# The Integration of Intermittent Renewable Energy Sources to Smart Grid: A Comprehensive View

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**Abstract-** Renewable energy resources are intermittent by nature. This intermittency influences the balance of the electrical system negatively and the influence grows with the increase of renewable energy penetration into the grid. The transion of the classic electricity power grid to a smart grid is one of the key promising solutions. It helps in many aspects including the integration of renewable energy resources and to cope with the increased demand over an aging infrastructure. This research provides a comprehensive view of the integration of renewable energy technologies into the smart grid. An overview of the key features to facilitate the integration of intermittent energy sources into the smart grid is discussed. The smart grid concept, its impact, and its challenges are presented and discussed. Furthermore, the proposed resolutions presented in the literature are investigated. This research sheds the light on the important areas in generation, transmission, and distribution phases to help in the decision making related to managing the impact of higher penetration of renewable energy sources to the grid including smart transmission, smart distribution methodologies, electric vehicles, and shifting the role of the demand-side from being passive and uncontrollable to active and controllable. The proposed enhancements can provide the needed reinforcement for the grid system to overcome its current challenges.

**Keywords** Smart grid, renewable energy, distributed energy resources, intermittent resources, demand response, demand dispatch, microgrid.

## 1. Introduction

The population of the world is growing. Besides the electrification of many aspects of our modern life, this population growth leads to an increase in electricity demand over an aging infrastructure. These aspects combined with the intentions to achieve net zero emissions by different countries led to the elevation of alternative resource installation over the past few decades. One of the most important alternative resources that drew high attention is renewable energy. According to S. Zhang and H. Minxiang [1], the global installed capacity of renewable energy is expected to attain over 50% of the entire electrical power production by 2050. The synergy between alternative resources and conventional resources will assist in overcoming the obstacles. However, it may render numerous unique challenges to the power grid system [2]. Therefore, to gain substantial benefits from renewable energy and other alternative resources that meet the requirements, solutions must be found to the problems caused by integrating renewable energy into the grid [1], [3].

Many important resolutions are proposed and studied for decades, various methodologies were introduced, and several pilot projects were implemented towards transforming current grids into smart grids through privileging the extraordinary advance in communication technologies by making customers proactive parties in the energy system [4]

Other essential concepts that were introduced to enhance the grid include distributed energy resources to decentralize the power generation, demand-side response in a regulated and automated manner [1], [5], and electric vehicles [6], which are also predicted to play a critical role since the electric vehicles industry is rapidly developing in today's market. Aggregation of a high number of electric vehicles will inevitably impact the grid. This impact is under consideration to be utilized as much as possible to the benefit of the desired smart grid [7], [8].

## 2. Smart Grid (SG)

Smart Grid (SG) is a digital enhancement of the current electric grid, which improves the communication between consumers and electricity producers as well as the decision making of when and how to generate and consume electric energy. This improvement helps in minimizing energy costs as well as emissions through permitting dynamic optimization of operations and integrating alternative energy resources. Implementing SG requires the utilization of telecommunication technologies to facilitate real-time and bidirectional operations. The smart grid is also an auto-balancing and self-monitoring grid that accepts power from different sources such as oil and wind [9]. Several basic functions are needed to be provided by the SG such as self-healing ability and fault tolerance through resisting attacks, the capability to incorporate demand response (DR) as well as allowing the integration of alternative energy resources.

A smart grid is intended to support the transformation of clients from passive to active elements in the system. It helps to improve the reliability, efficiency, power quality, and security of the conventional electric grid by deploying the digital layer that allows communication down to the last mile of the distribution network. These functions are carried out through advanced monitoring, control, forecasting, and optimization [10]. Furthermore, the implementation of a smart grid can enable countries with excess resources like wind energy and solar radiation to sell the electrical energy to neighboring countries. Pazheri et al. [9] illustrate how a country like Saudi Arabia, which is the largest oil producer and exporter in the world, can become a megawatt exporter through a smart grid.

### *2.1 Motivations for SG adaptation*

Many motives are behind the need for transforming the current grid into a smart grid. Some of those include the need for higher reliability and operational efficiency considering the growth of electricity demand over an aging infrastructure. Accordingly, there is a need to replace the blind and manual operations in the energy system by privileging from the substantial advance in communication technology. Additionally, meeting the environmental goals, accommodating enhanced DR, and supporting the integration of both electric vehicles (EVs) and distributed generation (DG), through renewable energy sources (RESs), and storage devices [11], [12].

Significant investments are designated to smart grid technologies including advanced metering, distribution management, and supply security [13]. The market size was estimated at 36.9 billion USD in 2021 and is forecasted to grow to 55.9 billion USD by 2026 as can be seen in Figure 1.

### *2.2. SG impact on existing infrastructure and costumers*

Implementation of a smart grid requires the support of advanced metering and communication infrastructure, DR approaches, and management strategies for distributed resources. The execution of these services will influence many operational aspects and information systems, including but not limited to planning, scheduling, and energy markets. The high penetration of intermittent RESs and EVs might cause overloads and system imbalance [14]. Thus, the smart grid system must maintain higher reliability, regulated voltage, and automated switching. Hence comprehensive monitoring will be necessary through an advanced communication system [12], [15] Figure 2 depicts the goals and impact of the smart grid on the system.

### *2.3 Challenges of SG projects implementation*

The transformation from the existing classic grid into a smart grid is a long-term process. Although the potential ultimate benefits of applying smart grid projects are significant, many obstacles hinder smart grid project implementation [16]–[18]. Ipakchi and Albuyeh [12] introduced several challenges from managerial and enterprise points of view. These challenges include but are not limited to 1) non-clear and non-defined end state, this problem is related to many external factors such as the economy and governmental regulations; 2) the involvement of many stakeholders in planning such as consumers, energy markets, and smart meters; 3) transformation of the smart grid ought to be done without affecting the reliability and the performance of the current grid;

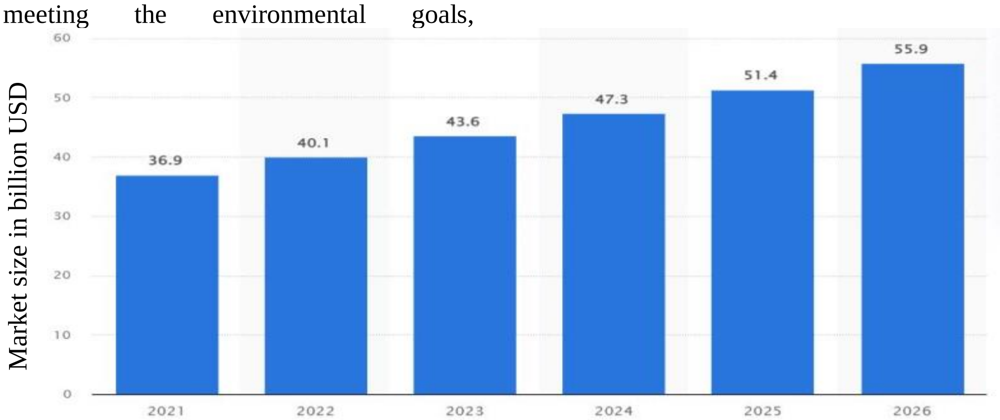


**Fig. 1.** Global market size of smart grid technologies 2021-2026
Source: Statistica Energy & Environment 2022 [19]

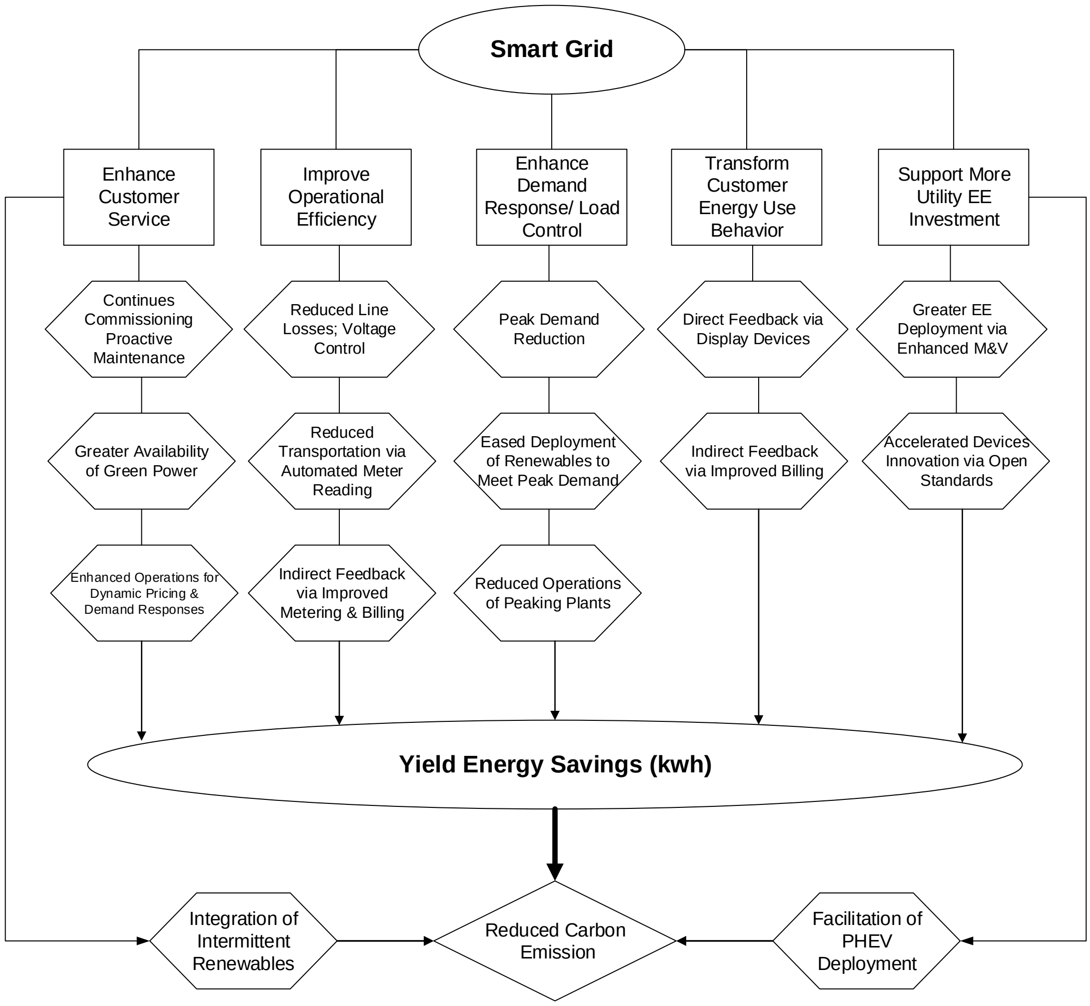


**Fig. 2.** Smart grid goals and impact on the current system
Source: Okoroigwe and Madhlopa [4].

**Table 1.** Classic grid versus Smart grid
Source: Glinkowski et al. [18]

| | **Current Grid** | **Smart Grid** |
|---|---|---|
| **Communication** | None or one-way | Two-way, real-time (fast) |
| **Ctstomer Interaction** | None or limited | Extensive |
| **Operation & Maintenance** | Manual, time-based | Remote monitoring and diagnostics, predictive |
| **Generation** | Centralized | Centralized and distributed, substantial renewable resources, energy storage |
| **Power flow control** | Limited | More extensive |
| **Reliability** | Based on static, off-line models and simulation | Proactive, real-time predictions, more actual system data |
| **Restoration** | Manual | Self-healing |
| **Topology** | Mainly radial | More networked |

4) the lack of SG standards on an international level since the concept is relatively new to the industry; 5) the implementation comes with high costs. The high cost is expected to be reduced due to economies of scale as the adoption of SG features increases.

Additional challenges and needs, especially for smart transmission grid were presented by Li et al. [17] from four aspects: 1) environmental challenges, which concerns mitigating climate change and reducing greenhouse emissions; 2) market needs, which consider the customer satisfaction through improved quality and transparency of dynamic pricing; 3) infrastructure obstacles, which focus on the aging components in the existing transmission network versus the increasing demand which leads to more congestions; 4) innovative technologies, this aspect considers the need for new materials, advanced power electronics, and communication technologies, taking into account that these areas are still not mature enough commercially for the revolution of transmission grids. A comparison between the current grid and the smart grid in different aspects is illustrated by Glinkowski [18] in Table 1.

### *2.4. Smart transmission grid*

The existing grid is composed of three fundamental phases, generation, transmission, and distribution. The majority of smart grid studies focus on power distribution, including DG and DR [17]. The transmission aspect of transforming the current grid into a smart grid is considered in several studies [20]–[22] and elaborated by Li et al. [17], who emphasize the big picture of smart transmission by introducing the framework and characteristics of the smart transmission grid by listing its required smart features to be as follows: 1) digitalization, which is done via fast and reliable measuring, maintenance, sensing, …. etc.; 2) flexibility that features in four aspects, expandability, adaptability, multiple control strategies, and compatibility with various market operation styles; 3) intelligence, through the incorporation of intelligent technologies and human expertise; 4) resiliency, via fast self-healing that enables the system to reconfigure itself after blackouts or system failures; 5) sustainability, which features as sufficiency, efficiency, and user friendly; 6) customization which facilitates liberating power market through higher transparency. A vision of an integrated smart power transmission grid is proposed by Li et al., [17]; this vision consists of three interactive smart components: smart control centers, smart transmission networks, and smart substations:

- **Smart Control Centers:** the expected new functions of smart control centers are enhanced monitoring, analytical capability for predictive security analysis, controllability through real-time proactive protection setting, interaction, and customized information with electric markets.
- **Smart Transmission Networks:** a new architecture of transmission networks is to consider providing high efficiency and quality transmission networks to ultimately balance demand and supply on national bases by linking major areas' interconnections. Smart transmission networks are also expected to enhance reliability and asset utilization, self-healing, robust electric transmission, and advanced transmission facility maintenance to reduce cost and the possibility of catastrophic failures.
- **Smart Substations:** a substation ought to be digitalized, coordinated, self-healing, and autonomous, from control centers and other substations, yet communicate with them for improved efficiency. Smart substations' functions include smart sensing and monitoring, advanced interfaces with distributed resources, diagnosis, and prognosis.

### *2.5. Smart distribution*

Today's high energy costs along with the limited funds to build large power plants to cope with the increasing demand are critical reasons for the adaptation of smart distribution through the smart grid. Distributed generation (DG) is a key concept in a smart grid that provides relief to conventional power transmission and distribution which are stressed. Instead of constructing enormous power plants far from loads and then transmitting power with huge power losses, the smart grid tends to the distributed energy resources (DERs) which are located closer to loads [23].

## 3. Distributed Energy Resources (DERs)

A DER is defined [24] as a "small scale electric generator located next to and connected to the load being served either with or without an electric grid interconnection and it is sometimes referred to as Distributed Generator". There are many types of small-scale generators or the so-called microsources, some of these types are Solar Photovoltaic (PV), solar thermal, wind turbines, and hybrid systems.

It is important to consider that the growth of the world population and electricity demand should be followed by an increase in electrical generation system assets and infrastructure improvement to keep up with the increasing need. This has been done mostly by boosting energy production by adding central conventional generators on a large scale by building Conventional Power Plants (CPPs). However, for economic, environmental, and future capability reasons, and the desire to adopt more proportions of renewable energy, recently DERs are drawing more attention. DERs are built closer to consumers, thereby, facilitate the reduction of distribution and transmission bottlenecks and losses, improves voltage profile, and delays the need for a huge investment in large-scale generation systems [12], [25]. For instance, building solar and wind power generation systems where they are needed is easier and faster than building CPPs [12]. The basic objectives of distribution systems are to improve reliability and generation efficiency, support high penetration of RESs, and dynamic islanding capability. The current electrical system suffers from poor utilization of resources. Line losses and heat wastes result in central power plants' efficiency of 35% maximum [25].

Lasseter [25]–[27] and Koh et al. [10] discussed the merits of DERs which include better efficiency by using waste heat, reduced losses due to shorter transmission to loads, and higher reliability through dynamic islanding in case of power system outages. Increased efficiency, along with controled usage of carbon-intensive fuels and boosting carbon "sinks" like forests are the acknowledged reasons to mitigate the greenhouse emissions. Kok et al. [8] refer to two key reasons to suppose that DERs are going to play a major role in electricity systems in the future. The first reason is the increasing penetration of RESs and DG, which leads to reduced controllability of the supply side. The second reason is the increase in demand as a result of growing populations as well as electrifying more and more sectors in the communities (e.g., EVs).

*3.1. Distribution management*

Managing power distribution is a similar process to congestion management, which is currently conducted in the transmission system through reservation and scheduling strategies [12]. In a smart grid, distribution management is thought to be done more smartly by employing energy markets. Advanced meters are utilized to allow the implementation of dynamic tariffs, facilitate the managing process of demand-side energy resources, and integrate the demand-side retail capability with the wholesale energy markets.

In smart grid, end users' devices like smart appliances will have the capability to make automatic decisions without interference from an operator. This is done through their vision of congestion conditions and dynamic prices which are provided through energy markets and advanced communication systems. This process helps move the grid into "Generation Following", instead of the currently conducted approach "Load Following", through load shaping strategy [12]. Multiple small generators are found to deliver higher efficiency and security than one large generator [12], [25], [28], [29].

Lasseter [25] suggests that DERs must have the ability to autonomously respond to events based on local information, to overcome any problems that might occur to controllers and software errors, which might cause systems blackouts. He argues that well integration of DERs into the distribution system results in enhanced reliability, availability, and power quality without the need for two-way command and control systems which are complex and expensive.

Mukhopadhyay et al. [24] point to a number of key requirements for the integration of distributed generators and RESs into the smart grid such as the forecasting of weather for wind and solar generation. Furthermore, controlling the redundancy or drop in DER generation. The system must be capable of self-healing (e.g., from energy imbalance) through storage devices or grid connection with real-time response. Pudjianto et al. [30] present an assessment of the value of energy storage to the electric system and determine the optimal volumes of bulk and distributed storage for an electrical system.

A distribution management system (DMS) is an important concept that represents a decision support system to facilitate the control room and system operators in a smart grid context [18], [22], [31]. Information technology integrates independently distributed facilities in a coordinated and efficient manner. Seal and Uluski [31] define the DMS functionalities that are already utilized in implemented utilities. These functionalities mostly concentrate on fault prediction and isolation, voltage management and balancing, congestion analysis, DR, and management of EVs and microgrid (MG). The role of DMS in MG is to monitor and ensure that the voltage and the frequency of the loads and the MG are within the acceptable limits.

*3.2. Microgrid (MG)*

MG concept is defined to be "the concept that assumes a cluster of loads and microsources is operating as a single controllable system that provides both power and heat to its local area" [32]. It is also defined by means of its relation to the power grid as an "integrated energy system consisting of interconnected loads and DERs which as a system can operate in parallel with the grid or in an intentional island mode" [25]. MG strategy is put forward to develop DER in power systems through optimizing the problems of large-scale integration of distributed renewable resources in the system to deliver their optimal benefits to the system. The concept of MG offers many advantages to the system in terms of improved reliability, more flexibility, higher efficiency, and fewer feeder losses compared to the distributed microsources or generators as autonomous individuals. MG also increases the robustness of the distribution system and helps it in utilizing more small RES utilities as DERs. Moreover, Zhang and Minxiang [1] state that MG facilitates keeping power balance and reduces scheduling difficulty of system dispatchers. Jing et al., [33] hybridized energy storage and demand side management to absorb the gap between demand and supply in a MG. They combined power prediction model with multi objective model to optimize the charge and discharge scheduling of battery pack to compensate for the RESs intermittency.

The main difference between individual DER and MG is the ability of MG to perform well in both grid-connected and isolated modes. From a utility point of view, MG is treated as a single dispatchable load. This single load represents a number of systems, and thus, responding time and complexity are reduced, and more controllability is afforded. The MG architecture needs a local controller for microsources (that responds in milliseconds using local information), a system optimizer, and distributed protection to cater to the needed flexibility and controllability [14], [32].

MG is created to solve the problem of RESs fluctuation which causes many difficulties to the integration of centralized and DERs into the system. [1]. It contributes to easing the complexity of managing and controlling a high number of distributed energy resources and can be effective complementary to the central power system. In addition, MG offers the DERs utilities the ability to work in islanding mode and grid-connected mode, plus the capability to switch between them, if needed. MG can disconnect from the utility during faults or collapses as well as the ability to purposely islanding from the main utility if power quality degrades beyond a certain threshold [25]. An important role of MG is to ensure frequency regulation; hence, it is responsible for compensating for any lack of power to ensure the stability of the system. Consequently, it requires an enhanced communication system as well as storage devices when working on islanding mode to regulate power in case of an imbalance between demand and generation. However, if connected to the grid, the need for storage devices becomes less urgent as the grid could be utilized to meet the energy balance. Also, over-generation needs to be handled either by reducing generation or sending the surplus power to storage or the grid, and this is a key aspect for the importance of bidirectional power flow in SG [32].

Several Challenges are faced during the implementation of MG including technology deficiency (e.g. interconnection interface), islanding standards, the efficient market mechanism (fare and safe), and proper management [8], [25], [34], [35]. Figure 3 depicts the MG system configuration. It illustrates the link between various conventional and renewable microsources and their connection to the grid.

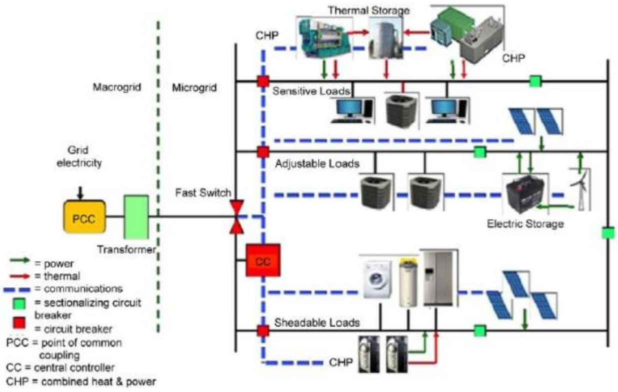


**Fig. 3.** Microgrid Configuration
Source: Seal and Uluski [31]

## 4. Integration of Intermittent Energy Sources to the Grid

The penetration of RESs to national grids is increasing in many countries. For instance, wind power covers and exceeds a load of Denmark in some low-demand hours throughout the year. This situation is predicted to occur more often in the future [36]. High penetration comes with many requirements such as prediction and load control which are key factors in the smart grid because they are critical for demand response. Integration of intermittent energy sources like RESs and EVs brings many obstacles to the system due to variability and uncertainty in operation. A variable yet predicted power source can be handled through early scheduling. However, the uncertainty introduces the need for backup supply (e.g., storage devices or grid connection) to provide the mandatory balance between generation and demand [3]. SG aims to enable higher integration of RESs to the grid by improving matching generation fluctuation to load through adjusting the distribution of the load in a way that follows the RESs fluctuation without violating the convenience of customers [18].

### *4.1. Impact of source intermittency on the grid*

The impact of rapid integration of intermittent energy resources will stress the transmission and distribution of grid operations [12]. Several issues are addressed by Enslin [37] including the need for a new and in-depth focus on system planning, the importance of accurate forecasting of loads and resources, raised the need for ancillary services, and strong interconnection. The increased penetration of intermittent sources requires an increase in regulation service provided by peaking generators which results in high emissions with the speed ramping. However, the rapid ramp-up contradicts the ultimate goal of reducing emissions and the savings gained by using RESs in the first place. To avoid this, ancillary services can be provided by consumers to support the grid balance. Further, the presence of different types of generation along with renewable intermittent sources eases the integration process since it provides the required balance through load-following capability to compensate for renewable energy sources' intermittency [37].

Additionally, the growth of EVs will increase electric consumption substantially. This increase requires advanced management and control for charging processes to fine-tune loads and curtail peaks [12]. Moreover, if bidirectional power flow is adapted to use EVs’ batteries to support the ancillary services, then the management and control processes become more complex and critical. Many aspects of the distribution system are subject to enhancements such as automation, information, condition monitoring, and asset management [7], [8], [12]. The fluctuation of sources, like wind and solar, makes the utilization of backup mandatory. Therefore, the systems with high penetration levels of intermittent sources require some or all of the following: dispatchable supplementary storage devices, demand dispatch strategy, and integration to the grid to cover temporary loss of energy due to sources’ intermittency [25].

Incentives and regulations through legislation that are set by governmental agencies are key factors to drive the development and increasing penetration of intermittent energy resources into the grid. Das and Balakrishnan [11] introduce several regulations to enhance national power shortage difficulties during peak demand moments through the integration of RESs using a virtual service value network. A service value network is defined as “the flexible dynamic delivery of service such that the value-adding service is efficiently delivered to the customer” [11]. Some of the suggested policies to encourage electrical energy providers to incorporate more renewable energy power are: 1) specify certain percentages for electric companies to procure from renewable energy sectors via regulations (such as Renewable Portfolio Standard (RPS) in the USA [38], [39]. 2) provide incentives for existing and new power plants to modernize, renovate, and enhance their efficiencies by increasing the penetration of renewable energy sources; 3) energy auditing of large industrial consumers; 4) adapting labeling programs to encourage power utilities gaining better reputation [11]. The high penetration of intermittent resources requires the combined effort of generation mix by means of using different complementary sources, advanced transmission facilities, and demand-side response [37].

### *4.2. Challenges of large penetration of intermittent sources*

The main challenging issues faced by the grid as a consequence of the increased penetration of RES include operational, forecasting, scheduling, interconnection standards transmission, and distribution [12]. Ideal locations for wind or solar power generation according to weather might be far from the existing transmission lines or consumers, hence, to benefit from such sources in optimal conditions, a new transmission infrastructure is necessary. However, transmission infrastructure development takes a long planning and implementation time, besides the high costs. On the other hand, the distribution side faces several challenges like the need for higher protection, control, automation, MG capability, and management. For the penetration of intermittent sources through interconnection to be smooth, a higher level of standardization is required. An instance of operational challenges is a high wind speed which might lead to the over-generation conditions or it could even necessitate turbine controllers to cut-off generation to prevent damage to the turbine blades. This cut-off leads to generation shortage which must be compensated to maintain frequency regulated [12].

Governments today initiate programs like RPS because the economic profile of various RESs is still not competitive compared to the conventional energy sources without incentives. It is noteworthy that storage systems are necessary for intermittent power utilities to balance the draw of the grid between conventional and RESs and maintain reliability. However, RPS became an incentive for wind and solar plant operators as well to not install storage systems since their main focus is to sell the entire generated energy immediately regardless of the regulatory requirement of the receiving grid. The challenges that resulted from intermittent resources penetration could be mitigated through distributed resources management, DR or demand dispatch (DD), EVs, and energy storage [12].

Hart et al. [3] present two strategies to alleviate the impact of intermittent energy sources on the grid. On the one hand, diversify collocated renewable resources that are utilized to generate power. On the other hand, use geographically dispersed utilities of the same renewable resource. The aggregation of either of these two strategies is facilitating the reduction of intermittency impact on the grid. National renewable energy roadmaps are needed to set policies for the diversification of RES by means of selecting which technology to prioritize in terms of commissioning as well as research and development (R&D). Using Multi-Criteria Decision Making (MCDM) Models is commonly adopted and recommended in literature to guide the decision-making process in prioritizing the RESs adoption based on many criteria and involving stakeholders with quantitative and qualitative measuring parameters [40]–[42].

## 5. Demand Response (DR)

RESs intermittency makes it difficult to schedule generation and leads to voltage and frequency imbalances. In comparison with the real-time load, both, over generation and under generation lead to a deviation from the nominal frequency of the network. In conventional generation cases, power plants provide ancillary services to the grid to normalize the frequency by ramping power up or down quickly. On the other hand, ramping is not flexible in RES's case due to its weather dependency. Thus, the increasing integration of RESs requires a simultaneous proportional boost in the conventional generation or storage to compensate for the curtailed generation caused by the intermittency to sustain the frequency level. However, increasing conventional generation contradicts the ultimate goal of decreasing fossil fuel emissions, therefore, the demand-side response is proposed [8], [33], [43]–[45].

### *5.1. Demand Dispatch (DD)*

The demand response (DR) refers to the capability of shedding the loads at peak times. The impact of reducing loads on the net power of the grid is similar to increasing generation. Today, the direct solution to demand rise is mostly increasing generation, however, the quest is towards having more control overloads to participate in providing ancillary services that are primarily provided by power plants currently. In other words, dispatching the load to match generation rather than the opposite [7]. Ancillary services through the participation of loads offer various benefits to the power system such as providing more reliable resources that are available for the system operator, enhanced system flexibility to manage variability and uncertainty, and better system efficiency [46]. DR aims at privileging the technology advance to radically shift the role of the demand-side from being passive and uncontrollable to contributing to the operation of the system depending on loads flexibility, availability, and their aggregation scheme [36], [46]. DR facilitates the electric energy system by reducing power prices, increasing awareness of energy usage, providing more efficient market operation, supporting the utilization of smart meters, and supporting the integration of renewable energy and distributed generation. Hence, DR leads to the improved economic operation of the power market [12].

Brooks et al. [7] suggest the implementation of demand dispatch (DD) as an evolutionary qualitative extension of DR. The main difference is that demand dispatch controls and aggregates individual loads at all times instead of only at peak times. DD reinforces the integration of more intermittent RESs since it improves attaining the balance of a power grid between generation and load. Therefore, the DD benefits from the flexibility that some electrical devices can offer, to compensate for the absence of flexibility from the generation side that results from using RESs [7], [44]. Dukovska et al., [47] adopted a multi-agent system model to investigate the feasibility of demand side services in the low voltage distribution networks. They analyzed the costs to benefits of different market strategies and emphasized the results dependency on regulatory frameworks.

### *5.2. Energy management*

Many concepts have been proposed in the literature to manage energy flow optimally to accomplish the maximum advantage of SG. The objective of an energy management system (EMS) comprises balancing generation and demand, preventing congestion, and providing ancillary services. In addition, EMS helps minimize generation costs, losses, and power imports [48]. Table 2 presents some of the common proposed system elements that are involved with energy management.

**Table 2.** Energy management systems for demand dispatch

| Energy management systems | Description |
|---|---|
| Aggregator | An energy service provider in the system is meant to provide an interface between the grid operator and individual loads. It aims at delivering the needed energy to loads, and an accepted aggregated demand dispatch to grid operators at the same time [7], [36], [47], [48] |
| Energy Manager | A similar concept to an energy aggregator but meant for the MG system. The task of an energy manager takes place when MG is connected to the grid. It grants system optimization by determining the amount of power drawn from either the microsources or from the main grid. The energy manager needs to perform many functions such as ensuring loads are met, maximizing microsources operational efficiencies, and minimizing emissions and losses. However, when the MG is on islanding mode, the energy manager is not used except to facilitate the process of reconnecting to [32], [49] |
| Real-Time Power Market (RTPM) | An energy-trading service through bids and offers. RTPM is an efficient approach to meet future hardships of balancing, supporting the spread of DERs, and increasing power markets competition [8], [36], [50], [51] |

Transforming the consumer from static (inactive) to a dynamic (active) segment of the electrical system is important in shifting some responsibility of balancing the system to the demand side. Bakker et al. [52] introduced a control methodology for the optimized management of demand-side load which is based on three steps. The first step starts with a prediction of the generation and consumption patterns of the customer microsources and appliances for the coming day. The second step is done by using a central planner to exploit the potential to set system objectives (e.g. compensate fluctuation). The third step is a real-time control algorithm that decides when to switch appliances on or off [53]. Consumer comfort is always prioritized in any control strategy, thus, any conflict between planning or error in prediction with the customer choice will be solved to the advantage of the customer. This ensures the comfort of the customer as well as the optimization of demand side control. Different control methodologies are proposed by other studies. One important methodology among them is the Power Matcher.

*5.3. Power Matcher*

Power Matcher is an intelligent distribution coordinator software for energy real-time power markets, which are complementary to the regulating power market that addresses large conventional generating units [36], [54]–[56]. Power Matcher is invented by Netherlands Organization for Applied Scientific Research (TNO) [57]. It coordinates electric devices of DERs (producers and consumers) by implementing complex and distributed Information and Communication Technology (ICT) systems through software agents' interactions. Power Matcher targets the vast number of DERs, storage devices, demand response appliances, and electric vehicles that will contribute to forming the future electrical system [8], [54].

Power Matcher organizes information exchange between agents (e.g. smart appliances and EVs), and the market auctioneer who is responsible for the price forming by searching for price equilibrium. The Power Matcher could be utilized in two ways, it either receives price signals and forwards them to the end-users (e.g., Ecogrid UE project [36]), or receives bids from the end-users. (e.g., the approach introduced by MacDougall et al. [54]) in which the information exchanged through Power Matcher is the bids that represent the level of priority or flexibility each agent is willing to give. Accordingly, Power Matcher calculates the market-clearing price, which means the equivalent point or net point at which the entire energy production is directed toward the appropriate consumers based on their bids [54]. The information then is sent to agents and they act accordingly by producing, consuming, or waiting. Power Matcher is attached to devices allowing them to trade in the energy market [8].

It should be noted that taking advantage of consumers' flexibility for scheduling is a critical task. MacDougall et al. [54] proved that improper forecasting of power consumption could yield a later inability in the system to satisfy its obligations. Power Matcher considers coordinating consumption based on information from the auctioneer without the need for previous scheduling. Through the pilot, Power Matching city, and large scale Virtual Power Plant (VPP) simulation, Kok et al. [8], [55] illustrate that Power Matcher is a scalable technology that proves its ability to enhance the wholesale market for energy trade and participate in managing energy distribution via optimizing the utilization of consumers to their own produced energy, which is denoted as "prosumer" referring to producer and consumer at the same time. Power Matcher also facilitates optimizing the usage of renewable energy resources.

Contrary to bidding market solutions, the "Ecogrid EU project" is a bidless market that depends on real-time electricity price signals. It aims to enable small-scale DERs and small-end customers to contribute to the energy market by deducting barriers such as the requirements on size and online services. Furthermore, the project facilitates lessening the administrative regulatory burden including the bidding in the market [51]. It is worth mentioning that this bidless scheme does not interfere with the balance responsible party which uses scheduling and bidding for day-ahead planning. Instead, it is meant to replace the short-term interval bidding and the auctioneer methodology with the real-time market operator that sends price signals every five minutes. Accordingly, the aggregators, DERs, and end-users react. This project illustrates that information and communication technology (ICT) and innovative market solutions can enable the operation of DERs with more than 50% penetration of RES. In Ecogrid EU, real-time prices are equal to the day-ahead schedule unless imbalance or congestion occurs. Therefore, production and consumption are modified according to price signals to sustain the balance of the grid [36].

*5.4. Shifting demand and dynamic pricing*

To understand the importance of optimized scheduling, it is important to realize that almost 20% of the generation exists only to cover peak demand, which occurs only 5% of the time [25]. 17 countries have yet applied the Time of use (ToU) tariffs including USA, Sweden, Germany, India, and France. In a pilot project in Sweden, 23% of the total electricity consumption was found to occur in the most 5 expensive hours. Applying the ToU tariff helped reducing this percentage up to 19%. Additionally, over 200 kWh representing more than 5% of the consumed electricity was saved through a demand response programs in the USA in 2015. In Europe, the potential power capacity to benefit from the demand side management through real-time pricing and advanced metering is estimated to be 1,520 GW [58].

Shifting demand and dynamic pricing techniques aim at optimally utilizing electrical system assets through using the flexibility that can be offered by households in the best possible way while maintaining their comfort at the same time. Privileging this flexibility on a large scale leads to incredible results [54]. Dynamic pricing produces self-interested agents, which leads to electric consumers who seek to shift their consumption to low demand (i.e. low price moments), and producers who seek to shift their production to high demand/price moments. This scenario results in a better balance in terms of demand and supply [8]. Bakker et al. [52] illustrate how advancing and postponing the switching points over the planning horizon facilitates altering the energy profile.

Load control services are classified based on time scales from hours to less than a second. In today's grid the power plant ramps generation up or down following the load in an approach called "load following". This approach faces many challenges, especially with the increased penetration of RESs. Power plant ramping is slow and accelerates the wear and tear of the equipment. It also drives higher levels of emission. Moreover, the ramping rates of power plants are limited. Add this to the dependence of RESs on weather conditions which leads to a further limitation of the ramping process. Therefore, dispatching loads is a trending approach to complement generation dispatch [7]. This approach is called "generation following". Based on the load, the "generation following" is conducted on hours, minutes, seconds, or less than a second basis. An instance of the hourly-based class is wind generation, in which wind speed is forecasted for the following hours (maximum one day accurately). Based on the wind forecast, loads are dispatched to follow the generation. For minutes or seconds class, the dispatch is regulated with ancillary services every four seconds to balance the generation and demand [7], [59]. Ancillary services are provided today by power plants, but the goal of the "generation following" approach is to make loads and storage devices participate in delivering the ancillary services to the SG [7], [12]. Figure 4 presents the difference between the scheduled and unscheduled loads. It illustrates that a higher utilization factor can be achieved through optimized load scheduling.

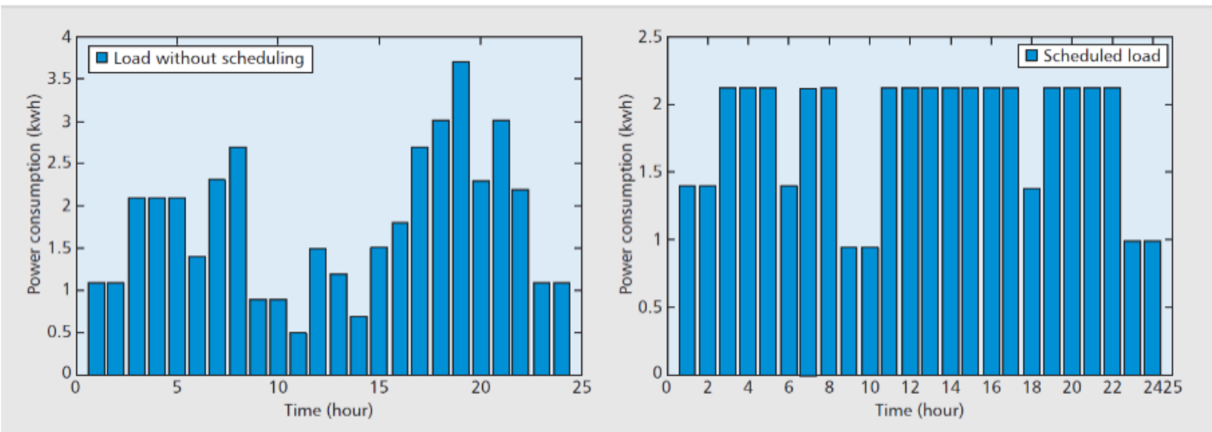


**Fig. 4.** Hourly load over the day, (Lift): without scheduling, (Right): with scheduling
Source: Lambotharan et al., [44]

*5.5. Regulation ancillary services*

Ancillary services involve proportionally small amounts of energy. However, they are essential and valuable energy capacity held in reserve because of the technical capability to respond quickly and reliably to imbalance incidents in the system. Ancillary services are provided in many forms including regulation services (moment-by-moment), contingency reserves (spinning and non-spinning), and flexibility reserves (respond to large unexpected wind and solar ramp events) [46]. Amongst ancillary services, regulation is the most important because it requires the fastest control and response [7]. DD is appropriate to provide regulation to the system. Precise criteria are set for the candidate loads to be controlled for providing regulation ancillary services as follows: 1) loads that would not cause inconvenience to the customer if they are controlled remotely; 2) loads that need a known amount of energy; 3) loads that have a slack time, which means they need only some of the available time they are plugged in to use energy; 4) loads that do not have critical time to be turned on. Instances of such loads would be, EVs, dishwashers, electric water heaters, etc. The impact of dispatching millions of individual loads is predicted to be enormous in coordinating the ancillary services for the grid. Up to 33% of loads would be capable of meeting the above conditions [7]. It is worth mentioning that when regulation is provided by the power plant, regulating up means increasing the generation, and vice versa. On the contrary, when regulation is provided by the demand-side, regulating up dispatch means decreasing the load and vice versa. Demand dispatch is intended to involve the coordinated control of an enormous number of loads. This comes with many obstacles such as software bugs and human errors. To mitigate such risks, several approaches are suggested such as putting limits on the size of aggregation entities and integrating sanity check commands to end users' loads [7], [46].

## 6. Electric Vehicles (EVs) for Regulation Ancillary Services

High penetration of EVs will result in raising load peaks significantly and thus charging coordination becomes essential. An EV could almost double the electric consumption of a household especially if homes are heated using other energy sources than electricity [8]. The EVs industry is developing rapidly in today's market. EVs meet the conditions to be good candidates for providing ancillary services to DD for the grid while meeting car owners' needs [35].

An average EV needs 2-5 hours of charging time (10 kWh) and yet it could be plugged in for 10-15 hours a day [7]. Therefore, EVs could be aggregated to provide dispatchable load resources. EVs are connected to the grid for power and the internet for communication. In conventional grids, information flows in one direction from utility to loads, whereas, in SG communication is bidirectional between the utility and the MG or DERs [60]. Therefore, when an EV is connected, it immediately communicates with an aggregator to inform it of the vehicle profile including its location, the required energy, and the time at which the owner needs the car to be ready. This profile information is set in a default mode by the owner and could be altered online [61]. The aggregator then determines how and when the car must be charged taking into consideration a balance between driver requirements and grid regulation. The driver can request an immediate charge if needed. The aggregator receives prices generated by dynamic pricing coordinators, such as Power Matcher [55], [57] to optimize service provision at low peak time (low price) taking into account scheduling the aggregation of EVs to form a balanced power usage profile.

Brooks et al. [7] suggest that the aggregator should follow the four-second class, which means the aggregator updates its information from the grid operator every four seconds. Accordingly, it determines which vehicle charging states ought to be altered (turned on or off) to achieve the grid power regulation and at the same time meet the needs of each vehicle. Smart charging of EV would take a longer time than regular charging. However, it prioritizes the needs of consumers and at the same time optimizes the utilization of "slack-time" and provides incentives to users who offer more flexibility in charging time. EVs can help in the load shaping strategy, to participate in achieving the "generation following" approach. A distribution management system could be used to reduce the demand of a given substation feeder by limiting the amount of fast charging to curtail the demand [31]. When EVs are treated as an aggregation they represent enormous storage capacity.

Vehicle to Grid (V2G) capability is a concept that is introduced to enable EVs to facilitate the ancillary services of the demand side. EV batteries are designed with the ability to fast charge, for drivers' convenience when needed, and fast discharge with fast acceleration and other conditions which need a burst of power. Therefore, they can participate in providing ramping and power regulating to support the grid through peak shaving and load balancing [6], [12], [31]. EVs can contribute to balancing fluctuations of renewable energy [48]. Dehaghani and Williamson [62] shad light on the concerns that make the V2G concept questionable such as the degradation of EVs' batteries due to many charging and discharging cycles and the effect of EVs owners' behavior on the reliability of the grid since their main concerns would be using their vehicles instead of satisfying grid needs.

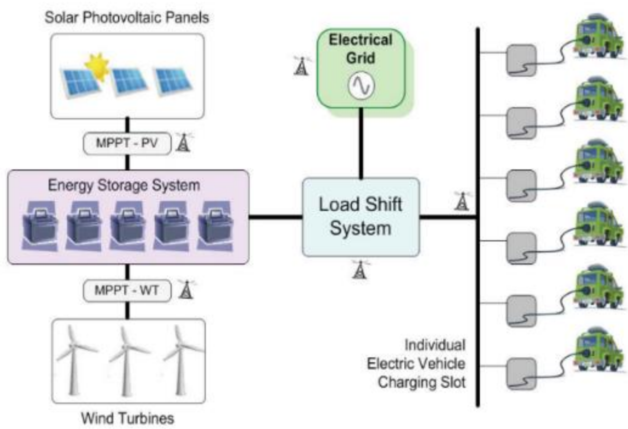


**Fig. 5.** Integration of PEV, RES, and storage systems to SG Source: Monteiro et al., [63].

## 7. Conclusions and Future Research Directions

This research presents a comprehensive review of the integration of intermittent renewable energy resources (RESs) into a smart grid (SG). The concept of SG, its motivations, and challenges are reviewed. Concepts like distributed energy resources (DERs) and microgrids (MGs), which are proposed in the literature to support the decentralization of energy generation and to ease the cooperation between large-scale grids and DERs, are presented and discussed.

The intermittency of RESs is a critical issue that brings challenges and strongly influences the power system frequency. Therefore, generation uncertainty and fluctuation are important factors to be considered to benefit from renewable energy. The need for SG and RESs led many researchers to seek solutions to overcome the current shortcomings of these systems. The current study shed the light on many proposed solutions in the literature such as demand response, demand dispatch, dynamic pricing, energy management, regulation ancillary services, and electric vehicles.

Communication represents the backbone of SG to facilitate the utilization of increased penetration of renewable energy, thus the advance in communication technology is essential for the reinforcement that is needed through information and communication system.

Researchers in the field of integrating RESs to SG need to carry out original work in both long-term planning and short-term operation. In terms of long-term planning, it is necessary to develop models for selecting and ranking the priority of different RESs technologies utilization to formulate national roadmaps, thereby optimally achieving the diversification of RESs that facilitate the enhancement of aggregated intermittency. Adopting RESs integration to the current electrical grid includes complex decisions related to different sectors and many stakeholders that are involved in RESs projects, hence proper planning and decisions are mandatory to assure steady and reliable electrical supply.

The quest for complementary DERs is proposed in the literature to be combined with central generation to facilitate the integration of RESs to enhance system reliability, improve efficiency, reduce greenhouse gas emissions, and postpone the need for new large-scale central power plants and transmission lines. However, there is no abundance of studies to illustrate what is the optimal combination of central and distributed generation to achieve the most cost-effective, sustainable, and resilience system, or to what extent will replacing the current central system with a fully distributed system improve the aforementioned parameters in the electrical system.

Another important research direction is the transformation of consumers from passive into an active part of the system that assists in providing regulation ancillary services to curtail power plants' burden. Nevertheless, the sufficiency of services like customer demand dispatch and electric vehicles to provide sustainable regulation ancillary services is still questionable in the literature since the priorities of consumers might contradict providing reliable regulation ancillary services.

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