards the low carbon energy transition to reduce the harmful effects of conventional energy sources on the environment, as will be discussed below.

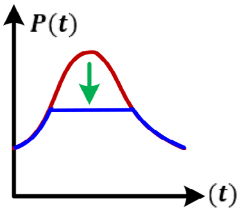
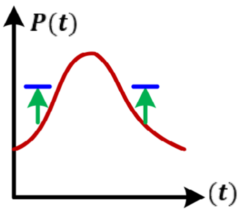
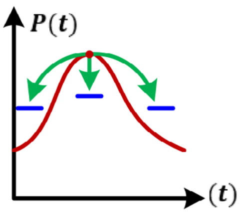
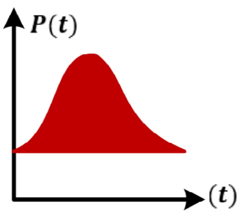
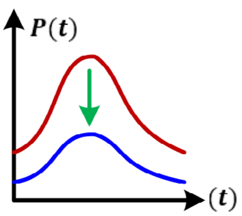
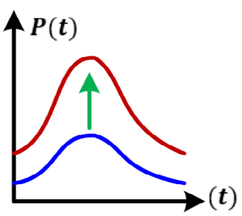
3.2.3 | Electrical vehicles

By regulating their charging and discharging periods, the EVs with their various types can be robust resources of the DSM strategies [192]. In reference [194], the EV charging topologies are discussed, which can be considered as ancillary services and domestic services. Detailed investigation of the EVs as a DSM strategy is highlighted in reference [31].

3.2.4 | Other DSM resources

- **Pre-cooling and thermal systems**: the EHs have the ability to manage the various DERs, ESSs, MESs, and EVs to provide electrical, thermal, and cooling demands. Thereby the pre-cooling and thermal systems (controlled loads and ESSs) can support the system flexibility and reliability according to variations in load consumptions and energy market prices, as discussed in references [195–197].
- **Distributed energy resources**: the DERs can be installed to deal with peak demands as they quickly respond and are less expensive compared to installing new generation stations to only supply peak periods. Which can be classified into dispatchable and non-dispatchable DERs. The non-dispatchable energy resources cannot be controlled by operators according to continuous variation in their availability such as wind energy. In contrast, other dispatchable

TABLE 8 Load management techniques.

Load technique	Description	Presentation
Peak clipping	To prevent power system interruption, this technique is used to restrict the peak demand within acceptable limits because of insufficient generations and being expensive to install new generation units or plants.	
Valley filling	Consumers are encouraged to increase their power demands in off-peak periods because of low energy prices.	
Load shifting	Consumers are encouraged to shift their power demands from peak periods to off-peak periods because of low energy prices. Which can be considered as a combination of valley filling and peak clipping techniques.	
Flexible load shape	The load pattern of willing consumers is modified and controlled by their electricity providers through DR programs over all time periods. Which can be considered as a combination of valley filling, load shifting, and peak clipping techniques.	
Strategic conservation (load reduction)	It is a less expensive option by motivating the end-users to modify their load demand level and usage patterns in response to energy markets and utility measures. Moreover, it is achieved by reduction in the use of unnecessary equipment and implementing high-efficiency equipment to save energy without influencing the better level of service or life.	
Strategic load growth	It is a part of DSM strategies in which the consumers are motivated to increase their load consumption whereas the power system stability and reliability are required to be maintained to sustain normal operation.	

sources can be controlled and scheduled in response to DSM strategies such as hydroelectric power and biomass energy sources.

- **Active consumers or prosumers**: in this situation, the consumers have the choice to respond to the DSM strategies and electrical prices by altering their demand profile through various load management techniques. Moreover, the prosumers can support the DSM strategies by providing their extra power generation to the utility grids at peak periods such as homes with roof-top PVs or EV batteries.

3.3 | DSM requirements

The DSM strategies have the same requirements of the PSF to be implemented which can be grouped into monitoring systems, communication systems, and standards and protocols. The monitoring systems consist of several instruments and technologies to monitor, detect, and control the variations of various variables such as smart meters, advanced/automatic metering infrastructure, smart appliances, smart EV plugs, and smart sensors. To transfer the collected data from the monitoring systems to system operators or consumers, robust communication systems can be wired or wireless topologies with various sorts, as discussed previously. Hence, the control schemes can regulate the generation and demand based on the DSM strategies within applied policies, protocols, and international standards of energy consumption, generation, and market. All these requirements are discussed extensively in references [30–32].

4 | DEMAND-SIDE FLEXIBILITY: ESTIMATION AND MANAGEMENT

Here, the mathematical modelling of various power system components is investigated. Moreover, the DSM indices and factors are considered with the aid of a combination of objective functions and constraints that should be carefully stated. Then the estimation, enhancement techniques, and control methods for various DSM applications are discussed.

4.1 | Mathematical modelling

For estimation of the PSF, it is essential to express the technical behaviour of various power system components mathematically that can support the PSF, as a function of parameters, inputs, output, and operational boundaries. These expressions can be used in various optimization methods to estimate the PSF [198–200]. So, various studies have used various model presentation methods such as white-box, grey-box, black-box, and operational boundaries models [34]. In white-box, presentation is dependent on physical equations without any experimental data, so there is a lack of studies applying it. While the grey-box models require both physical equations and experimental data. In contrast, the black-box models generate mathematical equations that are not based on physical laws, but use data and approaches, data-driven methods, to present and predict the system behaviour based on measurements or observations. In operational boundaries models, the system behaviour is expressed abstractly based on inequalities that restrict the power flow of various energy resources to their operational boundaries. Here, the mathematical models of the most important components such as EVs/ESSs, wind turbine, PV, thermal storage, and loads, are presented in terms of only grey-box, black-box, and operational boundaries models in Table 9.

4.2 | DSM indices

For DSM analysis, several indices are applied which can be classified into energy management based or energy market based. In load management based, the DSM indices can be formulated as a function of several factors such as load factor, as concluded in Table 10. While the energy market-based indices express the DSM indices associated with the energy cost such as Lerner index, as summarized in Table 11.

4.3 | Objective functions and constraints

There are several objective functions used in optimization problems which the DSM strategies should deal with under specific constraints of various power system components. First, the objective functions can be classified into technical, regulation, and market objectives. The most important functions can be summarized as follows:

- Achieving optimal power system planning and the energy balance between generation and demand.
- Optimization of the capacity and location of various components such as ESSs, EVs, DGs, PV, and so on in order to improve the power quality.
- Enhancing the power quality (voltage violation, frequency regulation, harmonics, etc.).
- Minimization of the operational and implementation costs.
- Reduction in energy consumption costs.
- Increasing the benefits for DSO and prosumers.
- Reduction of the bad environmental impacts and carbon emissions.
- Decremental and modifications in load consumption patterns.
- To decline the tariff on electricity.
- To minimize T&D losses.
- To integrate new technologies without bad influences on the utility grids.

To accomplish the previous objectives, it is crucial to have accurate specifications of the constraints of various power system components. Which can be classified into the power system constraints and equipment constraints. In the power systems constraints, the general limits of the power system are specified such as power generation and demand, line voltage and frequency limits, or thermal overloading constraints. On the other hand, the constraints of various integrated components such as EVs, ESSs, or DERs, should be accurately indicated in terms of charging or discharging limits, energy exchange limits, and other operation and technical limits. Other constraints can be defined by the system operators such as energy market constraints (tariff). These objective functions with constraints should be stated significantly for DSM strategies.

4.4 | Estimation and forecasting approaches

As discussed in Section 2.5, there are several estimation and prediction approaches for the PSF which are also used for various DSM strategies in both the DSO and end-user flexibilities. It is worth mentioning that these approaches are mainly dependent on both the information interaction between

TABLE 9 Mathematical modelling of various power system components [34, 198, 200].

Element	Grey-box (GB) models	Black-box (BB) models	Operational boundaries (OB)	Studies
Utility grid	NAN	$P_{\text{out}}(t) = \eta * P_{\text{grid}}(t)$	$P(t)^{\min} \le P(t) \le P(t)^{\max}$	• BB: [201] • OB: [202]
EVs or ESSs	$SOC(t + \Delta t) = SOC(t) + \dfrac{P(t)_{\text{charge}} * \eta_{\text{charge}} * \Delta t}{C} - \dfrac{P(t)_{\text{discharge}} * \Delta t}{C * \eta_{\text{discharge}}}$		• $E(t)^{\min} \le E(t) \le E(t)^{\max}$ • $P(t)^{\min}_{\text{rated}} \le P(t) \le P(t)^{\max}_{\text{rated}}$	• GB: [203, 204] • BB: [205, 206] • OB: [207, 208]
Wind turbine	$P(\omega(t))_{\text{wind}} = \begin{cases} P_{\text{out}} \;\forall\; \omega_{\text{rated}} \le \omega(t) \le \omega_{cut\ out} \\ \dfrac{a + b * \omega(t) + c\omega^2_{\text{cut in}}}{\omega_{\text{rated}} - \omega_{\text{cut in}}} * P_{\text{out}} \;\forall\; \omega_{cut\ in} \le \omega(t) \le \omega_{rated} \\ 0 \;\forall\; \omega(t) \le \omega_{\text{cut in}} \text{ or } \omega(t) \ge \omega_{cut\ out} \end{cases}$	$P(\omega(t))_{\text{wind}} = \begin{cases} P_{\text{out}} \;\forall\; \omega_{\text{rated}} \le \omega(t) \le \omega_{cut\ out} \\ \dfrac{\omega(t) - \omega_{\text{cut in}}}{\omega_{\text{rated}} - \omega_{\text{cut in}}} * P_{\text{out}} \;\forall\; \omega_{cut\ in} \le \omega(t) \le \omega_{rated} \\ 0 \;\forall\; \omega(t) \le \omega_{\text{cut in}} \text{ or } \omega(t) \ge \omega_{cut\ out} \end{cases}$	$P(t)^{\min} \le P(t) \le P(t)^{\max}$	• GB: [209] • BB: [206] • OB: [206]
PV	$P_i(t) = PV^{\text{array}} * df^{\text{PV}} \left(\dfrac{S_i(t)}{S_{i,\text{STC}}}\right) * [1 + \alpha * p * (T_c - T_{c,\text{STC}})]$	$P_i(t) = P_{\text{installed}} * \eta_{\text{inv}} \left(\dfrac{S_i(t)}{S_{i,STC}}\right)$	$P(t)^{\min} \le P(t) \le P(t)^{\max}$	• GB: [203] • BB: [210] • OB: [205]
Thermal storage	$H\%(t + \Delta t)_{th} = (1 - \varkappa)\% * E(t)_{th} + \dot{Q}(t) * \eta_{\text{charge}} * \Delta t - \dfrac{\dot{Q}(t) * \Delta t}{\eta_{\text{discharge}}}$		$E(t)^{\min} \le E(t) \le E(t)^{\max}$	• GB: [211] • BB: [203] • OB:[212]
Other DGs	NAN	$P_{\text{out}}(t) = \eta * P_{\text{DG}}(t)$	$P(t)^{\min} \le P(t) \le P(t)^{\max}$	[12]
Loads	Can be presented by constant power, constant impedance, and mixture.			[199]

Note: All parameters and abbreviations are found in references [34, 198, 200].

individuals and corporations, and the utilized timescale. The conventional approaches such as deterministic, stochastic, and time series approaches, are applied in DSM strategies with several objective functions and constraints due to their compact simplicity and low computational time compared to advanced approaches. However, these approaches struggle to accomplish realistic operations with an increased number of scenarios and variables. Hence, some DSM studies apply them considering the stochastic behaviours of RESs and EVs in references [104, 105].

In the modified approaches (optimization based, hybrid, and other), the limitations of the conventional ones are reduced using a robust framework with a high number of operational scenarios however the computational time and the complexity are still challenging aspects. Several approaches are used for day-ahead financial planning of thermal units and RESs in references [168, 214]. Others are applied to optimize both the location and capacity of ESSs in microgrids or EHs [204, 208, 215]. Although data-driven methods are applied extensively nowadays, these approaches still need more developments to handle obstacles such as required extreme data availability, infrastructure ability, tools' performance, operators' judgment, and others. However, these approaches have given promising results in several performed studies such as residential energy management aspects in references [109–111, 207]. These approaches are used for the estimation of the PSF as well as the prediction of the system behaviour over upcoming time horizons, through several software and frameworks such as MATLAB, OpenDSS, and others.

4.5 | Control methods

Here, the control methods and levels are discussed to deal with the state or data gained from various power system components and take necessary actions to achieve the DSM strategies [216–218]. In the power system operation, the control strategies are divided into four control levels based on planning aspects and ordered response actions: local, secondary, central/emergency, and global [218]. The local control level regulates the primary frequency or power quality issues of the generators to respond to any energy interruptions due to an unbalance between generation and demand and to restore normal operation after these disturbances. While at the secondary control level, the system sustains its reliability after occurred disturbances in a few minutes by the authority control computer using load-frequency control or automatic generation control. In case of large disturbances and blackouts, the central or emergency control level is used by system operators. For long-term planning, the global control level is used to deal with the energy market objectives, the extension of T&D systems, integration of RESs, DERs, ESSs, etc. Regarding the data and control actions flow through the communication systems, the previous control levels can implement centralized, distributed, and decentralized control based on the communication structure, as discussed in detail in reference [218]. Moreover, the various applied controllers can be conventional such as proportional-integral-derivative (PID) controllers, non-linear controllers such as sliding mode controllers, predictive controllers, such as model predictive controllers, and AI controllers, as investigated in

TABLE 10 Demand-side management indices based on load management factors [213].

SR.	DSM index	Definition	Generic Formulation
1.	Demand factor (DF)	'The peak load demand divided by the average available electrical power during a specified time span' [213].	$DF \triangleq \frac{P_{\text{peak}}^{t_i \sim t_f} * (t_f - t_i)}{\int_{t_i}^{t_f} P_G(t)dt}$
2.	Utilization factor (UF)	'The average supplied electrical power divided by the peak load demand during a specified time span' [213].	$\gamma_{\text{UF}} \triangleq \frac{\frac{\int_{t_i}^{t_f} P_s(t)dt}{(t_f - t_i)}}{P_{\text{peak}}^{t_i \sim t_f}}$
3.	Load factor (LF)	'The average load consumption divided by the peak load demand during a specified time span' [213].	$LF \triangleq \frac{\frac{\int_{t_i}^{t_f} P(t)dt}{(t_f - t_i)}}{P_{\text{peak}}^{t_i \sim t_f}}$
4.	Capacity factor (CF)	'The average supplied electrical power divided by the maximum suppliable electrical power during a specified time span' [213].	$\gamma_{\text{CF}} \triangleq \frac{\frac{\int_{t_i}^{t_f} P_s(t)dt}{(t_f - t_i)}}{P_G^{\max}}$
5.	Delivery factor	'The supplied power divided by the available energy resource capacity' [213].	$\gamma_{\text{delivery}} \triangleq \frac{E_d}{P_G^{\max} * (t_f - t_i)}$
6.	Regulation factor	'The energy demand divided by the available energy resource capacity' [213].	$\rho \triangleq \frac{E_{\text{demand}}}{P_G^{\max} * (t_f - t_i)}$
7.	Adequacy coefficient	It is a function of the regulation factor.	$\lambda_{P_{\text{peak}}^{t_i \sim t_f}} \triangleq \widetilde{f_S^{\rho}} - \widetilde{f_S^{\rho-1}}$
8.	System productivity (SP)	'The adequacy coefficient multiplied by the delivered energy divided by the available energy resource capacity' [213].	$SP \triangleq \frac{E_d * \lambda_{P_{\text{peak}}^{t_i \sim t_f}}}{P_G^{\max} * (t_f - t_i)}$
9.	Energy Productivity (EP)	'The useful energy divided by the available energy resource capacity' [213].	$EP \triangleq \frac{E_u}{P_G^{\max} * (t_f - t_i)}$
10.	DSM index (DSMI)	'The adequacy coefficient multiplied by the useful energy divided by the available energy resource capacity' [213].	$DSMI \triangleq \frac{E_u * \lambda_{P_{\text{peak}}^{t_i \sim t_f}}}{P_G^{\max} * (t_f - t_i)}$

Note: All parameters and abbreviations are found in reference [213] with their relations.

references [217–219]. In references [218–221], various data-driven controllers are investigated as tools and applications for achieving power system operation and control.

4.6 | DSM enhancement techniques and applications

To manage and improve the PSF on the demand side, the various DSM strategies and resources are applied into the MPSs based on generation techniques (DERs and RESs) and load management strategies (load shifting, peak shaving, and load shedding), as discussed previously. Further, the DR programs are utilized for energy scheduling to achieve economic benefits such as time-of-use pricing, critical peak pricing, and direct load control. Other new technologies and instruments with sufficient communication infrastructure are used in smart homes that have the capability to support the PSF. Both the EVs and ESSs also have the ability to enhance the PSF at the demand-side level, especially in high peak demand. Nowadays, the EH systems using the various types of MESs, DERs, ESSs, and others, are used to optimize the electrical, thermal, and cooling demands to reduce the cost and achieve the optimal power flow operation that in turn enhances the PSF. Other control schemes and components (FACTs) can be applied to various system levels to enhance the PSF, as discussed previously. So, several studies have been implemented in the MPSs based on the DSM strategies, as summarized in Table 12.

5 | DEVELOPMENTS IN DR PROGRAMS

The DR program is a significant DSM strategy that deals with load reduction and scheduling of willing consumers over various time periods as a response to variations in the energy market, achieving benefits for the consumers and sustaining the normal power system operation, as investigated in reference [32]. This section highlights the latest developments of DR programs in terms of various classifications, implementation requirements, benefits and challenges, and their applications.

TABLE 11 Demand-side management indices based on energy market indices [30].

SR.	DSM index	Definition	Generic formulation
1.	Herfindahl–Hirschman index (HHI)	'It is defined as market competitiveness regarding the number of participants and market inequality' [30].	$HHI = \sum_{i=1}^{N} S_i^2$
2.	Lerner index (LI)	'The percentage markup of a farm's ability to charge over its marginal cost' [30].	$L\,I_i = (P_i - MC_i)/P_i$
3.	Must run ratio (MRR)	'It is defined as all generation capacity information of the generating company to generate the required amount of energy demand through a transmission congestion zone considering all the line constraints' [30].	$MRR = \dfrac{P_d - P_l - \left(\sum_{j=1}^{N_g} P_{gi.\max} - \sum_{j=1}^{N_{gA}} P_{gi.\max}\right)}{\sum_{j=1}^{N_{gA}} P_{gi.\max}}$
4.	Must-run share (MRS)	It is based on the variation of market power to demand level.	$MR\,S_k = \dfrac{P_{g_k}^{\text{must}}}{P_d}$
5.	Nodal must-run share (NMRS)	It is defined as the MRS at each bus or node.	$NMR\,S_{k,i} = \dfrac{P_{g_{k,i}}^{\text{must}}}{P_{di}} \quad \forall\, i = 1, 2, 3 \ldots, N$

Note: All parameters and abbreviations are found in reference [30].

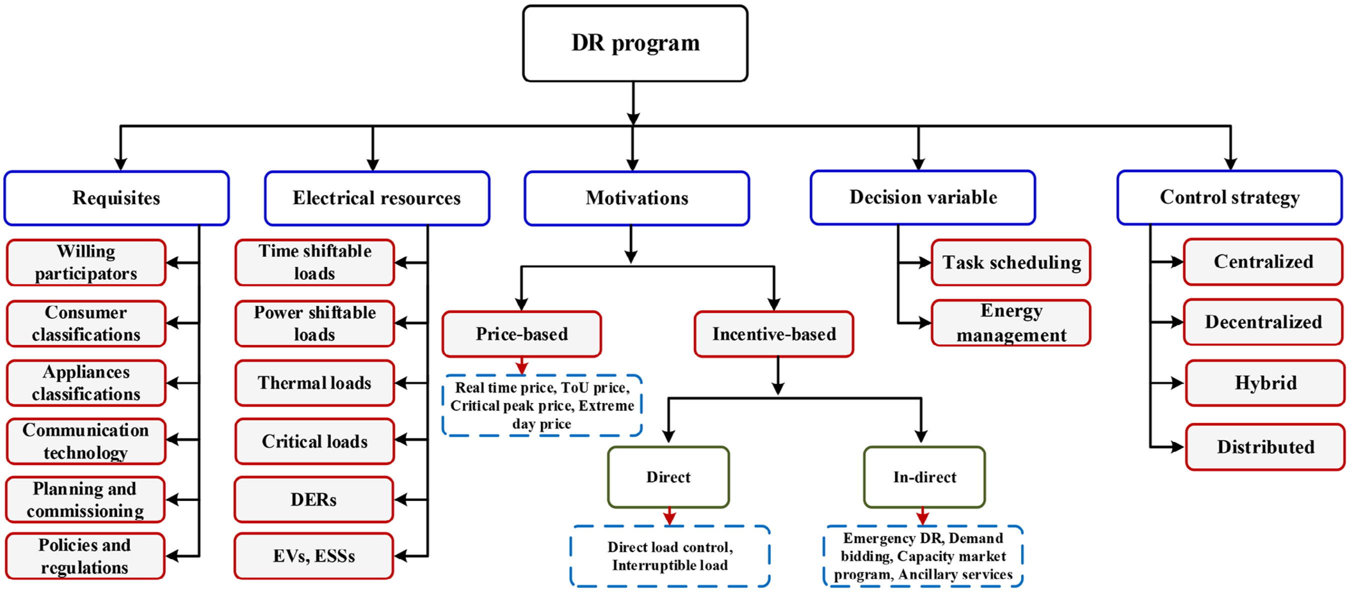


FIGURE 9 Classifications of demand response programs.

5.1 | DR classifications

In Figure 9, the various classifications of DR programs are depicted in terms of motivations, control strategy, decision variables, electrical resources, and requisites.

5.1.1 | Motivations

The DR programs can be classified based on the motivations which can be incentive based (explicit) and price based (implicit) [17], as shown in Figure 10. In an incentive-based

TABLE 12 Examples of demand-side management applications in the modern power system were collected from references [32, 34] and Scopus database.

Ref.	Year	System configuration	Application	Technologies	Estimation approach	Software	Modelling type	DSM strategy	Objective function	Constraints
[222]	2019	EH	Ris.,Cm.	EH with various components, DERs, RESs	Opt.	GAMS	BB	DR	Cost minimization	Grid, PV, WT, ESSs, EH components, energy market
[223]	2019		Cm.			EnergyPLAN			Minimize the annual costs, fuel consumption, and carbon emissions	Grid, PV, WT, ESSs, hydropower, geothermal, EH components, energy market
[224]	2020	Microgrid	Cm.	DERs, WT, PV, fuel cell	Hybrid (Opt., DT)	MATLAB	BB	DR	Cost minimization	DERs, ESSs, energy market
[205]	2020	25 households	Ris.	Grid, PV, BESS, thermal ESSs	Opt.	Python, Gurobi	BB,OB	Economic dispatch	Cost minimization, reducing frequency deviation	Grid, PV, ESSs, devices, energy market
[201]	2020	ISO, aggregator, and prosumer	Ris.,Cm.,Ind.	Grid, ESSs, DERs		MATLAB, YALMIP	BB	DR (bidding capacity, peak shaving)	Cost minimization	System components and energy market
[225]	2020	20 households	Ris.	Grid, appliances		MATLAB		DR (Load Shifting		Grid, loads, energy market
[226]	2020	Home			Hybrid (Opt., DT)	Experimental, MATLAB				
[227]	2021	Appliance	Ris.	Heat pump	Opt.	EnergPlus, Ecotope, Experimental	BB	DR (Load Shifting)	Cost minimization	Heat pump
[228]	2021	Industrial systems	Ind.	Thermal and industrial components	Hybrid	Planning tool	GB, OB	Modulation	Minimize the annual costs, fuel consumption, and carbon emissions	Components
[229]	2021				Opt.	FMU and embedded within a Python for industry 4.0 (RAMI4.0)	OB,BB	sector coupling		

(Continues)

TABLE 12 (Continued)

Ref.	Year	System configuration	Application	Technologies	Estimation approach	Software	Modelling type	DSM strategy	Objective function	Constraints
[230]	2022	Aggregator, and prosumer	Ris.	Fuel cell, PV, BESS, thermal ESSs and components	Opt.	–	BB	Economic dispatch	Cost minimization	System components and energy market
[104]	2023	IEEE 33-bus distribution system	Ris.,Cm.,	EVs,WTs, ESSs	Con.,Opt.	–	BB,OB	DR	Optimal planning, minimizing the operating cost, optimal allocation of EV charging stations	System components and energy market
[103]	2023	EH (IEEE 118-bus, 9-bus test systems)		Wind, various components of IEGHS	Opt.	MATLAB			Optimal planning, minimize the operating cost	
[95]	2023	IEEE-33-bus, IEEE-69-bus radial LVDSs		PV, EV, DGs	Con.	–			Minimize the power losses	System components
[109]	2023	Testbed house	Ris.	PV, ESSs, EV, smart meters	DT.	Dec-POMDP framework			Building energy management	
[110]	2023			PV, ESSs, various components of IEGHS		Matlab				
[108]	2023	33-node and 152-node ADNs	Ris.,Cm.,	PV, ESSs, flexible loads, thermal DGs, Wind		Python 3.7, the Tensorflow 2.8.0 open-source framework			Optimal planning, minimize the operating cost	

Abbreviations: Cm, commercial; Con, conventional algorithms; DT, data-driven algorithms; Ind, industrial; ISO, independent system operator; Opt, optimization algorithms; Ris, residential.

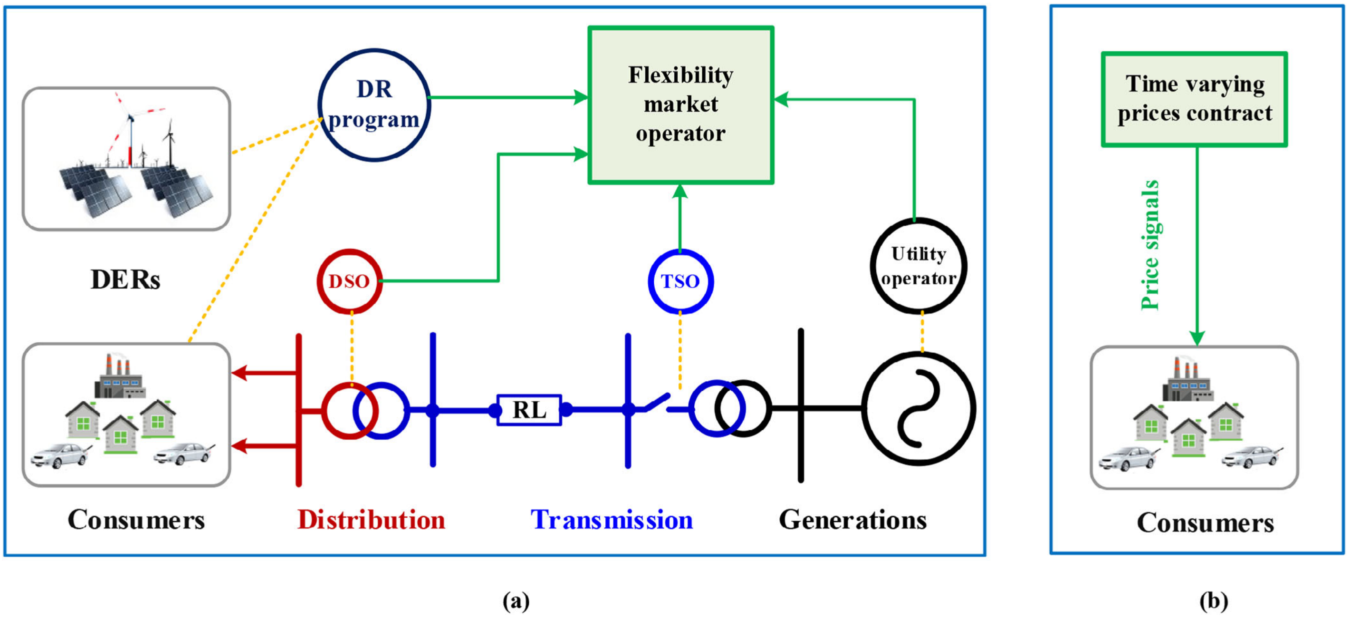


FIGURE 10 Classification of demand response (DR) programs based on motivations. (a) Explicit DR program. (b) Implicit DR program.

DR program, the consumers are encouraged to the load consumption scheduling (load reduction) over certain time periods or deliver an extra amount of their own generation to the unity in order to achieve beneficial profits (payments). While in the price-based DR programs, consumers voluntarily provide load reductions in response to economic signals. In Table 13, the various techniques of DR programs based on motivations are summarized with sufficient description and some studies.

5.1.2 | Electrical resources

Various electrical resources are used to support DSM and DR such as flexible loads, DERs, EVs, and ESSs, as discussed previously. The virtual ESSs were applied for optimally scheduling the demand response of thermostatically controlled loads (TCLs) to ensure the generation–demand balance [137]. Another optimal energy management framework was investigated for microgrids to schedule the demand response of TCLs in the presence of a DR program based on DLC, DERs (RESs), ESSs, and EVs [273], while in reference [274] the integration of hybrid RESs and ESSs is considered to optimize the demand response in the microgrids. The role of flexible loads in the DR program (load shifting and transfer) was investigated for optimal scheduling of microgrids considering the power quality constraints [275], and with the aid of the battery ESSs, the flexible loads were utilized for the same objective in reference [276]. Other studies considered the influence of EVs, hydrogen ESSs, RESs, EH systems, and DERs, as important resources to support the DR programs [277–284].

5.1.3 | Decision variables

To specify the suitable DR methods and their impact on the consumers and the DSOs, another classification is conducted based on decision variables for using DR programs which can be energy management or task scheduling variables [148]. In an energy management scheme, the regulating of power exchange among various power system components is an important variable for DR programs; while task scheduling controls the operation patterns of various appliances based on time, value, capacity, and location, to support the DR program. Various decision variables can be used with association to electricity price, appliance schedule, controlling indoor temperature, and load and weather data.

5.1.4 | Control strategy

The DR program can be categorized based on the applied control strategy to process the state or data gained from various power system components and take necessary actions to achieve the DSM strategies and DR program [216–218]. As discussed in Section 4.5, centralized, distributed, hybrid, and decentralized control strategies can be implemented as the communication structure for data flow and control actions among various control levels [218]. In reference [285], the techno-economic constraints were considered in the optimization algorithms for the local and coordinated control schemes of the DERs. Other studies considered various control schemes for acquiring the optimal energy management in references [286, 287].

TABLE 13 Classifications of demand response programs based on motivations.

Type		Technique	Timescale	Description	Applications
Incentive	Direct	Direct load control (DLC)	Less than 15 min	The utility or aggregators manage the energy demand of some appliances of the end-users without pre-notifications about interruption to reduce the net load consumption.	[231–236]
		Interruptible load/reduced rates (IL)	Day of economic dispatch	The consumers receive payments to reduce their load consumption on request.	[237–240]
	Indirect	Emergency DR programs (EDRP)		The consumers receive incentive payments by voluntarily reducing their load consumption to sustain the power system reliability in emergencies.	[241–244]
		Demand bidding programs (DBP)	Day-ahead economic scheduling	For large-scale consumers (more than 1 MVA), they choose voluntary reduction of their consumption and saving costs in response to DR situations.	[241–247]
		Capacity market programs (CMP)	6–12 months of operational planning	Consumers offer load curtailments as reserving capacity to swap the conventional generations or DERs.	[226, 248, 249]
		Ancillary services (AS)		Consumers receive payments from system operators for load reductions or power generations to support the power system's reliability on request.	[250–252]
Time based, price based		Time-of-use (ToU) pricing		Various fixed daily pricing blocks are offered at different consumption levels (on/mid/ off-peak, consumption in holidays, and various seasons). The tariffs are kept higher during peak periods, and the opposite during low levels of consumption.	[253–258]
		Real-time pricing (RTP)	Day-ahead economic scheduling (dynamic pricing every 15 min)	It is a dynamic pricing strategy in which the tariffs are varied continuously based on the energy market signal and usage patterns.	[204, 259–263]
		Critical peak pricing (CPP)	Day of economic dispatch	At large load consumption (higher 20 kW) at the critical periods, the TOU is replaced with CPP to motivate consumers to shift their demands outside critical periods. The CPP is considered a hybrid of RTP and TOU.	[264–268]
		Inclining block rate (IBR)		Different levels of tariffs are applied. For low load consumption, the low level of tariffs is considered. In contrast, in higher consumption, the higher tariffs are applied as a sort of penalty-based pricing.	[269–272]

5.1.5 | Requirements

Besides the above-mentioned discussion about the requirements of PSF and DSM, this section discusses in brief important requisites for the DR program [29], which can be summarized as follows:

- Suitable infrastructure including various required components, monitoring and metering instruments, and communication systems.
- Classification of the appliances and load types that are convenient to participate in the DR program.
- Classifications of consumers and electrical demands in the utility network.
- Advanced energy management and control systems.
- Declaration of the willing participators in the DR program along with achieving beneficial profits.
- Robust planning and commissioning strategies.
- Policies and regulations.
- Ancillary services and regulatory measures.

5.2 | DR benefits and challenges

To sum up, Table 14 highlights the various benefits and challenges of DR programs associated with system operators, end-users, and the environment.

5.3 | Practical/simulation implementations of DR

In reference [17], an extensive study about the international experience and applications of DR programmers was presented.

TABLE 14 Benefits and challenges of demand response programs associated with system operators, end-users, and environment.

	System operators	End-users	Environment
Benefits	• Improving grid reliability and flexibility. • Improving the overall operation of electricity markets. • Increasing the reputation and competition among different energy providers. • Increasing energy efficiency. • Achieving the balance between generation and demand. • Reducing energy costs. • Reducing the transmission and distribution losses. • Applying innovative technologies in various levels of utility. • Reducing the investments in new infrastructure or upgrading the system with new generations. • Improving other technical and economic aspects.	• Reducing the electricity bills. • Improving grid reliability and flexibility. • Reducing or maintaining rates and ensuring more reliable service. • Socio-economic benefits.	• Reducing the greenhouse and climate change impacts. • Reducing carbon emissions. • Maximizing the usage of clean and sustainable energy resources. • Achieving a well-being life for the community with good health status. • Reducing the use of fossil fuels that cause pollution, and harmful health-related and environmental effects.
Challenges	• Old available infrastructure. • Data privacy and security. • Integrating new technologies such as EVs, ESSs, and DERs. • Coping with the continuous development in energy markets. • Stating proper DR programs, regulations, and policies for various types of consumers. • Regulating the dynamic pricing in energy markets. • Enabling communication technologies. • Control technologies.	• Data privacy and security. • Consumer behaviours and consumption patterns. • Provide the required awareness for consumers about DR programs, regulations, and policies. • Changing the consumption patterns in energy consumption scheduling.	• Hard geographical locations for installing new technologies and upgrading old systems. • Uncertainties and availability of RESs. • Long-term climate predictions.

It is shown that various countries applied the DR programs as PTP energy markets such as Europe countries, the United States, Canada, Japan, and others. That established various projects as investigated previously in Table 7. In reference [288], the study presents renewable energy targets for nine countries based on their development levels and evaluates policies and incentive programs aimed at increasing renewable energy shares. It provides a detailed examination of the renewable energy promotion programs, DSM activities, and ESS incentives in these countries.

With the widespread of DR programs, several studies have been implemented to investigate the impacts of DR programs on system operators, end-users, and the environment in terms of various obligations and objectives such as optimal load scheduling to minimize cost and emissions and improve system reliability. These studies have been established based on real data of various systems and different strategies of DR programs, as concluded for recent studies in Table 15.

6 | MPS-BASED DEMAND-SIDE FLEXIBILITY MANAGEMENT

Nowadays, the operation of MPSs, especially in DSM strategies, involves several advanced technologies and components to achieve the system reliability and stability to accomplish the energy transition concept towards a better social, healthful-economic environment, as mentioned below.

6.1 | Energy hubs with multi-carrier energy systems

In order to supply the electrical, cooling, and thermal demands for consumers with high efficiency and low cost, the EHs with MESs are applied extensively in the MPSs in response to the increased integration of various DERs, ESSs, EVs, and flexible loads [100]. It is worth mentioning that the EHs are considered an open framework to apply the DR programs and strategies efficiently and significantly to achieve profits for both DSO and consumers, minimization of carbon emission, and implementation cost of new generation plants or upgrading old infrastructure, achieving system reliability, and other benefits, as discussed previously. In references [289, 290], the power quality issues are considered by optimal scheduling of the increased integration of ESSs and EV charging systems in their capacity and location to minimize the cost and achieve system reliability. Hence, various DSM strategies are applied to overcome the bad influences of increased penetration of DERs, EVs, etc., and realize the optimal operation of MPSs, as discussed in references [291–294]. Although there is rapid development of the EHs, some limitations of EHs should be considered in the research studies such as challenges for applying low carbon resources, system location with available energy sources and transport grids with their costs, etc., as investigated in reference [100].

6.2 | Integrated community energy systems

Integrated community energy systems (ICES) are developed as a solution to the challenges of maintaining the reliability of MPSs due to the increased integration of new industrial technologies, EVs, ESSs, etc., for providing various energy demand sorts regarding social-economic, and environmental directions towards expanding the use of clean and sustainable energy sources. The ICESs not only provide the required energy demands in local communities but also have the ability to offer ancillary services on request for the utility grids. The state of the art of the ICESs was investigated comprehensively

TABLE 15 Selective studies of demand response program applications in the modern power system.

Ref.	Year	System configuration	Technologies	DR program	Estimation approach	Software	Objective function
[248]	2019	Smart households	Load aggregators	CMP	DT	–	Optimal load scheduling
[226]	2020						
[251]		Smart grid	Energy market	AS	Opt.	–	Improve reliability
[238]		Industrial environment	Cement manufacturing components	IL, ToU			Maximum profit, reduced consumption, and reliability
[246]	2021	EV aggregators, RESs, flexible loads		DBP		GAMS	
[252]		IEEE 39 bus model	Battery ESSs, PV, and others	AS		Powerfactory	Achieve a balance between power generation and load demand
[273]	2022	Smart microgrid	EVs, ESSs, RESs, flexible loads	DLC	Opt.	GAMS	Consumption reduction, energy losses reduction, reliability
[234]		136 real-world residential users in Austin	Load aggregators, appliances, smart meters		DT	CEI-DR framework	Reducing the load consumption, minimizing cost and emission, and reliability
[242]		IEEE 24-bus test system	Load aggregators	EDRP	Opt.	–	
[243]		Five load aggregators				MATLAB	Maximum profit, reduced consumption, and reliability
[247]		Load aggregators		DBP	Opt., DT	Tensorflow, Python	
[270]		IEEE 123-bus system	DERs, ESSs, load aggregators, appliances, smart meters, others	IBR	Opt.	MATLAB	
[204]		Microgrid	WT, PV, ESSs, DERs, flexible loads, others	RTP		NSGA-II	Optimal load scheduling, cost minimization
[260]		Modelling of smart grid with various components (ESSs, DERs, etc.), and 1000 consumers with their home appliances		RTP, ToU		GAMS	Optimal load scheduling, cost minimization, achieve privacy and comfort of users
[261]		Real-world traces	EVs	RTP		–	Minimize the total charging cost
[263]	2023	Industrial environment			DT	PyGAD	Maximum profit, reduced consumption, and reliability
[271]		Smart household with appliances		IBR	Opt.	–	
[256]		80 households in Texas	Load aggregators, ESSs, PV, others	ToU		GAMS	Cost savings
[257]		Microgrid	PV, ET, ESSs, DERs, others			HOMER	Reducing the load consumption, minimizing cost and emission, reliability
[258]		Smart household with appliances				MATLAB	Offers optimal scheduling to decrease the overall energy expenses, peak-to-average power ratio, improve system load factor
[266]		Distribution company (DISCO)		CPP		–	Maximum profit
[267]		Households in Ottawa		DLC, ToU, RTP, CPP	Survey and statistics		Observes the effect of personal, socio-economic properties and environmental awareness of households
[268]		Data of industrial park in Guiyang City		CPP	Opt.	NSGA-II	Reducing the load consumption, minimizing cost and emission, reliability

Abbreviations: Con, conventional algorithms; DT, data-driven algorithms; Opt, optimization algorithms.

according to resources, energy services, technologies, implementation, adaptation, and benefits [295]. The key to the implementation of ICESs started from the widespread use of energy communities in the MPSs such as community microgrids or smart grids, virtual power plants, and EHs. That can be categorized based on different aspects, for instance,

- Activities: local generations, energy storage, power exchange, and DR.
- Grid connection: grid-connected or islanding mode.
- Location and scale: large or small, urban or rural.
- Initiatives: citizens, companies, and governments.
- Technologies involved: local generation (individual or community based) and DSF management.

So, the ICESs are defined as approaches for energy management of power systems involving various generation sources (RESs and DERs) and energy demands (thermal, cooling, and electrical) in the presence of new technologies such as ESSs, EVs, and MESs, based on the available infrastructure in communities and DSM strategies to accomplish long-term planning and minimizing the energy costs, increasing reliability, and eradicating the bad environmental impacts [296]. The DSM strategies and DR programs play a crucial role in establishing the ICESs by using the flexible loads, thermal loads, aggregators of EVs and ESSs, and signals of energy markets. Although providing the required ancillary services efficiently, several challenges are still raised such as cost allocation and social acceptance.

6.3 | Blockchain-based management technologies

Nowadays, the blockchain (BC) concept is widespread in different energy systems as it is applied to DR programs and DSM strategies, P2P energy trading, EVs, microgrids, smart grids, DERs, and energy management systems, as investigated in reference [297]. To enhance the operation performance of the ICESs due to the increased penetrations of new industrial energy technologies in the MPSs, the BC based on DR programs and DSM strategies are used. It is defined as a decentralized and secure energy management system that permits the end-users to actively participate in the energy market through regulating their energy demands in response to the signals from energy markets and the utility grids [298]. Also offers improved coordination and communication among system operators, grid components, end-users, and the energy market. The BC technology offers some important objectives for the MPSs such as,

- **Decentralized energy management**: by enabling the distributed control approaches to manage the DR programs with protected and temper-proof storage of acquired data from all system components and meters [299].
- **Energy efficiency**: optimizing the energy consumption of the end-users corresponding to energy market signals which enhances energy efficiency and system reliability [300].
- **Incentive mechanisms**: it can provide the end-users with potential cost savings and incentives offered by the energy market. Thus, the BC technologies provide a decentralized platform for DR programs ensuring the protection of consumers' privacy, energy data, and their contracts. As it exhibits a safe and transparent platform for P2P energy trading and consumption data [298].

Several researchers studied the application of decentralized BC technologies in bidirectional selection between the DR users and the aggregators based on the reputation aspects and behaviours [301]. Another study proposed a P2P energy trading system between EVs and system operators to provide the demand response [302].

6.4 | Demand-side flexibility aggregation

The aggregators represent a common connecting node between groups of consumers who have specified energy demand and the utility grid [27]. Which are considered vital flexibility resources to ensure the power system reliability as the increased penetration of new industrial technologies into the MPSs and MESs. At any power system, several aggregators are found as a single entity during engaging in the energy market as depicted in Figure 11, which involves various aggregator types in IEEE 14-bus distribution system (as an example) that support the DSF [303]. These aggregator sorts can be categorized as follows:

- Generations: involve several generation units such as conventional power plants, DERs, RESs, and other distributed generation units. Which have good flexibility and economic characteristics.
- Load: includes various load aggregation with different types such as industrial, residential, and commercial demand sectors.
- ESSs: contain all types of ESSs as previously discussed in addition to the EV parking lot, and home batteries, which have very good flexibility and economic characteristics.
- EVs: present the EVs that contain ESSs, and the EV parking lot with charging stations, which play a significant role in supporting the PSF by varying the operation patterns of EVs.
- DR aggregators: facilitate the automated controls for demands, prosumers' generations, and instruments based on the collecting data of monitoring devices of end-users and signals from DSO and the energy market.
- Miscellaneous: can be virtual power plants, ESS, inertia, reactive power compensation devices (FACTs), etc., that are responsible for supporting the PSF at any energy level in response to energy consumption and energy market.

Various types of aggregators and their development were investigated in references [22, 304–306].

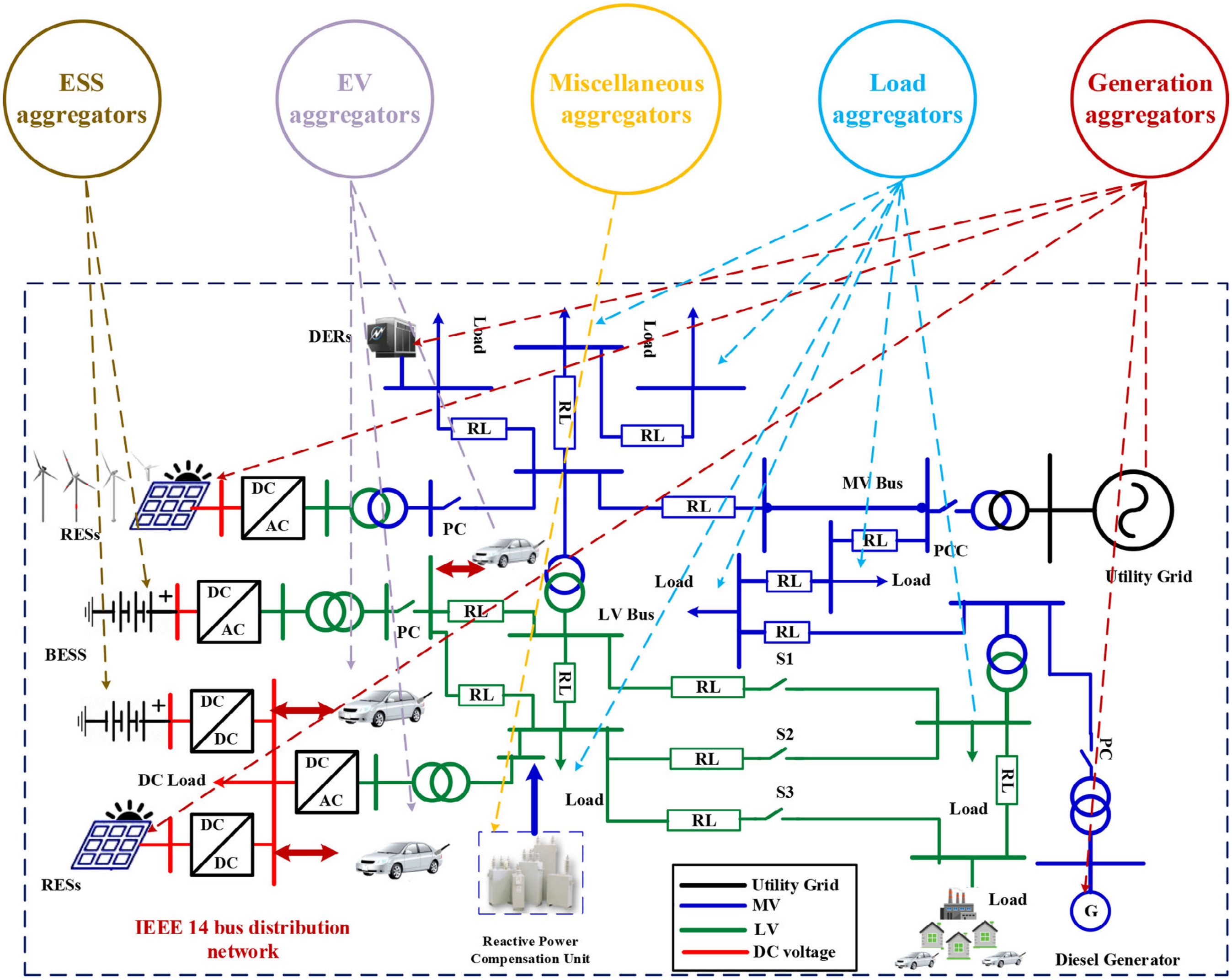


FIGURE 11 Demand-side flexibility aggregation types.

6.5 | Resilience, robustness, and cyber–physical concepts in MPSs with DSM

Other important requirements should be found in the MPSs in cooperation with the PSF. The energy providers not only supply the energy demands of the consumers with an acceptable level of power quality and reliability and support the PSF, but also should ensure the MPSs are resilient, robust, secure, and cyber–physical power systems. The power system resilience and robustness concepts describe the power system's ability to stand under urgent and strong energy interruptions and to recover its operational conditions quickly [307]. This is different from the PSF, which acts as an energy management tool to reserve the balance between the generation and demand to prevent interruptions from occurring. Another challenge is highlighted through applying the DR programs which is how to provide a secure environment for data transfer among various components and protect the consumers' privacy and consumption data [308]. So, the cyber–physical concept describes the procedures that have been considered to accomplish these objectives towards secure and reliable power systems using advanced sensors, intelligent automation, communication networks, and DERs. The state of the art of these concepts was investigated based on the operation of the MPSs in references [309–311].

6.6 | Role of demand response on hosting capacity improvements

The HC concept is defined as the maximum amount of DERs, EVs, ESSs and other energy technologies that can be added to the utility grid without causing any disturbances and deteriorating on the performance indices [312, 313]. In reference [314], a comprehensive and new concept of HC for MPSs is defined according to the integration of new industrial technologies and developments on MPS infrastructure. Hence, the DR program plays a crucial role in HC estimation and enhancements as it states the balance between generation and demand by enabling prosumers to adjust their consumption and own generations according to the maximum estimated value of HC in response to energy market signals and the operation of the utility grids. So, it is essential to take the HC value into account during the operation of DR programs over any timescale. The DR programs enhance the integration of the new generation and storage units by optimizing the load consumption to avoid any energy interruptions which maximize the HC value and reliability of MPSs. A comprehensive review of DR of HVAC systems as improved techniques of the HC was investigated in reference [315]. In reference [316], the DR program combines both load profiles and a number of integrated EVs in order to enhance the HC based on the IL technique of the DR program. The dynamic pricing based on the DR program was applied to optimize the integration of a large number of EVs and enhance the HC in reference [317]. Moreover, an optimization framework based on the DR program (load shifting technique for residential loads) was utilized to minimize the overall cost and improve the HC for sustaining the acceptable level of power quality [312].

6.7 | Low-carbon energy transition technologies

Recently, global efforts turned to widely using low-carbon energy sources to produce the required energy globally instead of the conventional sources which raises the carbon emission level into the atmosphere [318, 319]. Hence, several bad environmental impacts and health conditions have occurred. Therefore, the energy transition concept has been used to highlight the transition from conventional sources to low-carbon sources and RESs since 1977 by USA President Jimmy Carter after the oil crisis in 1973. One of these technologies is hydrogen technologies which emerged as a sustainable source to accomplish long-term climate goals and net-zero targets, as discussed previously [320–322]. However, some implementation restrictions should be overcome such as cost, required infrastructure, and decarbonisation.

Moreover, smart energy appliances and heating systems are becoming more popular tools to enhance energy efficiency and reduce the cost of energy consumption by regulating energy consumption based on the utility operation and energy market signals [28]. There are various examples of them such as smart appliances (water heaters, HVAC, and smart thermostats) which are increasingly applied in smart homes and energy management systems such as EHs.

7 | DISCUSSION

7.1 | Flexibility energy market

The energy market is considered a type of market which deals with the energy trade of electricity, thermal, and fuel products, over various applied sectors such as residential, industrial, commercial and transportation sectors [323]. The energy market can be classified as regulated or deregulated based on standards and regulations. Hence, the DR programs are popular in the energy markets by allowing for optimizing the load consumption based on the generation amount and energy market prices. Thus, the energy market involves various approaches for energy management based on flexibility measures which can be labelled as a flexibility market. This is considered a platform monitoring the utility grid operation and its performance indices and offers voluntary dispatch of assets for generation, load, and storage, with compensation established based on applicant bids [16]. As shown in Figure 12, the structure of the flexibility energy market is depicted which involves the various energy resources and aggregators that send information to the flexibility market operators and DSO and receive control signals from aggregators based on the design making of previous variables such as balance responsible operator, DSO, and flexibility market operator. This structure helps to manage the energy balance with an acceptable cost range over short-term timescales.

According to global energy statistics, the energy market is projected to significantly progress as energy consumption (electrical, cooling, and thermal) increases. Also, it is anticipated that energy sources will be cleaner and sustainable sources such as RESs. So, some future aspects and challenges of the energy market will be considered as follows:

- The global energy crisis and wars such as the Russia–Ukraine war, make the cost of energy sources higher than normal. So, it is essential to adopt the energy transition to clean and sustainable energy sources in various countries' policies.
- The integration of new technologies and energy sources into the MPSs is a challenging matter that needs to be considered in the dynamic pricing and DR programs for energy markets.
- Expansion use of hydrogen technologies and ESSs requires more awareness based on the implementation costs and the required infrastructure besides the available energy sources in the geographic energy market.

To conclude, the robustness of DR programs is based directly on various aspects of energy markets such as available energy resources and their costs.

7.2 | Prominent challenges

By application of PSF, DSM strategies, and DR programs, there are various significant challenges are being highlighted that require researchers to find suitable solutions for them. Besides the previously mentioned challenges of energy markets and the DR programs, here, the critical challenges and associated solutions for the application of PSF, and DSM strategies, are discussed as follows:

- The continuous integration of new technologies for generations (DERs, EVs, and ESSs) or as load types (heating systems) which cause several adverse impacts on power quality. So, it is crucial to upgrade the power systems to adapt these technologies and enhance the HC of the power systems using several enhancement techniques regarding economic factors.

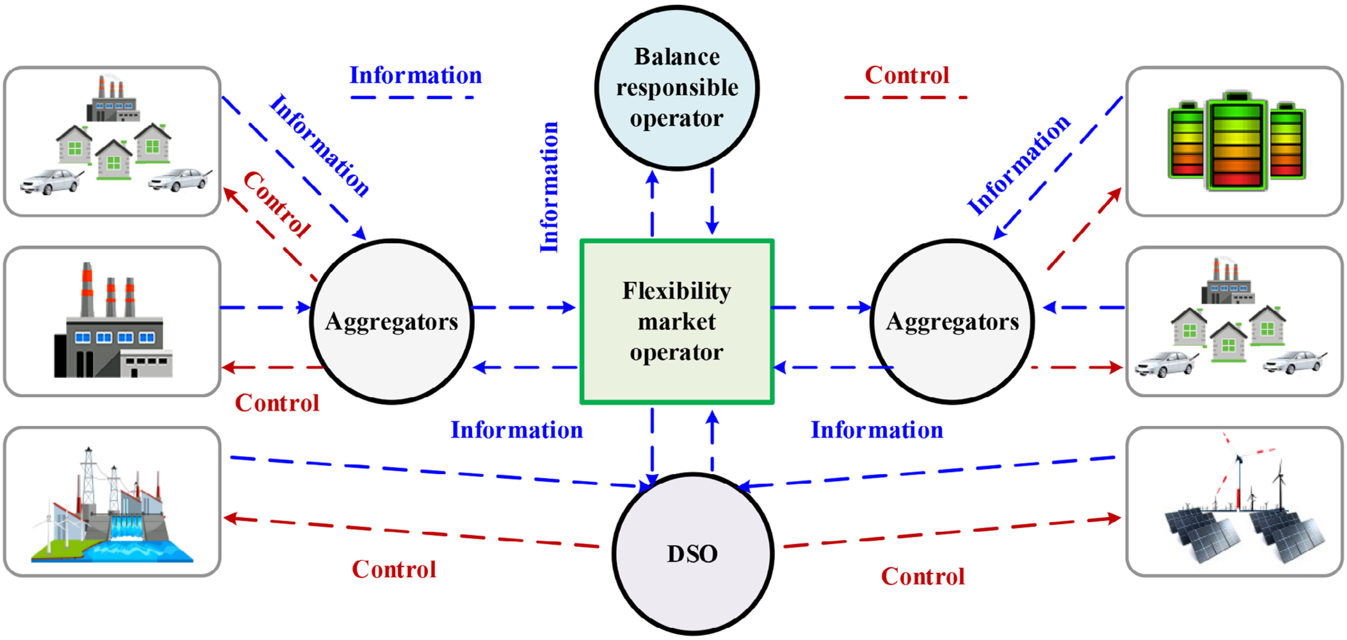


FIGURE 12 Presentation of the flexibility energy market.

- Accomplishing the energy flow balance between the generations and demand to reduce the energy cost, achieve reliability, and decline the load consumption during variations of climate conditions.
- The worst and old infrastructure to deal with the advanced energy management systems which require upgrading in turn will be very costly. So, the decentralized control systems and aggregators come into the picture as urgent solutions to reduce the impacts of bad infrastructure and limit the communication systems. However, some obstacles should be deemed.
- Regarding aggregator barriers, the initial investment costs come in first. Moreover, additional policies and agreements are required with certain identification of roles and responsibilities for DSO, participants, and the energy market. Also, lack of suitable infrastructure that involves smart meters and appliances with secure communication systems. Further, shortage of some components for flexibility service.
- To avoid repeating information, the challenges of DR programs and the energy market are mentioned in Sections 5.2 and 7.1, respectively.
- Consumer behaviour and suitable DR program.
- Updating the policies and protocols of DR programs which deal with the satisfactions of end-users, available energy sources, and infrastructure to achieve economic benefits for DSO and end-users.
- Integrating the available power generated from the prosumers into the grid can cause bad influences. So, it is required to encourage the prosumers to install ESSs and to support the grid into peak periods with fair prices.
- Installing monitoring and sensing devices is costly and necessity more requirements. So, this may affect the operation of DR programs and robustness and lead to wrong estimation of conditions which not only influence power systems and consumers but also have effects on the dynamic pricing on energy markets.
- Limited performance and accuracy of software in DR programs using new data-driven estimation methods.

7.3 | Research trends

The research field of PSF was utilized in 1964 as a result of seeking efficient energy management systems to deal with the increased electricity consumption globally with their critical issues. The data related to this research field is extracted using Scopus database with specific main keywords ('demand-side flexibility; power system flexibility; demand-side management; demand response program'). The most relevant documents are 14586 published over the period from 1964 to 2024, as displayed in Figure 13a. It is obvious that the United States contributes with the highest published documents (2602), then chain is in second rank with 2221 documents. Both Finland and Egypt record 301 and 175 documents which need to be increased to deal with their energy challenges. The remaining world participates in 9287 documents as shown in Figure 13b. Figure 13c represents the classification of published documents per type in which articles present 55.86% of total documents.

7.4 | Future perceptions and outlooks

The strategy implementations of the PSF in general, and DSM strategies are crucial for the MPSs to ensure the safe, flexible,

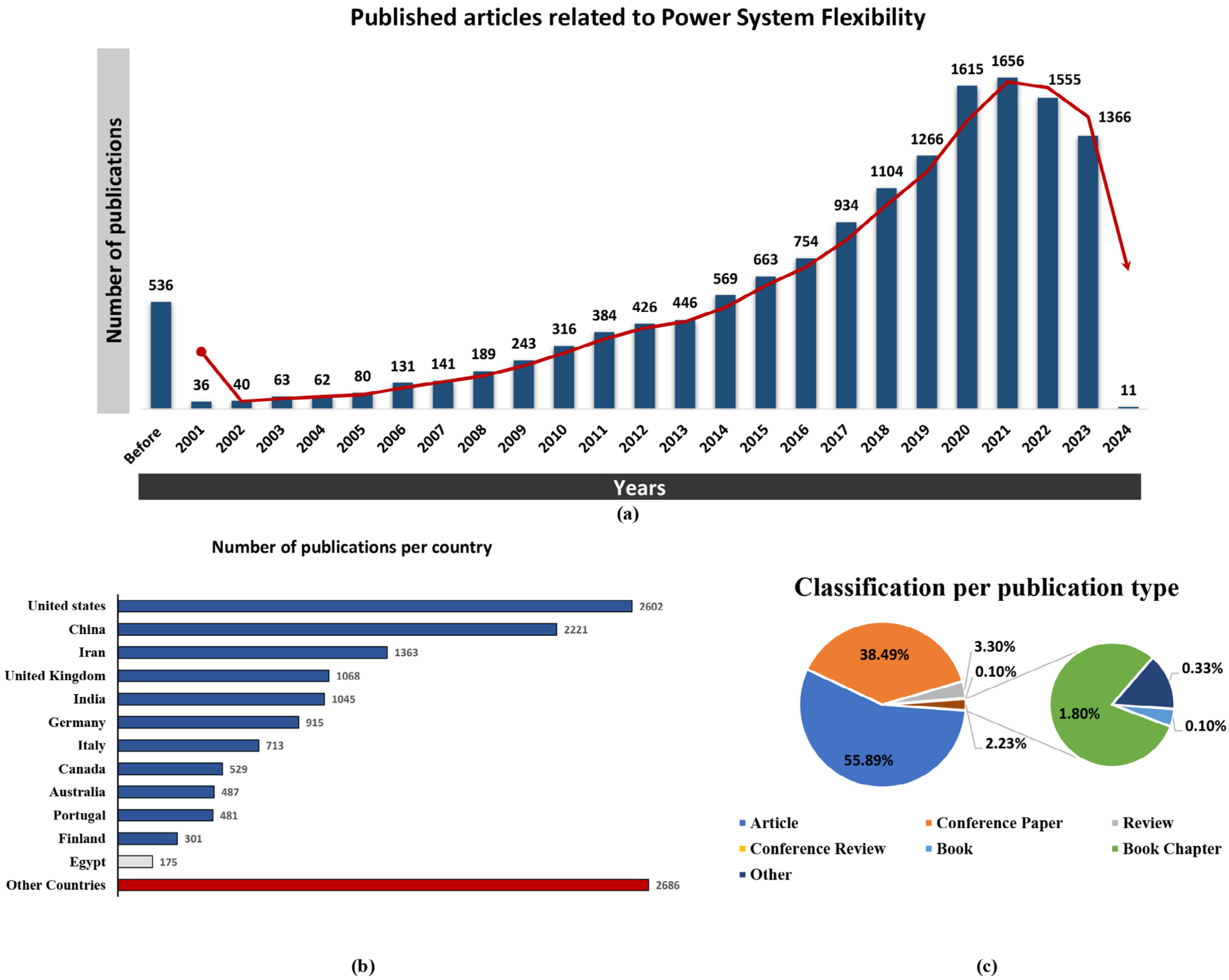


FIGURE 13 Research trend of power system flexibility.

and reliable operation of consumers on the distribution level. Thus, there are some important research topics that will be involved in the future for those purposes, as summarized in the following points:

- Improving the power system reliability and communication networks used in the PSF applications, DSM strategies, and DR programs besides secure data transfer to save the privacy of consumers.
- Achieving the balance between the generation and demand through powerful load profile modelling, and advanced energy management systems for generation units.
- Dealing with the consumers' preferences and priorities.
- Maximizing the HC of networks using enhancement techniques to ensure integrating the maximum limits of new technologies such as DERs, EVs, ESSs, etc., besides optimal placing and sizing of them at each feeder.
- Expansion usage the hydrogen technologies into generation and storage sectors.
- Using powerful optimization techniques and data-driven methods with suitable software for DR programs to achieve the PSF.
- Increasing the knowledge of consumers and making proper agreements and offers. Also using advanced energy price policies.
- Increasing the PSF resources and services. In addition to upgrading the infrastructure of power systems.
- Applying AI techniques in DSM strategies.
- Dealing with the barriers associated with infrastructure and relevant investment costs in addition to developments and expansion of new technologies such as EVs, ESSs, and MESs.
- Dealing with the challenges of energy market roles and interaction implications.
- Dealing with huge investments and potential conflicts of interest especially in implementing ESSs, which are due to the lack of transparent regulatory and tariff schemes.

8 | CONCLUSION

With the increased integration of various industrial technologies in generation and demand levels such as EVs, ESSs, DERs, and MESs, it is crucial for robust energy management systems to deal with their uncertainties and capacity variations without causing any power quality issues. So, the PSF, especially on the demand side, is applied to provide energy demands with low energy costs and an acceptable level of reliability. Here, an overview of the PSF and DSM strategies are discussed based on definitions, classification, quantification, characteristics and functions, estimation and forecasting methods, solutions, and applications supported with recent studies. As a result, the authors suggest new PSF definition is stated in terms of various significant factors and elements implemented in MPSs. Moreover, the developments of DR programs are highlighted based on classifications, requirements, and applications, followed by a discussion of prominent new penetrated technologies in the MPSs which directly influence the operation conditions. Further, the role of various energy management systems and energy market perspectives are highlighted. Finally, the research trends, challenges, and future considerations are summarized based on the PSF concept, DSM strategies, and DR programs.

NOMENCLATURE

DER	distributed energy resource
DR	Demand response
DSM	demand-side management
DSOs	distribution system operators
EH	energy hub
ESSs	energy storage systems
EV	electric vehicle
FACTS	flexible AC transmission system
HC	hosting capacity
MESs	multi-carrier energy systems
MPS	modern power system
PSF	power system flexibility
PV	photovoltaics
RESs	renewable energy sources

AUTHOR CONTRIBUTIONS

Hossam H. H. Mousa: Conceptualization; writing—original draft. **Karar Mahmoud**: Writing—review and editing; supervision. **Matti Lehtonen**: Writing—review and editing; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

No data was used for the research described in the article.

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