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A comprehensive survey of flexibility options for supporting the low-carbon energy future

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ABSTRACT

As a result of the increased awareness of the dangers posed by global climate changes (mainly caused by growing global energy consumption needs), the quest for clean and sustainable energy future is becoming of paramount importance. This can be largely realized via a large-scale integration of variable renewable energy sources (RESs) such as wind and solar, which have relatively low carbon footprints. In many power systems, the level of integration of such resources is dramatically increasing. However, their intermittent nature poses significant challenges in the predominantly conventional power systems that currently exist. Among others, frequency and voltage regulation issues can, for example, arise because of improperly balanced and largely uncoordinated RES supply and demand. Generally, the higher the integration level of intermittent power sources is, the higher the flexibility needs are in the system under consideration. Flexibility, in a power systems context, refers to the ability of such a system to effectively cope with unforeseen changes in operational situations, which are mainly induced by the inherent uncertainty and variability arising from the supply side, demand side or any other external factors. In the absence of appropriate flexibility mechanisms, it is increasingly difficult to manage the imbalances between generation and demand as a result of their natural variations in real-time. This paper presents an extensive and critical review of the main existing and emerging flexibility options that can be deployed in power systems to support the integration of "carbon-free" and variable power production technologies. Starting from a broader definition of flexibility, we highlight the growing importance of such flexibility in renewable-rich energy systems, and provide insights into the challenges and opportunities associated with various flexibility options provided by different technologies.

1. Introduction

Driven by several factors such as favorable RES integration policies and growing environmental concerns, investments in variable RESs such as wind and solar have been recently outpacing investments in conventional ones. And, this trend is largely expected to continue even in a more pronounced manner amid the ambitious emission reduction targets put in place by many states across the world. The European Union (EU), for example, has a target to reduce greenhouse gas (GHG) emissions in 2050 by 80–95% compared to the 1990 levels. This can only be achieved by integrating "clean" energy technologies, mainly, wind and solar [1]. In particular, wind and solar power sources are expected to provide half of the electricity consumption in the EU by 2050 [1]. This indicates that the installed capacities of wind and solar technologies will have to dramatically increase in the near future both at transmission and distribution levels [2,3]. Increased quantities of such resources creates enormous technical challenges especially in distribution systems [4]. This is because conventional distribution networks are not simply designed to accommodate generation sources. The presence of generation sources means distribution systems will face bidirectional power flows, making control, safety and flexibility more relevant issues [4]. Under these circumstances, maintaining the standard levels of reliability, security and power quality is not an easy task [2,5]. To effectively integrate wind and solar power, additional reserve capacity is needed [6,7]. It is known that conventional power plants often provide majority of the reserve capacity needed in power systems. But this may not be sufficient in the future because of the inherent variability and uncertainty of wind and solar which dramatically increase the amount of reserve required to maintain a healthy operation of the system. Moreover, under such circumstances, the traditional way

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of firming reserves may not be economical in the first place, and environmentally friendly in the second place [6–8]. However, the use of various flexibility options can substantially reduce the negative effects of integrating RESs such as this one. Note that flexibility should be understood as the ability of a power system to cope with the imbalances in generation and demand created as a result of abrupt changes in system conditions (which are triggered by unpredictable nature of some renewable power generation sources, contingency situations, etc.). Traditionally, such flexibility is largely provided by conventional power sources. However, due to the advent of new technologies and concepts such as demand response, this role has been changing especially in recent years. There are various emerging technologies that can provide efficient flexibility options (which are the subject of this paper). Therefore, the future energy sector is expected to provide secure, reliable and affordable energy services to end-users. For this, the sector needs to be highly efficient and possess environmentally-friendly energy sources [9]. In this context, flexibility options play a crucial role in achieving the required efficiency, reliability, cost effective tariffs for end-users and simultaneously reducing GHG emissions worldwide.

The unique feature of power systems is the need to match demand and supply in real time. Power systems require flexibility to continuously match demand with supply both of which are subject to high level variation and uncertainty [10,11]. When the penetration level of renewables gets higher and higher, traditional flexibility mechanisms (mostly provided by conventional power plants) are not simply sufficient. New flexibility options are required to ensure a proper balance between supply and demand [10,12]. Another issue is that sustainable energy management endeavors are being affected by an increased demand, ineffective production practices and insufficient power supply [13]. The flexibility options can take part in efficient strategies to integrate variable RESs in power grids [5]. Flexibility options are resources that help the system to effectively deal with imminent changes in operational conditions [5,12,14]. Such flexibility is also associated with frequency and voltage control, a useful tool in handling uncertainty and variability of power systems and ramping rates [7,8,10,14]. Flexibility options can also be used to defer investments in certain components of power systems, which implies that such systems operate optimally [14,15]. Correspondingly, an increased usage of carbon-free technologies requires greater flexibility, and enhances the "active management and better use of existing network-related" resources [16,17].

Flexibility options can be provided by technologies deployed at the supply, network and/or demand sides. The present work largely structures the flexibility options based on such hierarchical classifications. The flexibility options from the supply side, which will be shortly discussed in this paper, include enhanced ramping capabilities of conventional power plants, flexible generation, diversification of power generation, wide-area generation expansion, RES power curtailment, etc. Flexibility mechanisms on the demand side such as demand response, energy efficiency, electric vehicles, etc. are also broadly described in the following section. Electricity networks can also provide some flexibility options via optimal network reconfiguration, smartification of the grids, dynamic line rating, wide-area interconnections, meshing, etc. Apart from all these, energy systems integration, energy storage systems, effectively designed regulation and energy markets can also provide essential flexibility in power systems, and enable large-scale integration of intermittent resources. Fig. 1 schematically summarizes the increasing need for flexibility options and their main sources.

2. Review of flexibility options

As stated earlier, flexibility can be provided by different components of power systems placed at the supply, network and/or demand side. The flexibility options reviewed in this work are mostly structured into these main pillars. However, the review also encompasses flexibility options provided by emerging technologies such as energy storage systems which can be optimally placed at either side of power systems. In addition, the main institutional mechanisms such as energy systems integration that have proven or foreseen capabilities to enhance power system flexibility are broadly reviewed.

2.1. Demand-side flexibility options

In power systems, it is widely known that the demand side has huge potential for flexibility provisions. Such flexibility options mostly come as a result of changes in the consumption patterns of end-users in response to financial and non-financial incentives and/or dynamic price signals. The resulting changes could be permanent (such as energy efficiency) and/or temporary (demand response such as shifting energy consumption from peak to off-peak hours). Generally, demand side flexibility mechanisms are emerging as the most viable and "least cost" means of enhancing power system flexibility, and thereby increasing the integration of intermittent power sources. Among the most prominent sources of flexibility options reviewed here are demand response, energy efficiency and new forms of electricity consumption.

2.1.1. Demand response

Demand Response (DR) is one of the flexibility options obtained from the consumers' side, and involves alterations of energy consumption levels and/or patterns of end-users in response to dynamically changing prices and incentives (for example, see in Figs. 2 and 3). In other words, properly designed DR programs make electricity demand more flexible, responsive and adaptable to economic signals [2,18]. As shown in Fig. 3, the alterations could be in the form of reduction, shift in energy consumptions or both depending on the consumers' price elasticities of electricity demand. Note that an elasticity index quantifies the relative change in consumption as a result of marginal changes in an electricity price. When the values of such indices are high, more dramatic changes will be observed in consumption patterns. As illustrated in Fig. 3, higher self-elasticity values lead to higher peak shaving and valley fillings, and hence, a flatter demand profile along the day.

Demand response can be either incentive-based or price-based. The former category is characterized by changes in the consumers' electricity consumption in response to non-price signals (often, financial or non-financial incentives). Whereas, the second one relies on price signals to change consumption patterns. Incentive-based DR include demand side programs such as direct load control, curtailable load services, demand bidding or buyback programs and emergency DR among others. Price-based DR on the other hand mainly includes time-of-use (ToU), critical peak pricing (CPP), peak time rebate (PTR) and real-time pricing (RTP) programs. The example shown in Fig. 3 falls in the second category, specifically, in the RTP program.

Apart from the flexibility perspective, demand response has wide-range benefits, which can be found in the extensive body of literature in this subject area. Even if the benefits of DR are widely recognized, its penetration level is not significant in many power systems due to several limitations such as lack of appropriate market framework, effective forecasting tools, and communication and control strategies. However, the interest in DR has been growing in recent years because of many factors such as increasing level of variable power generation which in turn builds up the flexibility requirements in such systems, significant advances in IT and continuously improving forecasting tools, etc. Generally, there is a strong body of evidence on the potential of DR in reducing costs for end-users and improving the integration of variable RESs [2,19]. There is no cloud of doubt that DR will be part of the solution to the endeavors in creating a sustainable energy future, and addressing a multitude of global as well as local concerns such as climate change and energy security.

Demand response is normally achieved by introducing a new competitor in the market, called aggregator, to control the operation of

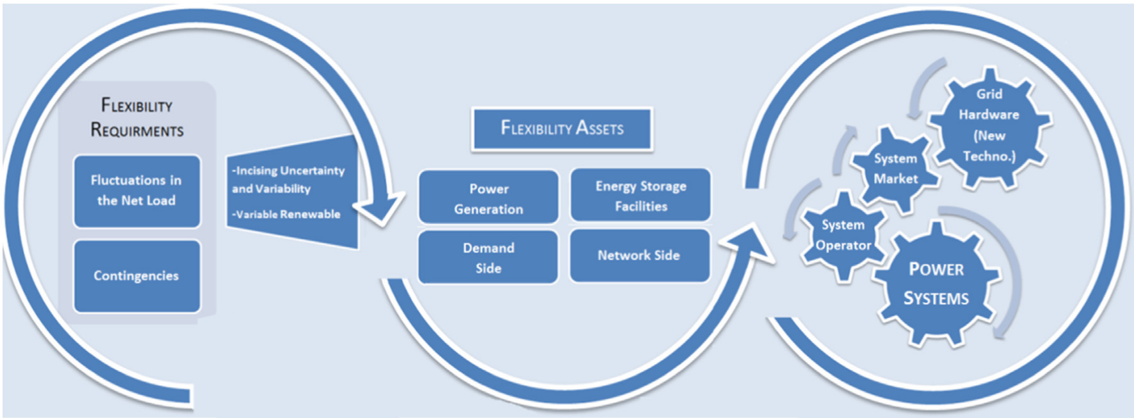

Fig. 1. Flexibility needs in power systems.

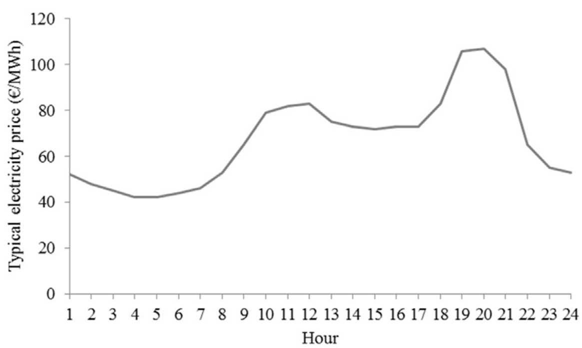

Fig. 2. Real-time electricity prices.

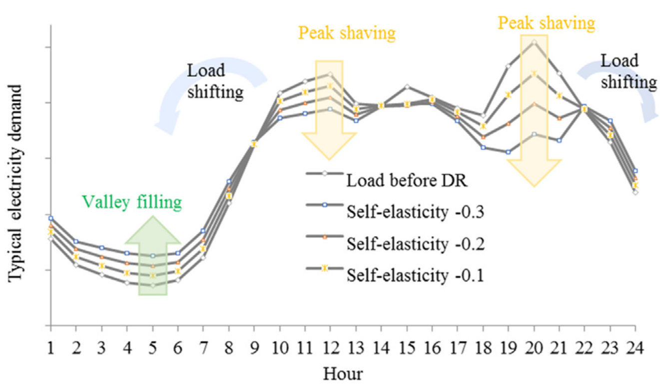

Fig. 3. Flexibility via demand response programs – an illustrative example.

contracted services, but also sell flexibility services to system operators or directly to an electricity market [14,18,19]. DR can be based on a direct control and an indirect control mechanism [20]. Under a direct control setup, the aggregator has direct communication with individual utilizations and comprehensive information on their relations with the neighboring environment [20]. Computationally, this may be very exhaustive, but it is characterized by an exact response, with controllable set-points that can be directed to each individual purpose, This enables demand control at the highest possible resolution [20]. Under an indirect control scheme, the aggregator has limited information about the actual demand. However, it must evaluate the price response of the collected demand, with prices being geographically fluctuating depending on the resolution of the information available to the aggregator [20].

The literature on DR is vast; the current work aims to complement earlier reviews by other researchers. Tulabing et al. [7] propose a methodology for DR that aggregates electrical loads, electric vehicles (EV) and storage. Del Granado et al. [11] formulate a dynamic optimization model for systems composed of a co-generation unit, gas boilers, electric heaters and wind turbines with storage units. The main purpose is to analyze storage policy strategies to satisfy heat and electricity demand and discover operational mechanisms for a more efficient utilization of distributed generations (DGs) under DR programs. Similarly, Agnetis et al. [19] use a mixed integer linear programming (MILP) model to optimize the profits of an aggregator who manages aggregated consumers, gather flexibility and generate bids for electricity market. Alcaraz et al. [21] resort to an analytical approach to illustrate the effects of DR on the efficiency of the network's operation. In their work, dynamic pricing has been used with critical peak shaving tariffs and hourly pricing schemes. Haque et al. [22] present an extensive discussion on a decentralized method to empower DR for managing congestions in a better manner. Despite its wide-range benefits, DR faces many challenges, which needs to be overcome. Eid et al. [23] have attempted to identify the main obstacles for DR aggregators in Europe and provide a policy review for European market designs to support aggregation processes. In relation to this, Zhang et al. [24] propose a flexible market aggregator, called FLECH to promote small scale distributed generation to participate in flexibility services such as ancillary services. Heussen et al. [25] also propose a similar FLECH aggregator. More works on DR mechanisms can be found in [26–112].

As mentioned earlier, demand response can in principle provide ancillary services, which are largely accepted to be more competitive and economically viable. As such, DR programs providing ancillary services are trivial players in the grid. Yet, it is necessary to evaluate the economic and regulatory frameworks to achieve the DR's maximum potential in providing such services. In reality, current regulations and rules are hardly adapted to reap the DR's full potential in providing ancillary services [53]. However, there are several studies that demonstrate the feasibility of DR as a key source of ancillary services. For example, Ryan [113] presents a method to optimally schedule ancillary service provisions by DR accounting for "the risk of consumer response fatigue". Backing with some numerical results, the author concludes that residential DR can solely provide between 50% and 75% of the total ancillary services needed in the considered system. In [114], authors further highlight the potential of DR in ancillary service provision. Their work extensively provides a quantitative analysis of demand response resources that can provide auxiliary services. The economic value and the impact of these resources on the entire energy system are clearly demonstrated in [114].

Generally, some of the wide-range benefits of DR (also contained in [7,11,20–112]) are summarized as follows:

- DR can be used to support the integration of RESs, and address the fluctuations of RES power outputs by means of load curtailment and shifting;

- Power consumption can be adjusted instantaneously with DR, permitting a more effective ramping rate from the aggregated demand than larger power plants;
- Cost reduction of the system capacity requirements can be achieved with DR.
- DR can balance fluctuations of power productions, reducing peak demand with demand shifting, resulting in big savings by avoiding or deferring investments in peaking plants which are often among the "dirtiest" means of power productions that cause immense environmental pollutions. In this way, existing plants can be better utilized, maintaining constant power output, and allowing a better management of the fluctuations in the generation-demand balances;
- Markets incorporating DR mechanisms may dramatically reduce the frequency of utilizing the most expensive peaking units, effectively lowering the system's marginal costs;
- Reduction in power generation using fossil fuels significantly abates GHG emissions;
- Allowing DR to participate in power markets may lead to an overall reduction in supply and locational market power because DR responds to time varying prices, limiting producers to manipulate wholesale price of electricity. This consequently leads to reductions of average wholesale price and volatility of peak prices;

Although demand response is not new, its implementation has been really slow due to a number of barriers. Despite the wide-range benefits, DR faces enormous challenges mostly related to the control and its optimal usage [20]. Some of the main barriers of DR are summarized as follows:

- *Unsuitable market*: Most of the current energy markets are designed in a centralized manner, and they are not suited for the natural demand diversity and distribution. However, emerging technologies such as blockchain technology and distributed market designs are expected to unlock the immense potential of DR.
- *Non-transparent regulatory and tariff schemes*: In most cases, regulatory and tariff structures are not setup to be visible for end-users. Addressing this issue allows consumers to respond to price signals.
- *Inadequate business environment*: Nowadays, there is an overwhelming difficulty in creating a business case for DR. It is recognized that incorporating demand in electricity markets increases social welfare. Welfare is distributed among different corporations, and can be difficult to create a business model that gather sufficient social welfare with satisfactory certainty to make the business feasible and justify investments in infrastructures.
- *Potential conflicts of interest*: A higher penetration level of DR can lead to potential conflicts of interest. For example, some power plants that participate in reserve capacity markets may be against the implementation of DR because of possible losses in their incomes. If the capacity value and the availability in times of the need for DR is very significant, DR will take over the responsibility for regulation and ramping, decreasing income for peaking power plants.
- *Complex end-users' behavior*: DR heavily involves customers' behavior, which is often difficult to predict. End-users can have different priorities. For example, some consumers may not give priority to reducing their electricity bills at all; others may be interested to participate in DR programs but concerned on privacy issues. The demand curve is affected by different and time varying external factors, like weather or any other factor. Because of all this, demand behavior may not be suitable for conventional economical models.
- *Forecasting, communication, control and modeling limitations*: In order to optimally reap the benefits of DR and maintain healthy operations of systems, reasonably accurate forecasting tools, appropriate communication and control infrastructures need to be put in place. In addition, the nature of DR necessitates accurate modeling of consumers' energy consumption behavior, which is often a challenging task. In many power systems, all these issues have been partly limiting the penetration levels of DR programs. However, over the past few years, there have been significant advances in forecasting capabilities and information and communication technologies (ICTs) as well as continuous improvements in the modeling strand, which can be rolled out to support the full integration of DR programs.
- *Massive investment needs*: Most power systems are not suitable for the DR programs to seamlessly flourish. Hence, effective integration of DR programs in power systems requires at least partly automating existing infrastructures, which means hefty investment needs. This is considered to be one of the biggest hurdles to the demand response penetration.
- *Inadequate incentives*: The savings consumers get from participating in DR programs may be oftentimes small, which may not be attractive enough not only for new consumers to join in but also existing ones to continue in such programs.
- *Privacy and data security issues*: The key factor to DR's success is ICT. But problems arise regarding privacy and security of users' data as well as the entire automated system. This is becoming one of the key challenges for the growth of DR amid increased cyberattacks in recent years.
- *Energy security*: One of the major obstacles to the wide implementation of these resources in the network comes from the fact of schemes that can be applied transversally, in different jurisdictions. As such, one way to assess the influence of these technologies on the level of security of supply is through the use of metrics [115]. For example, one of the metrics that can be used is the ratio between flexible demand and total demand, among others. The use of such metrics will level the use of different technologies which in parallel have the potential to accelerate the integration of these technologies, allowing the transition from the conventional network to an intelligent one.

2.1.2. Energy efficiency

Demand Side Management (DSM) is the ability to influence the use of electricity by end-users or alter the pattern and magnitude of demand [116–118]. Some strategies of DSM are peak clipping, load shifting, valley filling, strategic conservation and even strategic load growth [116]. Load shifting requires intermediate storage, and involves a mechanism for rescheduling energy demand. Some examples of load shifting are heat and cold storages. Normally, DSM strategies are employed by utilities when they predict unusual demand patterns [116]. Some of these DSM facets are illustrated in Fig. 3, and are largely discussed in the previous section under the auspices of demand response. The review in this section is devoted to energy efficiency (also known as energy conservation), which is one of the demand side management programs that are largely anticipated to partly provide some solutions to the energy crisis that may unfold over the coming decades. As graphically illustrated in Fig. 4, energy efficiency involves voluntary reductions of consumers' energy usage by investing in energy efficient technologies or responding to incentives designed to entice consumers to participate in energy conservation initiatives. Such initiatives heavily depend on the goodwill of end-users. Therefore, one of the key aspects to the successes of such initiatives is empowering consumers so that they voluntarily participate in energy efficiency programs (or, DSM programs in general). The most effective strategies are via appropriately designed incentive mechanisms, which could be financial or non-financial types. For example, consumers can be enticed by offering them contracts with low rates of electricity or giving them certain credits on the maximum demand charge.

Energy efficiency schemes also share some of the advantages of demand response programs discussed earlier. Some of the benefits of such schemes are as follows [10,117]:

- Balancing energy and capacity;

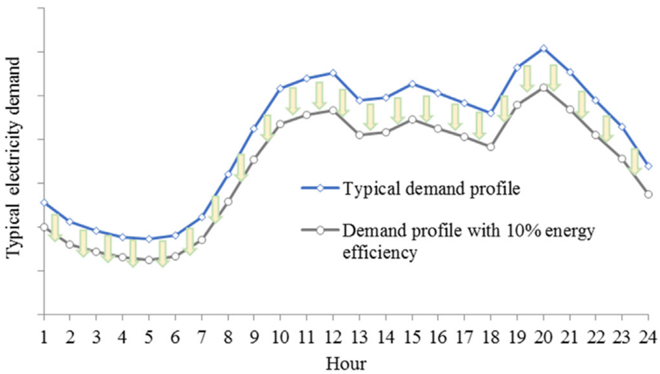

Fig. 4. Flexibility via energy efficiency measures – An illustrative example.

- Response in various time scales;
- Reducing price spikes and average spot price volatilities;
- Balanced market power i.e. roles shared between generators and consumers;
- Reduced investments in infrastructure expansion;
- Reduced system-wide costs as a result of reduced usage of peaking power plants;
- Reduced transmission and distribution losses;

Some of the barriers for energy efficiency measures are [10]:

- Lack of information and communications technology (ICT);
- Inadequate technology financing;
- Inadequate incentive mechanisms (often small savings for participating in energy efficiency programs);
- Lack of key stakeholders' strong involvements;
- Lack of adequate structural and market designs;
- Lack of appropriate regulatory and policies to promote energy efficiency programs.

2.1.3. Unconventional energy consumption forms

Currently, the energy consumption throughout the world heavily depends on fossil fuels. Fossil fuels are largely used among others in transportation, industry, commercial and residential sectors and even to generate electricity. In fact, on a global scale, nearly 80% of the energy consumption by mankind comes from burning these non-renewable fuels. This is however gradually changing amid growing concerns in several intertwined issues such as climate change and energy security. As a result, over the past years, a lot of countries have been gearing up efforts to decarbonize their energy industries by embarking on ambitious targets to increase the penetration levels of renewables. Apart from the conventional forms of final electricity consumption, new ones are taking shape across various energy intensive sectors. Among these "unconventional" energy consumptions is electric mobility (also known as e-mobility). Across this line, the numbers of electric vehicles (EVs) are growing rapidly in many countries. EVs can be considered as mobile energy storage devices, with relatively regular charging and discharging cycles. They are connected at the distribution level of power systems. Such vehicles can be plugged in to the grids during night at places where the end-users reside, and/or daytime close by commercial places. This makes EVs such good candidates for providing the much-needed flexibility in electricity grids. Generally, it can be said that EVs have relatively good availability, predictability and easy controllability [119]. This means they can offer a broad flexibility bundle including services like energy scheduling, reserve capacity, regulation, emergency load curtailment, energy balancing, power quality enhancement and supporting RES integration and utilization [10,120]. However, all this requires the provision of appropriate technologies such as smart counters, telemetry and two-way communications. It is worth mentioning here that DR mechanisms could be employed here to aggregate EVs to accomplish the required scale of flexibility. In this respect, Knezović et al. [119] deduce that the technical requirements and the organizational framework of the flexibility that EVs can provide to DSOs, with market design recommendations.

2.2. Supply-side flexibility options

There are a number of flexibility options that can be delivered by the supply side. The most important ones come from conventional power sources in the form of flexible generation and enhanced ramping capability, from diversified and complementary energy resources, strategic curtailment of RES power, as well as from wide-area variable power generation planning. These are discussed in the following subsections.

2.2.1. Conventional power plants

For a proper operation of power systems, demand and supply should be instantaneously balanced in every split second. In other words, flexibility is required to manage the unavoidable variations in demand, generation or both due to unforeseen operational situations. Such a balancing service (or flexibility) is traditionally provided by conventional power plants. The flexibilities given by such power plants are measures that can modify the output of power supply to achieve balance in the grid. Depending on their levels of flexibility, power plants are classified into baseload, peaking and load following regimes [10]. Baseload power plants such as coal and nuclear run at constant power outputs, and they hardly have ramping or shut-down mechanisms put in place due to technical and economic reasons. In other words, their power production regimes are often inflexible; hence, they are often intended to run as a baseload. However, this is expected to change in the future. Due to the increasing flexibility needs in power systems, such power plants will be required to put in place mechanisms that increase their ramping capabilities and provide considerable flexibility in power productions. Peaking power plants enter into action in high demand situations; so, they have very irregular utilization. The third category, i.e. load following power plants, includes gas and hydropower plants. These power plants traditionally serve as instant balancing units mainly due to their fast responses, start-up and ramping capabilities. For example, combined-cycle gas turbines (CCGTs) are characterized by high ramping rates (often in the order of 10 MW per minute) and reasonably higher efficiencies (often above 60%); hence, they are often attractive options to increase flexibility in power systems [10]. The fuel costs of CCGTS can however be prohibitively high. And, this may hamper their wide usage as flexibility mechanisms i.e. their use in balancing markets may be limited due to economic reasons [10,120]. Another example under this category is a combined heat and power (CHP) plant. CHPs are becoming as suitable technologies to enhance the flexibility of power systems, and increase RES integrations. The main flexibility of CHPs is underpinned in the emerging and existing technologies such as heat pumps, thermal storage, electric boilers, etc. They produce heat and power simultaneously with a conversion efficiency of more than 80% [10]. One of the main advantages of coordinating CHPs with RES integrations is the increased rate of load shifting due to thermal storage—an important source of flexibility, leading to a more efficient RES utilization [10].

2.2.2. Strategic RES power curtailment

The power outputs from variable energy sources such as wind and solar are subject to high level uncertainty as these sources heavily depend on weather conditions which are partially unpredictable. Sometimes, the actual power potential could be substantially lower than the forecasted value. Other times, the actual power productions by RESs could largely exceed predictions or even the actual demand. Either case leads to large unforeseen demand-supply unbalances in the system. Under such situations, the balancing process may be very expensive and/or technically impossible. One may argue here that situations with low RES power productions could be relatively easier to manage than those with excess RES power, especially in the absence of any energy storage medium. In the latter case, regulating RES power injection in to power systems could be economically feasible [10]. In other words, a strategic curtailment of RES power could be justified under the following situations: over-generations, oversupply of RES power outputs, congestions and widespread use of inflexible baseload generators. Strategic curtailment can also be done to dampen quick changes in power productions or in the provision of reserve power capacity by a ramp-up margin [10]. All this could increase flexibility in power systems.

2.3. Network-side flexibility options

Transmission and distribution networks are the backbones of power systems. These power system components can also provide important flexibility options by means of network reconfiguration (switching), smartification (both at transmission and distribution levels), dynamic line ratings, wide-area interconnections, meshed operations, etc. The following subsections present discussions of some of these flexibility mechanisms.

2.3.1. Smart-grids

Although the term smart grid is widely used in the literature, there is generally no agreed definition of this term. There is however a general consensus on its concept and technologies adopted for its adoption [122,123]. For example, according to the Strategic Deployment Document for Europe's Electricity Networks of the Future, a smart grid is defined as "an electricity network that can intelligently integrate the actions of all users connected to it", generators, consumers and prosumers, "in order to efficiently deliver sustainable, economic and secure electricity supplies". The Korean Smart Grid Roadmap 2030 states that, a smart grid refers to a next-generation network that integrates information technology into the existing power grid to optimize energy efficiency through a two-way exchange of electricity information between suppliers and consumers in a real time. It is important to note that the term "smart" refers to the integration of a set of technologies and software in the electrical networks, allowing such networks to function autonomously (or at least partly). This leads to a more optimal network operation in the short and long term time horizons. Smart grids are generally characterized by some sort of intelligence. And, such intelligence can come from different sources, such as through the automation accompanied by supervisory control and data acquisition (SCADA), state-of-the-art energy management systems (EMS), and demand management systems (DMS) among others. An example of this is demand-side intelligence, which, with the integration of smart meters and advanced metering infrastructure, enables sharing information not only with an aggregator but also with a network operator, so that the entire grid can be operated more efficiently.

The focus on electric networks in terms of flexibility provision has been dramatically increasing over the last decade or so. In particular, the issue of network smartification has been gaining more attention in the last few years. As mentioned earlier, the smartification process involves gradual transformation of existing passive electric networks into smarter grids which are equipped with state-of-the-art information and communication technologies (ICTs). This makes control, protection and energy management relatively easier [22,121].

In terms of flexibility, smart grids for example make it possible to know end-users' demand patterns in real-time thanks to a well-developed two-way information communication, smart metering facilities and immense automation [10,11]. The communication among energy producers, end-users and network operators is made easier in a smart-grids arena, leading to more efficient operations of power systems [10]. In addition, due to the communication and metering technologies, the use of RESs to balance grid services can be achieved. In particular, smart grids have been touted as one of the key ways for abating the negative effects of the increasing penetration level of variable RESs in power systems. For example, in smart grids, any shortfall in electricity supply can be easily counter-balanced by optimally changing demand in the form of an active demand response [11]. Smart-grids can be equipped with advanced technologies such as soft open points (SOPs), power electronic devices, replacing open points in active distribution systems, providing active and reactive power flow control and voltage regulation under normal operations, and fast fault isolation and restoration under abnormal situations [124]. González and Myrzik [125] estimate the degree of flexibility of an active distribution network which has RESs interfaced via full-power converters. Their results show the capability of the active distribution networks in providing ancillary services for a short period of time considering the availability and uncertainty of RESs.

In general, smart-grids are largely expected to play a key role in creating a sustainable, affordable and reliable energy future. In other words, smart grids will help to resolve a multitude of concerns related to energy supply worldwide; particularly, in increasing the reliability of power supply while reducing GHG emissions and other ecological impacts as well as savings in operation and investment costs. Smart grids are also expected to create a level playing field for all types of producers and consumers which is very crucial for having more optimal and efficient energy systems [10].

However, the gradual transformation of passive networks into smart grids comes with a number of challenges [126]. One of these challenges is security of supply. In the network transition process, a significant set of technologies will have to be integrated. In addition, conventional power generation regimes will be changed in order for power systems to become increasingly renewable. Consequently, the integration of large quantities of vRESs considerably reduces the amount of energy generated by conventional power plants. All this, along with the decommissioning of older thermal and nuclear power plants [115,127], may have strong influence on the security of power supply. This remains to be one of the key concerns in many jurisdictions. However, such concerns may be alleviated by deploying a set of smart grid enabling technologies such as ESSs and demand response.

2.3.2. Dynamic network reconfiguration

It is known that electrical power systems have several interacting components such as renewable and conventional power generators, energy storage media, large and small consumers, different network components, etc. Of a paramount importance in the day to day operation of such systems is keeping the interaction among these components at a standard level. In fact, the target of such interactions should be to create more reliable and efficient systems that can cope with any operational event that may unfold over time. Lack of proper coordination in such interactions may result in large-scale interruptions of supply, and even a complete collapse of the overall system. To ensure an optimal operation of such systems, it is very important to build mechanisms that take their dynamic nature into special account [128]. For example, the increasing penetration of renewables in distribution systems may complicate the control and energy management in these systems, especially considering the static and passive nature of electrical distribution networks. Basically, distribution systems may be built as meshed networks but they are normally operated in a radial manner, which is often kept static regardless of the operational situation in the system [128]. Such a network setup does not provide enough flexibility to the continuously changing and unpredictable conditions that may happen in current and future power systems. However, a dynamically changing network system can partly cope with this dynamism. An optimal configuration of the system can be achieved by maneuvering closed or opened branches [128,129]. The aim of a dynamic reconfiguration is therefore to automatically adapt the network to varying operational situations, which may be caused by variable RES integration or any unforeseen system condition [121,130].

Generally, network reconfiguration can be classified in two categories: static and dynamic. In a static reconfiguration, a single configuration is determined at a specific time, and considered to be optimal regardless of the changing operational conditions; hence, this topology is kept the same over an extended period of time [129]. On the other hand, a dynamic reconfiguration method considers different time intervals, and hence, new configurations are obtained that are fit enough to cope with different types of operational situations [129]. In fact, the optimal time intervals to perform dynamic network reconfigurations are subject to further studies [129]. But the major difference between static and dynamic reconfigurations is that, unlike the static one, dynamic reconfiguration considers varying operational situations [131]. In real systems, dynamic reconfiguration can be considered as a viable flexibility option that can provide a safe and more efficient power system operation because of the consideration of continuously changing operational conditions along a specified period of time. Apart from the flexibility provision, dynamic reconfiguration can play an important role in power losses minimization in smart systems [132]. Furthermore, it is important for restoration of supply after faulty events and to perform maintenance operations in power plants [133].

In the literature, Alcaraz et al. [13] propose a two-phase approach for a short-term operational scheduling of RESs in distribution systems. The first phase determines the power purchased from an electricity market and a number of DGs integrated in the system, while the second phase is a real-time scheduling coordination with an hourly reconfiguration. Novoselnik and Baotic [128] present a mixed integer second order program (MISOP) predictive control strategy for a dynamic reconfiguration of distribution system with DGs and ESSs. Milani and Haghifam [129] propose a genetic algorithm (GA) approach which aims to determine optimal time intervals for carrying out reconfigurations. Similarly, Huang *et al.* [130] present an optimal reconfiguration model based on dynamic tariffs for congestion management and losses reduction considering EVs. Li et al. [131] develop a multi agent system to perform dynamic reconfigurations of distribution systems by dividing each day into several time intervals managed by the agent. Ameli et al. [134] use ant colony optimization (ACO) algorithm to dynamically schedule feeder reconfiguration and capacitor banks along with DGs, dividing the planning period into several intervals to determine the optimal topology of the network which matches different operational situations. Tu and Guo [135] present a conceptual model of median current moment for dynamic reconfigurations. Yang et al. [136] employ a gradual approach that deals with dynamic reconfigurations of distribution networks. Canzhi et al. [137] present a new method of dynamic reconfiguration that is based on credibility theory, and considers day-ahead prediction of PV generation and forecast uncertainty. Meng et al. [138] consider large scale integrations of DGs with scheduling of active power outputs and dynamic reconfigurations.

2.3.3. Meshed operation of distribution networks

Electrical distribution networks are experiencing new challenges amid the growing changes in power generation from centralized to distributed paradigms. The level of DG integration in such systems is unprecedented. But such networks are not especially designed to support power generation sources. Their sole purpose so far has in fact been to direct power flows from upstream grid (transmission where the centralized generators are connected) to the end-users. This is however slowly changing with the advent of several enabling technologies. A lot of policy makers in the world seem to favor distributed power generation, to the dismal of conventionally centralized power generators. In order this to happen, distribution grids need to undergo a huge transformation process including dramatic changes in the operational scheme. One example from the operational perspective is the topologies of such grids, which are radial in nature. In order to support DG integrations (variable RESs in particular), new operational strategies should be put in place, which enhance the flexibility of the system as a whole, paving the way to more RES integrations. One of these strategies is meshed operation. This goes against the normal operation strategy in conventional distribution grids (i.e. radial) [128] but it can be an important source of flexibility in future electric power systems. Technology-wise, this is already feasible. It has in fact been shown in recent studies [121,139] that adopting meshed configurations of distribution networks increases DG integration and fulfils reliability requirements. Other previous works in this subject area include that of Ivic et al. [139] which present detailed comparisons of optimal power flow outcomes of radial and meshed distribution networks with DGs and compensating devices. Chalapathi et al. [140] perform studies on the allocations of DGs in weakly meshed distribution networks and evaluate the contributions of DGs in the meshed network. Yang et al. [141] model a method to approximate a large meshed structure of distribution networks to a simple load model consisting of two RLC elements. Yu et al. [142] have developed a time sequence load-flow method for steady-state analysis in a heavy meshed distribution system with DG integrations. Generally, previous studies show that a well-adapted distribution network (meshed one, in particular) is expected to play an essential role in future power systems, particularly, in terms of flexibility provisions.

2.3.4. Micro-grid and islanding control

Micro-grids can be described as local grids that supply energy to local consumers. Micro-grids are slated as one of the flexible systems that are expected to be part of the solution to integrate more RESs in power systems by properly balancing demand and supply [10,143]. A micro-grid can include small RESs, CHPs, ESSs, controllable loads and connection to a main grid [10,143]. Therefore, a micro-grid can be a component of a large distribution network system that can be islanded with a proper islanding control mechanism. In the event of unavoidable disturbances, micro-grids can be isolated from distribution systems, and continue to operate in an island mode supplying energy locally. However, challenges exist during the transition to the island mode. For example, power balance issues while islanding can lead to frequency instability, and such instability can cause a blackout in the islanded system because of lack of adequate reserve capacity from the main grid [144]. However, if we are talking about an island system that has installed DGs, they are used to re-stablish power balance and prevent blackouts in the islanded zone. In this manner, islanding operation and micro-grids can enhance reliability of the system [143]. Another possible problem that immediately arises is the coordination of feeder protection schemes when changing the topology of the grid. This must be well coordinated to avoid incorrect operation of protection devices.

Cheng [143] highlights the principles of a seamless grid islanding. Results show that DGs can be applied for grid control purposes. Chen et al. [144] have developed an Islanding Control Architecture based on the Islanding Security Region. With their method, system operators could effectively know in advance if an island operation a system would be successful given its current operating state. Majzoobi and Khodaei [145] have analyzed the application of micro-grids in effectively capturing load variability in distribution systems. In their work, an optimal scheduling of a micro-grid is proposed and coordinated in order to meet the micro-grid's net load with the aggregated net load consumed in the distribution system, focusing on ramping issues.

2.3.5. Network interconnections

It is widely recognized that interconnections of different electric network systems through enhanced transmission networks facilitate cross-border power flows, and hence access to neighboring energy markets. It is important to note that cross-border flows enable geographical smoothing both at the demand and generation levels, which is very important for scaling up RES integrations. For example, aggregated RES power outputs change softer and slower. And, this decreases flexibility requirements such as balancing services. In addition, interconnections create large balancing areas and a much improved energy management in the resulting systems. It is also worth mentioning that larger balancing areas provide greater access to varieties of load and power generation regimes as well as a larger pool of reserves.

All these result in huge flexibility and operational efficiency in the interconnected systems. Despite all these benefits, in most cases, investments in cross-border electricity networks are overlooked due to various reasons such as geopolitical, technical and economic issues. As a result, bottlenecks are created at border areas among different countries. Realizing the wide-range benefits of strengthening cross-border interconnections, many countries are now forging forward towards enhancing and interconnecting their electricity grids. And, this will undoubtedly be an important source of flexibility in creating a sustainable energy future.

2.3.6. Network expansion planning

Network expansion planning, which is often overlooked, is a very important means to improve power system flexibility. Such an expansion planning process includes reinforcement of existing transmission and distribution corridors, building alternative paths and installing power flow controllers, reactive power sources such as smart-inverters and other advanced technologies. All this helps to meet multiple objectives such as enhancing market efficiency, motivating new market players, proper and optimal management of congestions, and supporting more RES integrations among others.

2.4. Other sources of flexibility

This section is devoted to other sources of flexibility that mainly fall into the three pillars already mentioned earlier. For example, the flexibility provided by energy storage systems, properly designed market and regulatory aspects are reviewed in this section.

2.4.1. Energy storage systems

Energy storage is a mechanism that enables one to store energy produced at some time (usually when the demand is low or when there is over-supply) and use it later (often when the demand is high). The use of energy storage systems (ESSs) for enhancing the flexibility of power systems is nowadays at the forefront of many policy makers and planners. Until recently, storing electrical energy in bulk quantities has not been feasible because of economic and/or technological reasons. However, significant advances in storage technologies and their continuously falling capital costs are proving the viability of ESSs in providing flexibility at this important period of time, in which more integration of variable RESs is highly needed to address a multitude of global as well as local concerns. ESSs have multitudes of technical and economic benefits, and can be integrated at the supply, demand and/or network side. In addition, they can be incorporated into wholesale electricity markets and provide support in terms of ancillary services. During periods of low electricity demand, excess energy produced by such sources can be stored and utilized during periods of high electricity demand, reducing or even avoiding the utilizations of peaking power plants which are often expensive and among the "dirtiest" means of power generation [146]. In addition, ESSs can provide grid support. They have fast response, making them suitable to be part of ancillary services, providing frequency and voltage control services [147]. When ESSs are not providing (discharging) power to the grid, they can be utilized as capacity reserves with literally low costs, and are well-suited to restart system operation after black-outs [147]. Fig. 5 schematically illustrates the benefits and operational schemes of ESSs.

Generally, ESS technologies can be divided into five groups: 1) physical storages – e.g. compressed air and pumped hydro; 2) electromechanical storages – e.g. flywheels; 3) electrochemical storages – e.g. fuel cells and batteries; 4) electrostatic storages– e.g. capacitors and supercapacitors; and 5) electromagnetic storages – e.g. superconducting magnets [148,149]. Each technology has its own advantages and disadvantages, making them suitable for different applications. Table 1 summarizes the pros and cons of different ESS technologies [148–154].

Details of each of these ESS technologies and their applications can be found in the literature [146,148–150,153,154]. Among the much anticipated contributions of ESSs is the reduction in the effects of fluctuations caused by RESs. In the absence of appropriate management mechanisms such as ESSs, these fluctuations can cause several problems in terms of power system stability, security and quality of power delivered to consumers. Moreover, power outages may be common phenomena [150,153]. However, ESSs can help to prevent outages and enhance the overall stability of power systems. In addition, ESSs have the necessary flexibility capabilities to contain the intermittency of RESs and support an increasing penetration of these technologies in power systems. As mentioned earlier, ESSs store excess energy generated during off-peak periods that can be injected back to the grid whenever it is needed. This makes ESSs one of the most cost effective ways to alleviate the problems that may arise as a result of variability and uncertainty in system conditions. As shown in Fig. 5, ESSs also counter the possible fluctuations in voltage and frequency especially in systems where there is high penetration of intermittent energy sources.

ESS technologies with high lifetime cycles and shorter response times are especially suitable for regulating voltage and frequency [146,149,150,153]. Likewise, ESSs are able to add reserve capacity to power systems [146,148], and can further provide wide-range ancillary services [146,148,153]. Another interesting feature of ESSs is time and spatial shifting of energy consumptions and generations. Energy stored from a remote power generation source is shifted in time and geographical location [146,148,149,153]. Time and spacial shifting operations are related to load shifting, time of use and variable energy generation shift [146,148,149,153]. Load shifting allows the delivery of renewable energy from off-peak times to peak times, increasing the value of RESs [146,148,149,153]. A shift in variable energy generation reduces peak reverse power flows through power system components, respecting operational limits [146,148,149,153]. The process of supplying and discharging is related to time of use. If ESSs charge and discharge in specific time periods, such an operation can be defined when time-of-use tariffs for charging are economic while tariffs for discharging are more expensive [146,148,149,153]. Finally, ESSs can avoid, postpone or reschedule investments in transmission and distribution systems. Installing permanent or temporary ESSs in overloaded nodes can avoid or reduce congestion and hence investments to relieve such congestion, eventually saving funds for critical areas and reducing cost to the end-users. Further literature on ESSs include the work by Farrokhifar [15] which investigates the positive impacts of adding ESSs to distribution grids. Vandoorn et al. [17] presents a voltage-based droop control for controlling loads, DG units and storage equipment in islanded distribution network systems. Skarvelis-kazaos et al. [155] have proposed an agent-based model to control multiple energy carrier systems. Khasawneh and Illindala [156] consider a micro-grid consisting of fuel cell batteries to supply crusher-conveyor load when power from the main grid is not available. Moreno et al. [157] have developed a MILP model to schedule the optimal operation of ESSs by coordinating the delivery of various system services which are rewarded at different market prices. Mousavizadeh and Haghifam [158] have studied power flow analysis on AC/DC distribution networks, including weakly meshed ones, in the presence of DGs and ESSs. Palmintier et al. [159] explore design solutions that may never emerge when distributed energy resources are treated in a deterministic approach. Riaz et al. [160] present detailed analysis concerning the integration of RESs and ESSs in future grid scenarios. Other works in areas of ESSs and related subjects are compiled in [161–235].

The integration of smart grid enabling technologies such as ESSs raises a number of concerns, mainly in the security of electricity supply, beginning with the fact that the established security requirements in different jurisdictions are defined almost exclusively for conventional assets, this is also one reason integration of ESSs is being delayed. In this perspective, and to speed up the integration of ESSs in the different networks, different jurisdictions, one of the main points that has to be made is leveling the field of action of this and all the others smart grids enabling technologies [115]. Regarding the ESSs, this technology has

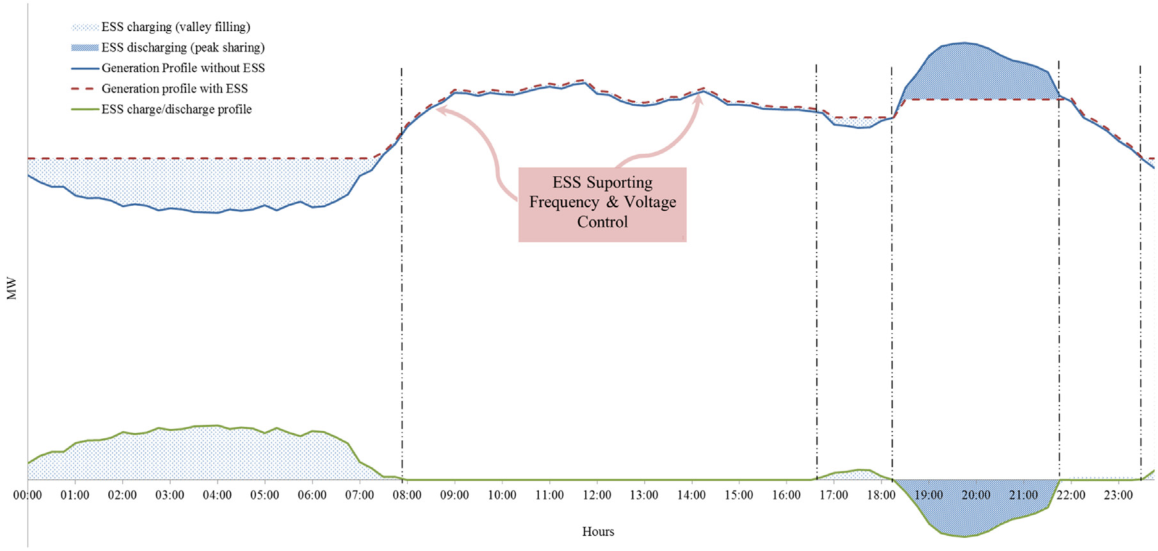

Fig. 5. Illustration of the possible roles of energy storage systems.

Table 1
Advantages and disadvantages of each ESS technology.

Technology	Type	Advantages	Disadvantages
Lead-Acid	Electrochemical	Easy installation; Low self-discharge	Short lifetime; Maintenance costs; Low power; Partial discharging; Premature failure; Needs temperature management
Lithium-Ion	Electrochemical	Efficiency (almost 100%); Improved lifecycle; Improved energy efficiency	Inflammable; Fragile; Lifetime dependent on temperature; Charge/discharge current limitations
Nickel-Cadmium	Electrochemical	Lifecycle; Low maintenance requirements; Wide range of sizes; Economic in cost per cycle; Long term storage capacity; Low temperature performance	Toxicity of cadmium; Costs ten times higher than Lead-Acid storage technologies; Low efficiency; High self-discharge rate; Suffer from memory effect; Continuous maintenance due to high self-discharge
Sodium-Sulphur	Electrochemical	Energy Efficiency; Not dependent on ambient temperature; Lifecycle; Energy capacity; Power density	Safety conditions for thermal management, seal and freeze-thaw durability
Flow Battery	Electrochemical	High power; Longer duration of operation; Scalable; Safe to replace electrolytes; Decoupling between power rating and energy rating; Fast response; No self-discharge	Low efficiency; High operation costs; Low energy density; Thermal management; Contamination can occur from mixing used and fresh electrolytes
Fuel Cells	Electrochemical	Continuous operation; no need for recharging the cells	Very expensive
Superconducting Magnetic Energy Storage (SMES)	Electrical	Capable of very quick discharge making it suitable for short term applications; Easy to increase energy storage capacity by increasing the current flowing through the coil	Very expensive; Dependent on the temperature of the coil
Supercapacitors/ Capacitors	Electrical	Fast response operations; High energy density; Long term storage; Low losses	Very expensive
Flywheel	Mechanical	High efficiency; Durability; Low maintenance; Minimal environmental impacts; High capacity	Very expensive
Compressed Air	Mechanical	Long term energy storage	Toxicity
Pumped-Hydro	Mechanical	Efficiency about 70%; Reserve capacity provision; Frequency control, Load balancing and energy management	Costly; Requires building a hydroelectric dam

the ability to cope with the supply variation and uncertainty (mostly from RESs). However, the effect that comes from the integration of this technology has to be quantified. A good practice is the use of metrics, for example, see in [115]. These metrics could be regarded differently in different jurisdictions. For the ESSs case, one metric that could be used is the ratio between the flexibility of the load that can be delivered in an hour and the maximum load that can be suppressed by the ESSs in the previous year. This ratio can be adapted to all sources of supply. This would make it possible to achieve greater security of supply, eliminating one of the major obstacles to the integration of ESSs in the network. In general, the key pros and cons of ESSs can be summarized using the following bullet points:

Pros of ESSs:

- ESSs facilitate effective utilization of intermittent renewable sources
- ESSs can be key components of a smarter and integrated energy system
- ESSs can reduce the need for increased peak generation capacity
- ESSs can enhance both grid reliability and stability
- ESSs have their performance and costs continually improving.

Cons of ESSs:

- Energy losses as a result of round trip inefficiencies
- Additional cost and complexity
- Additional infrastructure and space requirements

2.4.2. Energy systems integration

The integration of multi-sectoral energy systems (for example, power-to-gas initiatives, electrification of the transport sector, etc.) is believed to add more dimensions to the flexibility needed to pursue a sustainable energy future. The advent of new technologies and emerging business models are expected to make such integration possible. The energy required by the heating and cooling as well as transport sectors is largely met by conventional energy sources (which are often non-sustainable). However, advances in technologies and growing concerns in energy security and environmental changes among others are already resulting in a paradigm shift in many countries. It is now widely accepted that electrification of such sectors shall be one of the solutions for the energy "poverty" and severe effects of global climate change that may unfold over the coming decades. Technologies such as internet of things (IOTs) are expected to facilitate further integration of the energy systems. IOT technologies "*consist of the internet, global network based on communication protocols and things, which are the physical or virtual objects, devices, information and used interfaces*" [236]. The performance of energy systems can be substantially improved via automated responses of IOT controlled systems of various sectors [236].

In many countries, the transport sector is responsible for a significant portion of emissions. This is because of the heavy dependence of the sector on fossil fuels for mobility. Hence, this sector is identified as the main target for partly achieving the massive decarbonization process needed worldwide to address global climate change and mitigate its ensuing consequences. The flexibility potential that this sector possesses is immense, and this is vital to increase the level of RES integration in power systems.

Another promising initiative closely related to energy systems integration is the power-to-X program, which involves converting electrical to any other form of energy. Power-to-gas (P2G) is one example that is widely accepted nowadays in many countries. P2G transforms power to hydrogen by means of electrolysis or to methane by a process called methanation [10,237]. Hydrogen or methane can be stored in nominated pipe storage or in an underground reservoir. The conversion process to hydrogen can have an efficiency of about 75–80%; whereas, the conversion to methane is reported to have an efficiency of about 60–65% [237]. However, the reverse process (i.e. P2G-to-power) leads to a round-trip efficiency of about 36%, which can be the main source of controversy of such initiatives [237]. Hydrogen production from RESs can be understood as one type of ESS because this gas can be converted back to electricity using fuel cells or combustion power plants [10]. Methane could be absorbed by the gas distribution systems that have a large storage facility [10,238]. Hydrogen requires large storage capacities, making investment costs very high and possibly reducing revenues from such an option [237]. On the contrary, methane requires a lower amount of storage (4–5 times less than hydrogen), making it economically attractive [237].

It has been reported that P2G provides an important flexibility mechanism, and deals well with the variability of RESs with the seasonal demand of gas, storing the gas in special facilities to stream it with no interruption in winter seasons [237]. This way, the energy produced from RESs can be better utilized, avoiding or minimizing curtailments. In addition, P2G can be used for ancillary services accessible by TSOs and can be integrated in spot markets for temporal arbitrage [237].

In the future, P2G is largely expected to become one of the most competitive long term storage options, which at this moment is dominated by pumped hydro [238]. One advantage of P2G over a pumped hydro storage is that P2G can have dramatically larger energy storage potential [238]. The financial risk of P2G systems is the price risks originating from the gas sales [237]. However, suitable storage choices will help to alleviate price risks, and can enable P2G applications in the coming years [237]. Voluntarily or imposed by regulation, improvements in transparency and quality of accessible information on electricity prices and time series have been effectuated by many organizations [243]. The price uncertainty has appeared in most recent studies in the literature, for example in [241], where the operation and planning of systems with multiple assets are evaluated in terms of flexibility which incorporated in the steps of operation and investment, subject to long term uncertainties. However, majority of the models do not consider realistic time series of prices, turning into imprecise predictions of hourly electricity prices [243].

In general, energy systems integration has enormous potential in terms of flexibility. In other words, multi-energy systems can optimize different energy vectors such as gas, electricity and heat simultaneously, proving to be important sources of flexibility (for example, see [240–242]). In particular, the study in [239] discusses in detail the flexibility potential and economic aspects of energy systems integration for renewable-rich systems. In addition, the effectiveness and viability of energy systems integration in terms of ancillary services provision has been demonstrated in the same study, i.e. [239].

However, it should be noted that the integration of multiple energy systems brings more flexibility to power systems if holistically optimized using holistic approaches that deal with different system trajectories. This is because of the fact that holistic approaches help to better quantify the strategic value of such an integration, as reported in [241,244–248]. In [244], a stochastic decision support model is proposed for scheduling flexibility services in the next day, in which flexible consumers are exposed to dynamic prices in the retail electricity market. The problem has been modeled using a stochastic programming approach where uncertain parameters are represented through a scenario tree resulting in significant savings in terms of cost. In [245], Good and Mancarella present a multi-energy communities approach incorporating electrical and thermal storages. The approach covers all relevant energy vectors, allowing a more comprehensive modeling of the different flexibility options. In [241], a multi-energy system with different vectors is modeled, namely, electricity and heat simultaneously optimized, proving to be a valuable source of flexibility on the demand side. Planning these resources is done in the presence of price uncertainty of the energy vectors in the long term. However, the planning process of integrated energy systems is extremely challenging, particularly in the presence of long-term price uncertainty in the underlying energy vectors. The implementation of advanced tools to access the risk in the planning stages are encouraged to reach the potential of multi-energy systems, reducing risks from unfavorable realizations of uncertain parameters and capitalizing on the benefits of favorable realizations [241].

2.4.3. Energy markets

Physical or technological means are not the only ones that can provide flexibility. For example, properly designed energy markets can also increase the flexibility of systems [10,120]. Electricity markets are normally designed to meet the following purposes among others [249,250]:

- Balance demand and supply in real-times;
- Optimally use RES power outputs when congestion or any unforeseen condition occurs;
- Effectively manage transmission and distribution constraints, congestions and bottlenecks;
- Optimize sets for market agents taking into consideration grid requirements at specific times and locations;
- Reduce grid investments especially if flexibility is used effectively incorporated in the TSO's and DSO's planning processes.

A number of researchers have reported assessments in relation to the impacts of having flexible markets on various metrics. Eid et al. [120] provide a review of existing distributed energy sources acting as flexibility providers and trading platforms for distributed energy sources flexibility in electricity markets. In [251], authors have analyzed three projects in the Netherlands and Germany to understand if organizational models for flexibility management guarantee retail competition and feasibility of upscaling in Europe. Saá et al. [121] propose congestion management mechanisms in smart-grids which rely on the wholesale electricity market. Ramos et al. [249] have proposed a market design that enable access to flexibility contracts to solve network problems and balance the grid at a specific location. The designed market is dimensioned in time, space, contractual and price-clearing perspectives. Torbaghan et al. [250] propose a framework of two mechanisms. The first one is related to a pre planning process via markets and real-time dispatching, which includes day-ahead and intra-day mechanisms. This framework is operated by a local flexibility market operator. The second one is related to establishing a strategy for DSOs to seek the flexibility they need from the day-ahead and intra-day markets, as well as from the real-time dispatching at the lowest possible cost. Kornrumpf et al. [239] have modeled a framework for a local flexibility market based on Optimal Power Flow (OPF) calculations.

Generally, earlier works by researchers have clearly demonstrated that properly designed electricity markets can substantially enhance the flexibility of power systems, and create conducive environment for flexibility market players to provide services that ultimately lead to more efficient systems. In particular, integrated energy markets facilitate access to neighboring markets. In recent years, such an integration process has been touted as the main mechanism for addressing the long-standing energy problems. For example, market integration can substantially minimize the frequency and the amount of curtailments of intermittent power sources, increasing their values. The flexibility requirements of larger and integrated power systems are in fact lower than that of local grids, mainly due to the geographical smoothing effects. Moreover, designing and implementing faster electricity markets (i.e. with markets shorter temporal resolutions) help to follow actual system conditions, avoiding unrealistically high pricing of forecasted system conditions. Instead, faster markets result in better pricing of real-time operational situations. Such markets also create an institutional flexibility mechanism that can support large-scale integration and utilization of variable energy sources.

2.4.4. Regulatory policies

To abate global warming and meet climate change goals, a dramatically high reduction of GHG emissions is required worldwide. These targets are strongly dependent on renewable energy technologies [166,251]. And, this requires appropriate regulatory policy interventions to be put in place on a state-wide and global scale, which speeds up the integration of such “clean” energy technologies and ensures their efficient utilization. For example, it has been some years since the European Union embraced ambitious targets for sustainable energy developments. By 2050, all electricity consumption in the EU is expected to come from renewables [166]. EU countries have already drafted a number of regulatory policies designed to support these developments. Yet, there remain a lot of regulatory gaps in many countries (including the EU) that need to be addressed. For instance, investments in distribution networks are not being effectively stimulated by the present regulatory frameworks in many countries [166]. In particular, distribution systems can be at greater risks of outages, network congestions, inadequate RES integration and quality deterioration of energy delivered to end-users. Properly designed incentives for investments in distribution networks can improve the integration of RESs as well as their profiteering [166]. Regulatory revision of the financing model administered to DSOs by national energy regulators is essential for encouraging technological changes [166]. Regulators have leading responsibilities to encourage DSOs to invest and develop distribution grids in the best way possible. Nevertheless, the problem is that many regulators do not consider innovation in their regulatory frameworks, resulting in negligence to spend capital in innovative solutions and do not make the cost benefit analysis on their reports [166]. There are some exceptions, but most regulators seem to only seek for short-term optimization while largely overlooking long-term requirements. For example, current regulatory frameworks in many countries hardly provide conducive environments for emerging market players such as flexibility service providers and multi-energy carriers to flourish and become competitive [252].

Generally, new regulatory policies are highly needed to shape the long-term evolution of energy systems. Such policies play a critical role in creating flexible systems that are capable of efficiently handling all sorts of dynamics in the systems. It is important to note that effective regulatory frameworks clearly reflects market players' roles and responsibilities for managing flexibility options provided by different resources in the future energy market.

3. Conclusions

This paper has presented an extensive review of various flexibility options, rigorously discussing the prospects, challenges, advantages and disadvantages of each flexibility option. The flexibility options reviewed in this paper are structured into different categories that are not only easy to follow and understand but also sensible enough from structural and technical standpoints. Our work complements existing review works by other researchers in related subjects, highlighting the importance of flexibility mechanisms in power systems that are experiencing unprecedented transformations from the supply side to the end-users. In addition, we provide insights into the challenges and opportunities associated with various flexibility options provided by different technologies. The growing need to integrate more “carbon-free” energy resources dramatically increases the flexibility requirements. Traditional flexibility mechanisms are not simply sufficient to meet the flexibility gaps created as a result of increasing variable renewables. Fortunately, there are a number of emerging and promising technologies that can be deployed at the supply-, network- and/or demand-sides and fill in these gaps in close coordination with existing flexibility mechanisms. These flexibility mechanisms are extensively discussed in this work. The wide-range benefits of emerging flexibility options are widely recognized. Their future prospects seem promising. However, there are certain barriers that may hinder their developments in the short to medium terms. The most relevant ones that require attention are:

- *Lack of suitable market*: Most of the current energy markets are not designed to taking into consideration new market players such as flexibility operators, and hence require significant changes or even overhauls in order such players to succeed.
- *Lack of transparent regulatory and tariff schemes*: For most flexibility mechanisms to flourish and work efficiently, the transparency of regulatory and tariff structures is mandatory.
- *Inadequate business environment*: A conducive business environment is necessary not only for investments in emerging flexibility options to materialize but also ensure existing flexibility mechanisms work efficiently. This seems to be one of the biggest barriers in the developments of various flexibility options, which needs to be addressed.
- *Potential conflicts of interest*: The integration of emerging flexibility mechanisms (e.g. energy storage systems) may decrease incomes for established flexibility providers (e.g. peaking power plants). This may lead to potential conflicts of interest. New mechanisms for resolving such issues should be put in place.
- *Huge investment needs*: In order to reap the benefits of most of the flexibility options, hefty investments in automating existing infrastructures may be required. This may also hinder the development of some flexibility mechanisms.
- *Inadequate incentives*: The savings for consumers from participating in DR programs may be sometimes small, which may not be attractive enough not only for new consumers to join in but also existing to continue in such programs.
- *Privacy and data security issues*: The key factor to DR's success is ICT. But problems arise regarding privacy and security of users' data as well as the entire automated system. This is becoming one of the key challenges for the growth of DR amid increased cyberattacks in recent years.

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