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Review

Smart grids and renewable energy systems: Perspectives and grid integration challenges

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ABSTRACT

The concept of smart grid (SG) was made real to give the power grid the functions and features it needs to make a smooth transition towards renewable energy integration and sustainability. This was done by automating and digitizing the grid to give it the right amount of flexibility and reliability, while also giving it the ability to easily handle future changes. The need for SG exponentially increases as more variable renewable energy sources are integrated into the power system, with the power grid and the electricity market gradually being transformed from a centralized to a more distributed form. In this respect, the objective of this review paper is to highlight the pertinent challenges associated with SG that are necessary for its progressive practical realization from the perspective of user-end acceptance as well as operational flexibility for power system planners and operators in terms of regulatory and serviceability needs. Furthermore, it intends to highlight the complexities of power system related to planning, operation, and installation considering renewable integration, such that, the progression and utilization of SG can be quantified while highlighting research gaps that could potentially have a catastrophic impact, such as, standardization and protocols related to contingencies a especially black-start process. Therefore, a bottom-up approach for reviewing SG is carried out in this paper, which provides an in-depth presentation on the description and challenges associated with renewable integration, energy storage systems, security, and interoperability, along with comprehensive discussion on progressive research on their potential solutions and countermeasures.

1. Introduction

The global electricity sector is currently facing numerous challenges with its transition towards utilizing renewable energy sources (RESs) to meet electricity demand. Currently, the energy sector is predominantly linked to the availability of natural oil resources. Renewable energy (RE) sources facilitate establishing a sustainable electricity supply; nevertheless, they significantly impact reliability and power quality as they are stochastic, uncontrollable, variable, and mostly unpredictable. In addition, most of the commonly preferred RE technologies do not provide inertia support, which makes the grid vulnerable in the event of fault conditions. Overcoming these challenges requires additional auxiliary support systems and, more importantly, a monitoring and communication network. The present grid requires upgradation for various operational aspects related to the grid that range from generation, transmission [1–3], and distribution, including operation, as well as power system planning, in order to retain grid flexibility to encompass grid transformation and diversification [4–6] to facilitate both short-term and long-term uncertainties introduced with RE integration (see, e.g., Fig. 1).

The contemporary electric power network around the world has been developed over the past decades. It supplies electrical power from a central generation unit through transformers and various levels of the transmission network. The ratings of the central generation units, whether nuclear, hydro, or fossil fuel, go up to thousands of MW. The large generation units are currently connected to a transmission network that has a good communication framework. This allows for acceptable or at least commercialized system operation with enough security and reliability while maintaining a coordinated energy market [7]. So, the distribution network has a higher level of network complexity and a relatively low number of integrated communication links. This makes it harder to use modern control theories to control the distribution network at the local level. Similarly, communication links severely lack real-time monitoring to feasibly regulate the power quality of large loads, wherein the link only ensures the supply of power in accordance with the load demand [8].

Modern technological advances in communication systems allow for a much higher level of monitoring and coordination, which allows

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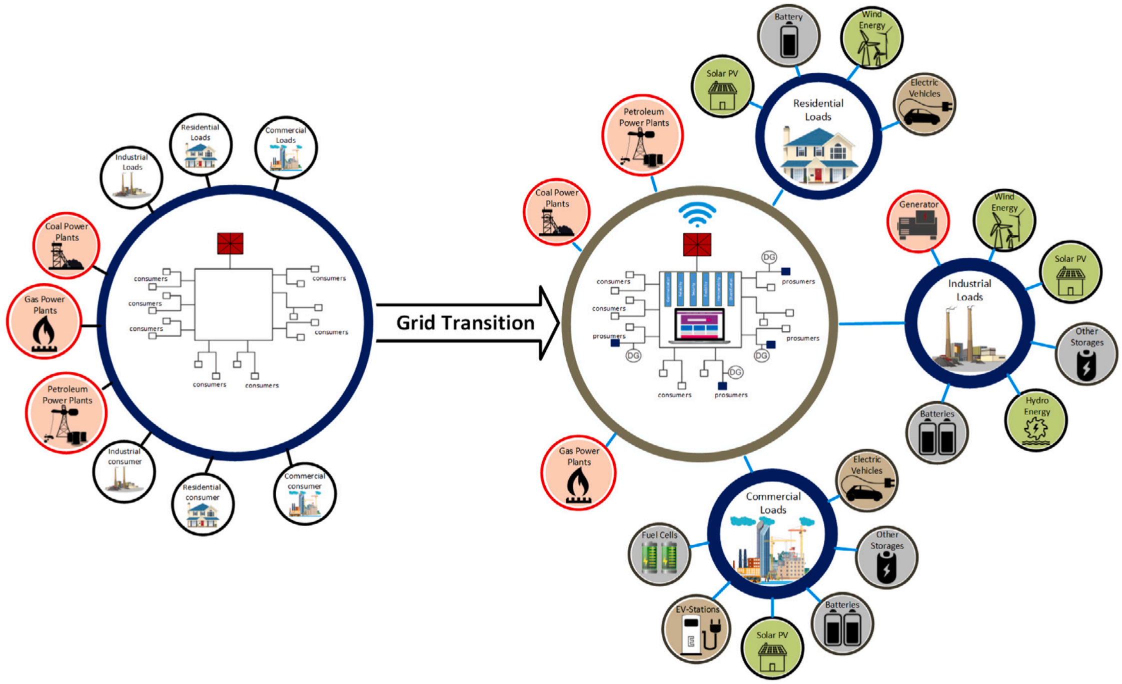

Fig. 1. The transition of power grid towards smart grid with diversification and distributed generation.

for better grid monitoring, controllability, flexibility, and lower operational costs, which is in line with the modern trend of integrating REs. In this respect, the concept of establishing a smart grid (SG) provides the accessibility to implement information and communication technologies (ICTs) to modernize the power network system [9]. Nevertheless, the large-scale network of present power systems imposes the need to establish an optimized SG that is justified considering the multi-faced requirement of the grid in terms of communication, sustainability, interoperability, and power quality to maintain the techno-economic significance of the entire network [10].

Concurrently, the present transition towards decarbonization for environmental preservation demands the inclusion of RES for establishing a sustainable power system and supplying the ever-increasing electric load demand. This generation-side transformation of the power system requires a higher degree of communication networks to maintain grid integrity [11]. Most of the current RES technologies are highly topographically and environmentally dependent, which makes them unpredictable and uncontrollable, consequently limiting their large-scale integrability into the power grids. This additionally requires demand-side management as well as innovative strategies in the field of renewable integration [12]. The efficacy of most solutions available in the literature in these fields, for instance, renewable forecasting, peak clipping, load filling, power electronic converters, smart meters, and smart inverters, require a state-of-the-art communication network [13]. Therefore, the establishment of an effective smart grid ensures viable management of the loads, considerable reduction of system losses, reduction of energy wastage, accurate data monitoring, and flexibility of expansion and integration in the power system network.

Similarly, the electricity grid, consisting of unidirectional communication, centralized generation, limited sensing devices, manual checks, and maintenance, allows customers limited options of participation. In this respect, SG is focused on providing enhanced efficiency while maintaining generation diversification with updated processes in terms of flexibility, self-healing, resilience, reliability, customer involvement, and security through intensive observability, controllability, and automation by utilizing intelligent and digitalized energy solutions [14–18].

A systematic transition towards SG development is observable globally, with concurrent intensive innovation in each domain of the SG framework considering their respective challenges [19–23]. However, at the same time, the multi-faced theory and application having of multi-disciplinary research and industrial development need to consider the technical, economical, and social requirements of the participants. In terms of the power grid, the technical challenges include flexibility, resiliency, and reliability to allow diversification and distributed transformation while being able to suitably maintain the power quality, stability, quality, and flow. The power system operators and planners ensure the technical as well as economic viability of the SG; therefore, research efforts towards better interoperability will ensure the development and formulation of standards and protocols that will allow the integration of existing as well as developing SG technologies of energy, communication, and information to be concurrently and expeditiously integrated into the grid operation with the potential to lower the overall cost through technological diversification.

Socially, governmental incentives encourage customers to upgrade to prosumers and participate in the electricity market. The progress of SG realization and expansion depends on the social aspects related to transparency, which include security, justice, and trust between the participants of the SG [24–28]. In this respect, numerous conceptual, terminological, and componential analyses of SG have been extensively presented to outline its foundational understanding and technological operation [29–33]. Also, to speed up the visualization and creation of SG, analytical, strategic, and business models such as strengths, weaknesses, opportunities, and threats (SWOT), political, economic, sociological, technological, legal, and environmental (PESTLE), etc., have been presented to promote the feasibility of SG. These models have helped to show the relevant factors that are hindering the successful implementation of SG [34–37].

Based on the available literature models, this review paper focuses on the perspective of power system planners and customers in terms of the required technological innovations and considerations needed for the accelerated development and implementation of SGs. compared to some recent works in [25,38–40], this study makes a substantial contribution by effectively amalgamating current knowledge in the fields of SGs, RES, energy storage, and communication systems in a comprehensive manner. Significantly, the study precisely delineates areas of inquiry that have not been well addressed, so providing direction for future research and serving as a helpful reference for academic researchers. The paper's value is enhanced by its practical focus on difficulties and solutions, as well as its distinctive bottom-up methodology. The review focuses on current developments and addresses contemporary concerns in the power sector, so maintaining its relevance to ongoing conversations. Furthermore, the aim is to build the bridge between the strategic reviews and quantifying their technological equivalents in terms of SG technologies by highlighting the identified SG analytical models presented and translating them into technological research advancements and focus areas needed for SG realization.

While numerous reviews have provided suitable outlines for SG terminologies and development. The current work places significant emphasis on delineating research gaps that have the potential to impede the ongoing development of SGs. These gaps include, but are not limited to:

1. **Standardization and Protocols:** The paper brings attention to the current deficiencies in standardization and standards pertaining to SGs, particularly in regards to the management of contingencies and the black-start procedure. The current work also reviews the challenges associated within SGs digitization, the integration procedures with green sources and storage systems, and the modern communication scenarios within power industry.
2. **User-End Acceptance:** This study examines into the difficulties related to the acceptability of SG technology by end-users, specifically examining the gaps in society's view and acceptability that need to be comprehended and resolved.
3. **Operational Flexibility:** The review highlights deficiencies in attaining operational adaptability, particularly in light of the growing incorporation of intermittent RESs and storage facilities. The work also highlights the deficiencies in security measures and interoperability standards that arise due to the intricate nature of the power system and the incorporation of various SG technologies.
4. **Discussion on Progressive Research:** This work also address the current gaps in knowledge by offering a thorough examination of advanced research, potential solutions, and countermeasures pertaining to the issues faced by SGs.

The purpose of this review is to lay the groundwork for future research on SG technology by dealing with these research gaps.

The main aim and contribution of this review paper is to highlight the need for SGs in the context of complex, exhaustive aspects related to renewable integration in terms of power system planning, operation, installation, and grid integration. Hence, a framework for SG architecture is presented, and in concurrence, systematic power system challenges related to renewable integration are described in this review. The review paper targets providing a state-of-the-art comprehensive review of the definition and research advancements achieved that will benefit upcoming researchers, policymakers, and global energy regulators as guidance towards focusing their industrial as well as academic focus towards renewable and sustainable energy development.

The remainder of this paper is outlined as follows: Section 2 discusses the definition and types of smart grid components with their current and future technological inclinations. In Section 3, the many challenges of renewable and smart energy systems are described with a detailed framework. In Section 4, the importance of energy storage systems is explained with a detailed presentation on the many ways that energy storage can be used to help integrate renewable energy. Section 5 presents the technologies related to smart communication and information systems, outlining the associated challenges, innovations, and benchmarks. Section 6 presents the present summary on specific problems in power networks resolved by SGs. Finally the discussion and conclusion was presented in Section 7 and Section 8, respectively.

2. Smart grid: Digitalization of electric network

The interest in the field of smart grids originated at the beginning of this century. The advancement and development of information and communication infrastructure led to the recognition of its applicability in electrical networks and its pivotal and realistic requirement to establish renewable-based sustainable energy systems in terms of monitoring and effective energy decarbonization. Additionally, the need for a smart grid also coincides with several current requirements of the electrical system. Firstly, most power system networks around the world related to the equipment installed at the transmission and distribution networks as well as the generation system are now utilized up to their life expectancy and consequently require replacement. Therefore, the cost to refurbish and categorically reinstate them at their technological level might be very costly, and additionally, the need for corresponding skilled staff is lacking. This provides the opportunity to innovate the existing power network to not only meet the quality of supply but also to comprehend the technological gap both in infrastructure and human resources [41–43].

In the same way, the fluctuations that occur when RES are added to a traditional power grid make it hard for them to be used, especially at the transmission level where power is already being sent at full capacity [44,45]. This hinders the integration of RESs in the power network and, conversely, affects the dire global need for a sustainable energy sector. In similar terms, the thermal constraints of most of the existing electrical lines at the transmission and distribution levels limit their power transfer capability. Over-loading, that is, the transmission of current in excess of the thermal limits of the electrical line, will cause an accelerated deterioration and life reduction that reflect an increased probability of fault occurrences. Therefore, the need for dynamic ratings is pertinent, as these thermal constraints are also environmentally dependent [46–48].

Second, the voltage and frequency limits established for the power system largely determine the operational constraints of the power system. The network experiences insulation damage that ultimately progresses to short-circuit faults and equipment malfunctions with system tripping due to over-voltage and under-voltage conditions, respectively. These challenges were conventionally mitigated through wide-area interconnection at national and international levels and solved using voltage regulation equipment such as on-load tap changers [51,52]. Similarly, in terms of system frequency, that requires instantaneous monitoring through the demand-generation profile. A small deviation in frequency causes desynchronism and is maintained using mainly automatic generation control (AGC) strategies; in emergency cases, load-shedding strategies are also prescribed. Therefore, considering the dynamics of RES, which undergo unpredictable output power fluctuations, the need for rapidly responding control strategies and equipment is needed, and most of the conventionally developed solutions prove to be inefficient [53–55]. Based on the presented solutions pertaining to RE integration, a combination of forecasting, energy storage systems, spinning reserves, reliability, and system flexibility is mostly prescribed to maintain the techno-economic viability of the overall operation. Nevertheless, most of these solutions require system upgrades in the form of state-of-the-art communication for data acquisition, data processing, and optimization.

Finally, the usage of electricity has now been incorporated into many critical fields and human welfare that are classified as critical loads. Ensuring a reliable and secure power supply to these loads is necessary, and previously, redundant circuits were installed that required high capital costs due to environmental negligence. In this perspective, the establishment of smart grids ensures an intelligent framework that empowers algorithms for post-fault detection with appropriate optimal utilization of each element in the power network, thus obviating the need for redundant circuits. Therefore, the establishment of smart grid ensures a transition from the conventional grids to a modernized network that facilitates cooperative and responsive interaction [56].

Table 1
Characteristics of smart grid technologies in terms of power grid terminologies [49,50].

Category	First generation smart grid	Second generation smart grid
Customer interaction with Energy and Information	Utilization of data from smart meters enabling actor-based electricity management, storing, and generation.	Automated and/or autonomous initiatives towards electricity production, storage, and management based on incentive-procuring patterns.
Market	Assets of the energy market are managed between the participants. Predominantly, involves third-party dependency to enable Peer-to-Peer (P2P) trading.	Introduces smart contracts, enables P2P trading allowing generation controllability to actors. Obviates the need for third-party dependency.
Operation	Electricity flow is managed by the operators with the actors based on the current state information of the power grid.	Electricity flow is managed through real-time data between the operators and actors. Enables plug-and-play feature in the information and power data.
Interoperability	Multiple standards for interoperability for various structures and approach of grid formulation.	Internet Technology based universal protocol.
Generation	Decentralized or centralized supporting coordination and operations of auxiliary components	Decentralized or centralized supporting coordination and operations of auxiliary components
Transmission	Management energy and power flow from the generation to load.	Management energy and power flow from the generation to load with operational support facilitating coordinated asset management and power quality regulation.
Distribution	Enables prosumers participation in energy market with limitations from the capability of the third-party and technology implemented.	Enables prosumer participation with diversified energy source integration and with easy foundational support to contribute towards the power quality through storage and other auxiliary devices without the need to third-party intervention.
Physical Controllability	Focused on electric power system.	Power system and extendable to transportation, as well as natural gas.
Energy form	Mostly electric energy.	Electric, thermal, and chemical energy.
Optimization Capability	Localized	Localized as well as wide area co-ordinate.
Energy Transferability	Network architecture with power and communication channel for power supply management.	Layered architecture with P2P mode of power supply management.
Information Accessibility	Bi-directional communication channels.	Performed though the internet protocol.
Security Concern	Information and data leak predominantly due to diverse protocols and third parties.	Machine-to-machine communication obviating third party fallacies. Security threats pertaining to the information, data, and access to components exist. Furthermore, increased interoperability increases device inclusions with lower degree of security, such as non-PC devices. This can increase the risk of security threats.

This also enables and encourages the introduction of pro-consumer-based contributions into the energy sector, which is inherently pertinent to establishing a deregulated power network that is needed considering the limitations and requirements of the current RES technologies. Furthermore, activation of high-grade bi-directional communication in smart grids allows the incorporation of a complex intelligent algorithm that enhances the robustness and self-healing capability of the power network. Modern electricity sectors are globally encouraged to transition towards smart grids. This is mainly to systematically achieve net-zero carbon emissions in the energy sector while maintaining minimal impact on the environment and simultaneously establishing technologically advanced power systems that are compatible with end-users. These factors are not only initiating good corporate citizenship, but some countries have also taken the initiative to impose regulations for limiting carbon emissions and legislatively introduced incentives towards infrastructural modernization and smart grid transformation.

Furthermore, the concept of internet-of-energy (IoE) has been formed considering the practical development and operation of smart grids and smart cities around the world in terms of interoperability [57–59]. This is also referred to as smart grid 2.0 or second-generation smart grid, which postulates the associative advantage to direct towards internet-connected SGs that will prove beneficial to its actors and components in terms of enhanced communication capability, big data handling, and optimization. Still, both smart grid approaches lead to the same goals, which are: (i) the grid's ability to make decisions on its own; (ii) communication between the grid's parts and actors; (iii) multiple ways to send energy and information about it; (iv) easy control and operation of a variety of distributed energy sources with different power ratings; and (v) the ability to switch between a centralized and decentralized power system [33]. Table 1 outlines the characteristics advantages and disadvantages of the first and second generation of SG in parametric requirements of a renewable integrated power grid.

Dealing with an increasingly complex system along with the trend towards a distributed approach in all aspects of energy, communication, and information, the basic concept of SG establishes these objectives following a centralized approach. This consists of the utilization of ICTs (i.e., sensors, smart meters, etc.) that are allocated at substations and the consumer end for monitoring, controlling, and regulating the energy exchange between the producers and the customers [59]. Accordingly, IoE facilitates machine-to-machine (M2M) communication that allows the obviation of third-party intervention in the process of energy exchange between the producers and the customers. While M2M enables better interoperability with a foundation to appropriately implement artificial intelligence, machine learning, and other state-of-the-art internet technologies that remove the trust and leakage issues associated with third-party delegation, many issues still exist that are associated with security, costs, corporate structure, transition, and a high degree of interoperability, leading to the integration of non-PC devices that have low protection against threats [49,50,60,61]. So, as the power grid slowly moves from a centralized to a decentralized architecture, many new technologies have been created and proposed to support a systematic decentralization of the communication and information infrastructure of the smart grid. These technologies are based on new and standard models that have been used successfully in other parts of the industry [62].

3. Challenges of renewable energy sources

RE sources are inherently intermittent. Due to the uncontrollability, limited dispatchability, and intermittent nature of the power from the most common renewable energy sources (wind and solar), dedicated ancillary services, such as spinning reserves and other regulatory operations (Fig. 2), are needed to ensure reliability and operational needs. The figure facilitates a visual representation of the ancillary services needed for viable power network operation that are required in numerous aspects for maintaining power quality across all the planning horizons associated with power systems. Furthermore, one of the main root causes of RE integration is the potential rapid variation of the generated output power. This, in combination with existing load variability, increases the stochastic nature of the entire power network. Therefore, the complexity, as well as the support systems, need to be enhanced and upgraded.

Seemingly, the existing power network is centralized, dealing with bulk power generation transmission, and distribution projecting a lower degree of energy measurements and generation management in accordance with the requirement of comparatively rapidly varying RE sources. Similarly, at the distribution level, the complexity is limited to maintaining the power quality of the supplied power, where generation management is not considered. Systematic RE integration on both the generation and distribution levels will require a coordinated system upgrade to monitor, control, and regulate the RE-integrated generation framework. Specifically, the current distribution level will require upgradation in terms of monitoring and control to suitably enable optimization, reliability, and security to ensure flexible operation of the diverse small-scale renewable-based generation systems as well [63]. The main idea is to necessitate an optimized quality of power flow and supply while reducing the complexity of stochasticity.

While the existing power network is equipped to deal with load variability, the stability, controllability, and other auxiliary support provided by conventional synchronous generators for reducing the impact of load variability will significantly decrease in the case of RE integration. Hence, replacing or transforming the capacity of synchronous generators will require a systematic re-enforcement of the grid while considering the time-scale variability, i.e., the rapid fluctuation of the RE sources. For instance, wind turbine output varies with available wind speed. Typical wind turbine output increases dramatically with variations in wind speed from 5 ms^{-1} to 13 ms^{-1}, achieving 100% output from a modest 8%. Wind turbines often operate in this window, producing extremely fluctuating outputs. Wind speeds above 13 ms^{-1} to around 25 ms^{-1} maintain 100 percent output, but above 25 ms^{-1}, the output becomes zero [64]. The outputs of wind turbines change over time due to the varying wind speeds, and the generation that these machines produce can only be predicted to the same degree as the weather.

The high penetration of wind power may also result in more generation than is required during peak hours. Accurate wind and solar production forecasts are necessary to enable other unit commitments and extra services while preserving the required hourly ramping, which would require more intelligent equipment and algorithms to compute the unit commitment. In addition to energy, regional scheduling procedures for intermittent resources must be improved further to accommodate the energy market requirements [65]. The major issue is determining an effective model of the RE sources and forecasting their production. Wind and solar energy need substantially more intensive forecasting and scheduling due to their applicative scope, intermittency, and fluctuating nature [66].

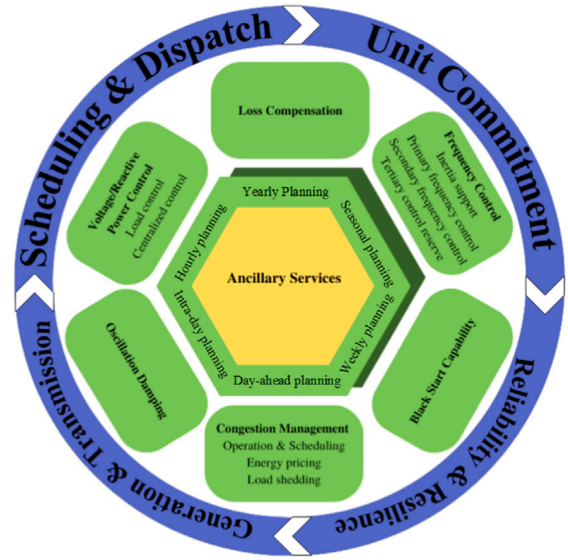

Fig. 2. Ancillary services for appropriate performance of electrical energy systems.

Short-term and long-term forecasts of renewable energy production and weather must be evaluated and investigated [67–69]. In contrast to conventional generators, the unpredictability of RE sources limits their operation at full capacity, especially at peak hours, and supplies additional load demands as it makes the system vulnerable to instabilities and power failure. As a result, networks that incorporate RE sources need sophisticated energy management systems based on electricity availability, demand, energy unit pricing, storage, and generating costs. Furthermore, RE output might be considered noise by the grid if it accounts for under 5%–10% of total demand [70]. Similarly, the intermittent nature of RE sources creates complications for the planning of the day-to-day operations of electric networks.

Since RE fluctuates across many time horizons, operators are required to readjust the system operation in real-time, for a few hours, or with day-ahead planning. Therefore, to meet the load demand, the conventional generation system must be varied all the time as the RE output varies every minute. This cycling operation proves to have a negative impact on the system, as it puts the generators under pressure but also decreases their efficiency. This issue becomes significantly more pronounced when combined with variable load demand. Quick variations in solar or wind energy outputs affect the grid's hourly load-following planning phase, even disrupting the second-to-second balance between total demand and supply. Hence, the fundamental problem is lowering the cost of regulating the intermittent nature of renewable energy sources [71].

Conclusively, a wind turbine can replace conventional synchronous generation in the power grid if it is placed, sized, and run correctly. However, their unpredictable output power fluctuations need to be taken into account because they will affect the flow of power and the way the grid works. Moreover, the challenges will fall under numerous different fields of electrical power systems, while the identification, optimization, designing, and implementation will be under a multi-disciplinary domain of engineering and energy science [72–75]. Accordingly, four fundamental necessities of power system operation

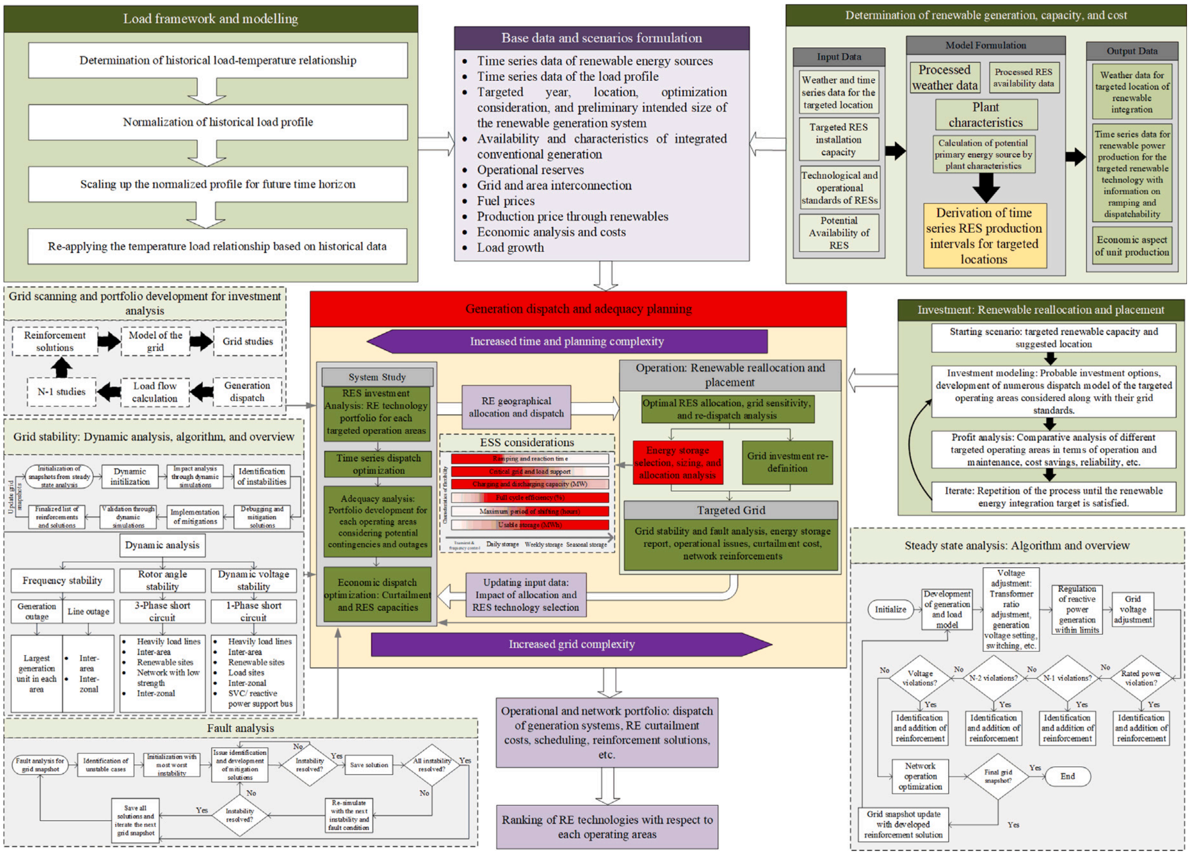

Fig. 3. Typical planning aspects associated with renewable integration considering power quality, contingencies, and investments.

have been considered, namely, power balance, power quality, optimal power flow, and grid stability.

The challenges associated with power balance include issues that are related to the short-term and long-term balance of the system's generation and demand. The ramp rate capacity and minimum production capability of the grid must be coordinated on a large scale to achieve a system-wide balance. This is a difficult task due to the unpredictability and uncertainty of RE sources. End users have the most demanding performance requirements, the most important of which is adequate power quality. The criteria for an uninterrupted power supply, stable conditions of voltage and current, and safe circumstances in the event of power outages are all considered in the case of challenges associated with power quality. In this respect, the non-synchronous characteristics combined with the modularity of RE generators are the two fundamental aspects that are primarily responsible for the difficulties encountered with power quality.

The challenges associated with optimal power flow are concerned with the effective transmission and distribution of electricity. In contrast to other challenges, the associated issues in the case of the challenges associated with optimal power flow arise due to numerous diversified reasons for RE sources that include transience, the capability of modularity, and topological dependency. The regulation of the frequency and voltage in the power system, as well as the recovery of the system after blackouts, are the primary focuses of the challenges associated with stability issues. The modularity of RE generators and the fact that those generators are non-synchronous are the most significant factors contributing to stability issues. A detailed summary of the challenges and issues due to RE integration considering these classifications is presented in Tables 2 and 3 highlights some of the global research studies that address these challenges considering long-term and short-term power system planning strategies. Finally, a comprehensive flowchart related to the studies involved with renewable integration is presented in Fig. 3. It illustrates the power quality, contingencies, RE allocation, and financial aspects of renewable integration that are typically considered in the case of utility-grade bulk renewable installations.

4. Smart grid and energy storage

Most of the solutions and ancillary services posited for mitigating the impact of RE integration require a form of energy buffer. The ancillary services formulated for RE integration will ultimately require the incorporation of an energy storage system (ESS) to initiate optimal performance of RE as well as suitability for the energy market. The viability of combining various ESS technologies with distributed energy on the electric grid and traditional power plants requires an in-depth investigation. This takes into consideration hybrid power systems, power parks, nano/mini/microgrids (AC or DC), grid-tied systems, as well as autonomous standalone systems. It is difficult to successfully adopt standardized control techniques for ESSs without first taking into account both the storage side and the grid side operation [147]. Nevertheless, not only advanced power electronic converters are pertinent, but also a complex control algorithm is required to provide a successful interface between the electric grid and the power electronic devices. These frameworks lead to a quick planning and integration strategy. The planning helps set up an automation platform for the real-time operation of the system, including its operation modes, control and cost functions, as well as its behavior and characteristics.

In terms of dependability and reliability, geothermal and biofuel generation are comparable to that of conventional generators. However, wind and solar generations have a negative influence on these

Table 2
Summary of the challenges and issues associated with RE integration.

Issue (s)	Challenge (s)	Description	Impact (s) Flexibility	Reliability	Resilience	Ref.
Power Balance	Inadequate short-term ramping of the generators	With the incremental RE integration into the grid. The operation of the conventional synchronous generation will prove to be pertinent to maintain the stability of grid in terms of reactive power support, and inertia support among others. The degree of fluctuation of RE integrated into the system might require the synchronous generation to have rapid ramping capabilities, especially at higher RE penetration levels. Otherwise, a systematic loss will be incurred technically and especially economically while maintaining the frequency stability of the grid.	X	X		[76,77]
	Inadequacy in long-term generation operation	With increasing levels of variable RE sources into the power grid, the operational aspects of the grid in terms of seasonal and annual energy balancing will change that will impact the scheduling of the synchronous generation system. Therefore, the system can be vulnerable to long-term system instability due to inaccuracies resulting from the RE's unpredictably variable output power. Consequently, systematic generation deviation can prove to be economically demanding.	X	X	X	[78,79]
	Insufficient forecasting of RE generators	Unscheduled operation of the grid can be observed in the grid due to forecasting inaccuracies of the RE output power generation. The degree of loss can range from economic to technical, and equipment damage.		X		[80]
	Limited dispatchability of RE sources	In accordance with the properties of most of the RE power generation technologies, the frequency stability of the grid cannot be stabilized with the operation of the RE generators. This will lead to unforeseen outages due to the demand-generation mismatch.	X	X		[81,82]
Power Quality	Voltage Flickering	Locally integrated RE through power electronics increases flicker leading to reduced equipment lifetime.			X	[83,84]
	Harmonics	RE integration through inverters increases harmonic distortions. This leads to reduced equipment lifetime, trips, or equipment damage at end consumers.			X	[85,86]
	Low reliability during blackout	RE generators that continue generating electricity within areas that are disconnected from the larger network are vulnerable to stability and power balance issues leading to safety and operational concerns	X	X	X	[87,88]
	Voltage congestion at distribution level	Integration of RE low voltage level of the grid leads to an increased voltage violation. Over-voltage at peak RE production or during low load demand time interval.	X	X		[89,90]
Optimal Power Flow	Increased overall voltage profile	RE integration increases the overall voltage level especially in radial distribution areas.	X	X	X	[91,92]
	Grid capacity limitation	The existent grid networks may not be able to integrate the capacity of the RE generators. If planned, the RE integration will result in power curtailment. Inversely, unplanned integration will result in system vulnerability to faults and equipment damage.	X		X	[93,94]
	Increased potential instability and uncontrollability power at lower levels of the grid	RE integration, especially at high penetration, will result in an increased unpredictability of power generation. This can result in increased curtailment of the RE generators, requirement of stability, and if unplanned will lead to equipment damage.	X		X	[95]

(continued on next page)

Table 2 (*continued*).

Issue (s)	Challenge (s)	Description	Impact (s) Flexibility	Reliability	Resilience	Ref.
	Grid Protection	Usually, lower voltage levels of the grid lacks protection readiness in terms of resultant dynamics of the stochasticity that will be introduced due to the RE integration. In conjunction to the existent load unpredictability, lack of adequate protection planning at the lower voltage level of the grids will incur in an increased overloading and unplanned trips, and detrimental impact on equipment lifetime.		X	X	[96,97]
	Increment in short-circuit current	The change in the power flow and system dynamics due to RE integration, especially at lower voltage of the grid level, increases the level of the short-circuit current during fault conditions. Therefore, vulnerability of system equipment and security is high in accordance with the degree of the RE integrated into the grid.		X	X	[98,99]
	Low degree of controllability over the REs	Increased RE integration in the form of multiple small unit capacity that are unplanned will collectively impact the power flow and system dynamics. This decreases the forecasting and planning dependability that can lead to systematic instability of the grid.	X	X	X	[100,101]
	Low degree of observability of the REs	The lower voltage levels of the grid lack adequate measurement devices that complement the variability of the RE generation systems. Therefore, an unobserved power flow will incur at these voltage level that can result in unscheduled operation of the grid that may be harmful both technically and economically.		X	X	[102]
	Limited transmission capacity of the grid	The integration of REs into the existent grid might in many cases require installation of additional transmission lines. Otherwise, the grid will incur RE power curtailment, reduced transmission capacity statement during the planning phases, and reduced regional power dispatch.	X	X		[103,104]
	Increased transmission line distances	Along with unpredictability with certain level of uncontrollability, REs also has location dependability. Therefore, in some cases longer transmission lines will inadvertently lead to an increment in the overall transmission lines losses.	X			[105]
Grid Stability	Decrease in reactive power support	Most RE generation technologies make a negligible contribution towards reactive power injection. In line with the grid standards and dynamics, the transmission lines require reactive power support to maintain the voltage standards. Therefore, expansion and penetration levels of REs will be significantly limited due to the resultant potential voltage violation occurrences. The lack of reactive power support will also impact the power quality and stability leading to curtailment or isolation of the RE generators.	X	X		[106,107]
	Reduced capability towards fault detection	Fault detection and voltage instability can be undetected owing to the comparatively lower value of short-circuit power of the RE generation system. This can create complications towards stable grid operations and isolation of the RE microgrids.		X	X	[63,108]
	Decrement in the grid inertia	Most of the RE generation technologies are electronic dominated lacking or having negligible inertia. Comparatively, to the synchronous dominated existent grids, a rapid frequency excursion may lead to the grid being highly unstable. Therefore, owing to demand-generation equality constraints the generation curtailment or load shedding operation might be needed to maintain the system operational stability.	X	X		[109–111]

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Table 2 (*continued*).

Issue (s)	Challenge (s)	Description	Impact (s) Flexibility	Reliability	Resilience	Ref.
	Increased reserve for frequency control	RE generation lacks the facility to provide reserves for grid operational aspects. The short-term, and at times highly unpredictability fluctuating output power of the RE generation needs specialized and additional reserves to equip the grid towards stability issues due to frequency deviations. In case of unplanned RE integration and operation the operators might have to curtail RE generation, shed load, or need decision-making to regulate the stability during critical conditions of the grid.	X			[112–115]
	Increased controllability and observability for inverter-dominated grid	RE generation in line with the de-centralized transformation of the grid will require inverters as the interface that connects the RE to the grid. The resultant transformed grid will have power oscillations that are unobserved. Consequently, the grid might observe increased unexplained tripping increasing the need for dedicated control algorithm for effective regulation of such instances.		X	X	[116–119]

indices. This is attributable to their inconsistent output and limited capacity, which is challenging to regulate, especially when the net demand profile grows steeper. Other problems include the difficulty in demand profile forecasting, congestion of DG sources, control of voltage and frequency, congestion of transmission lines as a result of big installations, and regulation of voltage and frequency. Among other solutions, the traditional approach to the problem of fluctuating demand has also been the integration of ESS technologies. It is possible to implement more dependable storage systems as well as electric vehicles (EVs) to accommodate wind and solar electricity. The present trajectory indicates that storage devices will become increasingly widespread for grid systems as RE becomes a more significant part of the energy supply mix [146,148].

The infrastructure of the power system makes use of ESSs at numerous stages. The ESS technologies, on the other hand, vary depending on their application [149–152]. Though ESS have a multi-dimensional application, it is pertinent to identify their application and its scope in accordance with the requirement with respect to the technical characteristics of ESS (such as power density, rating, energy density, lifetime, self-discharge rate, etc.) [153]. Batteries are the most implemented, and they can be utilized in a variety of contexts, including the conventional and renewable generation side, the demand side dealing with consumers, the side dealing with transmission and distribution, and the side dealing with independent system operators (ISOs). On the generating side, ESSs provide an alternative to the construction of new plants. In addition, they do not produce any emissions, which confers significant benefits on utilities considering the emission norms and aging plant infrastructure. The generating process may benefit from their greater supply capacity and time-shifting capabilities.

ESSs are especially beneficial for RE sources since they provide an ideal solution to the inherent intermittent nature of these RE sources and may also make it easier to send electricity to the grid. These things make it possible for renewable power facilities to achieve capacity expansion, time shifting, and a more seamless interface with the grid [154]. Storage facilities not only provide choices for energy management and demand management, but they also guarantee improved stability and power quality for end users, which is particularly important during power outages. By using ESS, ISOs can improve the quality and stability of their grids, which are made up of diverse sources and loads that are constantly changing. Hence, they are able to regulate the ISO system, gain reserve capacity, load following, and maintain the system voltage. Storage is beneficial to the transmission and distribution sectors as it allows for congestion relief, deferment, and the provision of transmission support and substation on-site power [147]. These systems may be meticulously categorized based on mechanical, electrochemical, chemical, electrical, or thermal, depending on the techniques that they utilize to store and provide electrical energy [155].

ESS technologies, like batteries, are becoming more mature, and as a result, new business models have begun to emerge that provide improved frameworks for incorporating these technologies into the existing electricity setting. Combining these ESS advancements with the emerging electricity market, these factors unequivocally point to the increasingly rapid presence of storage systems on the premises of the utilities. Even though the majority of consumption has been for utilities up to this point, it is anticipated that residential usage will see a significant increase in the years to come owing to residential RE installations, the introduction of electric vehicles, and charging stations. The advent of widespread deployment of ESS poses both an opportunity and a problem for the conventional utilities that are already in existence. The difficulty arises from the likelihood of a decreasing customer base, which may be brought about by residential applications of rooftop solar paired with storage devices that encourage consumers to break ties with the grid-based utility. Utilities may face a significant obstacle in the form of a substantial increase in operating expenses if customer numbers continue to decline, since this will make it more difficult to turn a profit [147].

The utilization of variable renewable energy sources introduces a higher degree of complexity for energy management systems. Therefore, the system operators must maintain power quality and reliability, considering the uncertainty of energy sources. The utilization of intelligent and machine-based algorithms is posited to appropriately facilitate an energy management framework. However, optimal utilization of power units such as energy storage systems and power electronic interfaces is pertinent considering the harsh weather conditions of some countries [156]. Since a single type of energy storage system is unable to optimally perform in accordance with the multi-faced challenges of renewables, hybridization or the identification of viable ESSs is necessary.

Modeling power networks in great detail using monthly and yearly generation dispatch and unit commitment models allows for the possibility of appropriately considering the individual temporal features of storage technologies and defining an appropriate energy mix. The limitations of these technologies' storage capabilities must be taken into careful consideration. Analysis continues until all identified adequacy requirements are met, at which point the optimal investment is retained based on a comparison of operating cost gain to the equivalent annualized cost. Such analyses require comprehensive tool-chain analysis with detailed input data to carry out the initial planning of RES optimal allocation and probabilistic adequacy assessment. Next, the feasibility of new generating investment opportunities, including conventional generation and battery storage, is investigated. An investigation of the most effective distribution of storage technologies and locations is a component of the optimum deployment of RES. Further investments are

Table 3
Selected studies to outline power system planning, operation, uncertainties, and optimization considered with renewable integration around the world.

Ref.	Time-steps/ Time slices	Planning Horizon	Years under Study	Generation Mix	Data under Uncertainty	Optimization under Uncertainty	Location	Description
[120]	Yearly – 6 to 9 segments	100 years	2000–2100	Coal, oil, gas, gas capture and storage (CCS) concentrator Solar PV, wind (onshore and offshore), hydrogen, light water reactor, fast breeder reactor, hydrogen, hydro, bioenergy, bioenergy CCS, coal and oil CCS, solar PV and storage technologies	No	No	Global	Resource-based slicing approach to evaluate their projected efficacy.
[121]	–	15 years	2010–2030	Hydro-power plant, Solar PV, wind, and biomass	No	Yes	Brazil	A multi-objective expansion model optimization for renewable integration. Objective function includes cost minimization, generation maximization during peak load, and increased utilization of non-hydro renewable energy sources.
[122]	Daily	2 years	2030 and 2050	Nuclear, solar, and wind	No	No	France	Evaluation grid flexibility of nuclear power plants with increasing variable renewable sources.
[123]	16 time slices, weekly, day and night, and seasonal variation.	20 years	2015–2030	Decentralized Solar PV, concentrator PV, hydro power plants, wind turbines, conventional power plants (fuel fired steam, combined cycle, and large/small open cycle), and power exchange with neighboring countries Algeria and Libya.	No	Yes	Tunisia	Linear optimization using open-source energy modeling system (OSeMOSYS) based on local as well as international process of power exchange with job-creation constraint. A bottom-up model for developing the optimization framework is formulated considering the technical, environmental, and economic aspects related with renewable integration.
[124]	Hourly	1 year	2050	Solar PV, wind (on-shore and off-shore), hydroelectricity (run-of-the-river and reservoir), biomass, geothermal, concentrated solar power systems, lignite-fired, coal-fired, natural gas fired (open cycle and closed cycle), and nuclear power plants. Storage technologies: Pumped-hydro, lithium-ion, adiabatic compressed air, and redox-flow.	No	No	Europe	Grid planning and operation with optimal selection analysis for energy storage technologies to facilitate techno-economically feasible joint optimization roadmap using REMix- capacity expansion model platform.

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Table 3 (*continued*).

Ref.	Time-steps/ Time slices	Planning Horizon	Years under Study	Generation Mix	Data under Uncertainty	Optimization under Uncertainty	Location	Description
[125]	Hourly	10 years	–	Biogas, geothermal, Solar PV, Hydro (small and large), biomass, wind, coal, oil, gas, and run-of-the-river hydroelectric	No	No	Portugal	Generation expansion planning and unit commitment problem associated with thermal power plants performance with wind and hydro based renewable integration using GAMS's DICOPT solver.
[126]	Hourly	–	2015	On-shore wind and solar PV	No	Yes	Belgium	Impact study and prescription for short-term flexibility considering dispatchable and non-dispatchable sources in the dynamics of the power system.
[127]	5 min	24 hours	–	Solar PV	No	Yes	Saudi Arabia	Fuzzy-based output power smoothing of solar PV systems.
[128]	Hourly	–	–	Wind and co-generation plant	No	No	Finland	Flexibility strategies for coordinated cost optimization and energy revenue maximization with large wind integration in CHP-dominated grid.
[129]	Hourly – peak and base loads	15 years	2015–2030	Hydroelectric, natural gas, coal,	No	No	Columbia	Generation and transmission expansion planning with demand-side management considering cost minimization and governmental targets against clean energy integration.
[130]	Yearly	35 years	2015–2050	Oil, Gas, coal, nuclear, hydro, wind, solar, and biomass	No	Yes	China	Evaluation on mitigation of renewable variation was performed considering the energy mix of the grid. The performance was evaluated using global change assessment model.
[131]	Hourly	1 Year	2035	Nuclear, coal, gas (combined cycle, combined cycle post combustion storage, and open cycle), integrated gasification combined cycle, wind (onshore and offshore), and solar PV.	No	No	UK	Valuation of technologies in the power system considering conventional, renewable, and energy storage systems
[132]	Hourly	1 year	2030	Gas, oil, hydro, solar, wind, run-of-river hydroelectric, pumped storage, CHP	No	No	Germany	Impact study of demand flexibility considering secondary/tertiary control reserves using Balmorel partial equilibrium model for optimization.

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Table 3 (*continued*).

Ref.	Time-steps/ Time slices	Planning Horizon	Years under Study	Generation Mix	Data under Uncertainty	Optimization under Uncertainty	Location	Description
[133]	Yearly – 4 segments	15 years	2015–2030	Nuclear, coal, natural gas (turbine and combined cycle), Solar PV and wind.	Yes	Yes	Korea	Long-term capacity expansion planning model using stochastic optimization for large scale renewable integration.
[134]	Hourly	1 year	2035	Coal, nuclear, solar, and wind	No	No	Germany	Unit commitment model and evaluation is performed to reduce the requirement of flexible operation from future solar and wind RE sources.
[135]	Daily	30 years	2020–2050	Wind (onshore and offshore), biogas, biomass, Solar OV, hydro, nuclear, gas, hard coal, lignite,	No	No	Poland	Long term optimization planning model development for quantifying the requirement of primary, secondary, and tertiary reserve energy required due to renewable integration
[136]	Hourly	–	–	Solar PV (large-scale and rooftop), wind (onshore and offshore), run-of-river hydroelectric, nuclear, geothermal, battery, coal, natural gas, conventional hydroelectric, Concentrating solar PV, thermal energy storage, pumped hydroelectric storage,	No	No	America	Linear programming model for comparative analysis, flexibility assessment, and outlining feasible energy mix considering different levels of renewable penetration.
[137]	Hourly	20 years	2010–2030	Solar, wind, nuclear, coal, oil, hydro, biomass, and liquefied natural gas	No	No	Tokyo	Techno-economic optimization considering generation, operational, and transmission constraints to determine viable renewable energy mix considering load distribution.
[138]	Hourly	19 years	2020–2039	Wind, solar PV, hydroelectric (run-of-river and series) Diesel (motor and turbine), coal steam turbine, combined cycle, gas, hydroelectric reservoir	Yes	Yes	Chile	Uncertainty based optimization framework for operational and evaluation of large scale renewable integrated expansion.
[139]	Hourly	85 years	2016–2101	Wind, hydroelectric (run-of-river and reservoir), solar PV, biomass, coal, and gas			Chile	Assessment of climatic condition on the power generation of wind power plants using mixed integer linear programming.
[140]	36 segments yearly analysis with 3 segments daily for monthly data.	30 years	1984–2014	Solar PV, Fuel-fired steam, natural gas (reciprocating gas engine, steam, gas turbine, and combined cycle), gas oil (gas turbine, combined cycle, and diesel generator), coal-fired, nuclear, hydro, concentrating solar PV, and wind.	No	No	Iran	Retrospective impact studies on generation and demand side strategies towards potential integration of variable renewable energy sources using MESSAGE optimization model.

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Table 3 (*continued*).

Ref.	Time-steps/ Time slices	Planning Horizon	Years under Study	Generation Mix	Data under Uncertainty	Optimization under Uncertainty	Location	Description
[141]	Numerous time slices considering day, night, peak load, and seasons to formulate yearly model	41 years	2014–2055	Nuclear, coal (subcritical and supercritical pulverized), gas (open cycle and closed cycle), wind (onshore and offshore), and solar PV	No	No	Belgium	Studying the impact of temporal dimension on the power system planning models considering different resolutions of temporal representations and techno-economic operational details.
[142]	–	25 years	–	Nuclear, oil, natural gas, hydel, wind, and solar PV	No	No	Pakistan	Valuation of 750 MW solar PV integration into the national grid considering the grid constraints, technical, and economic aspects
[143]	Hourly	1 year	2020	Solar, wind, hydroelectric, pumped storage, natural-gas fired (combined cycle and open cycle) lignite-fired, oil-fired, combined heat and power, biomass.	No	No	Greece	Long term unit commitment problem to perform day-ahead scheduling considering ramp rates and capacity, highlighting the dynamics and grid flexibility in terms of ancillary services.
[144]	Hourly	–	2014	Coal, hydro, gas, heavy fuel oil, high speed diesel oil, and imported power	No	No	Bangladesh	Operation and planning for renewable integration for developing countries with limited resources.
[145]	–	10 years	2031–2040	Coal, gas, coal CCS, gas CCS, biomass, solar, wind (onshore and offshore), hydro, and nuclear	No	Yes	Canada	Multi-stage stochastic optimization programming model considering the GHG emission and lifecycle costs of 10 power generations units.

Table 4
Application of energy storage technologies in numerous smart energy based renewable integration [120,124,132,146].

Energy storage technologies	Time shifting (Hours to days)	Arbitrage (Hours to days)	Load leveling (Hours to days)	Seasonal shifting (Months)	Load following (Minutes to hours)	Ramping (Minutes to hours)	Power quality and stability (< seconds)	Frequency regulation (Seconds to minutes)	Spinning reserves (within minutes)	Secondary reserves (Minutes to hours)	Efficient use of transmission lines (Minutes to hours)	Autonomous grid operation (Seconds to hours)	Critical load support (Minutes to hours)	Black start (Minutes to hours)
Sodium sulfur (NaS) battery	X	X	X				X	X						
Compressed-air energy storage (CAES)	X	X	X		X	X								
Pumped heat electrical storage (PHES)	X	X	X		X	X		X	X	X				
Redox flow battery (RFB)	X	X	X		X	X	X							
Hydrogen				X										
Synthetic natural gas (SNG)				X										
Batteries					X	X	X		X					
Flywheel					X	X		X	X					
Lead acid (LA)							X					X	X	X
Lithium-ion battery								X			X			
Supercapacitor						X	X	X				X	X	X

necessary to ensure the reliability of the supply. In this sense, adequacy calculations are made based on probabilistic models to incorporate the unpredictability of renewable resources and the possibility of power plant breakdowns. These calculations are undertaken to ensure that there is enough energy to meet demand. The investments are then developed further in terms of technology, either based on the conventional generation that is already in place, the installations of RE, the battery storage, or an ideal blend of these several power technologies. Based on the literature, numerous applicative scopes of various ESS technologies are presented in Table 4.

5. Potentiality of smart communication and information systems

In the context of developing a renewable-based sustainable energy network, it can be observably postulated that a bi-directional communication and information flow is the key to successfully implementing

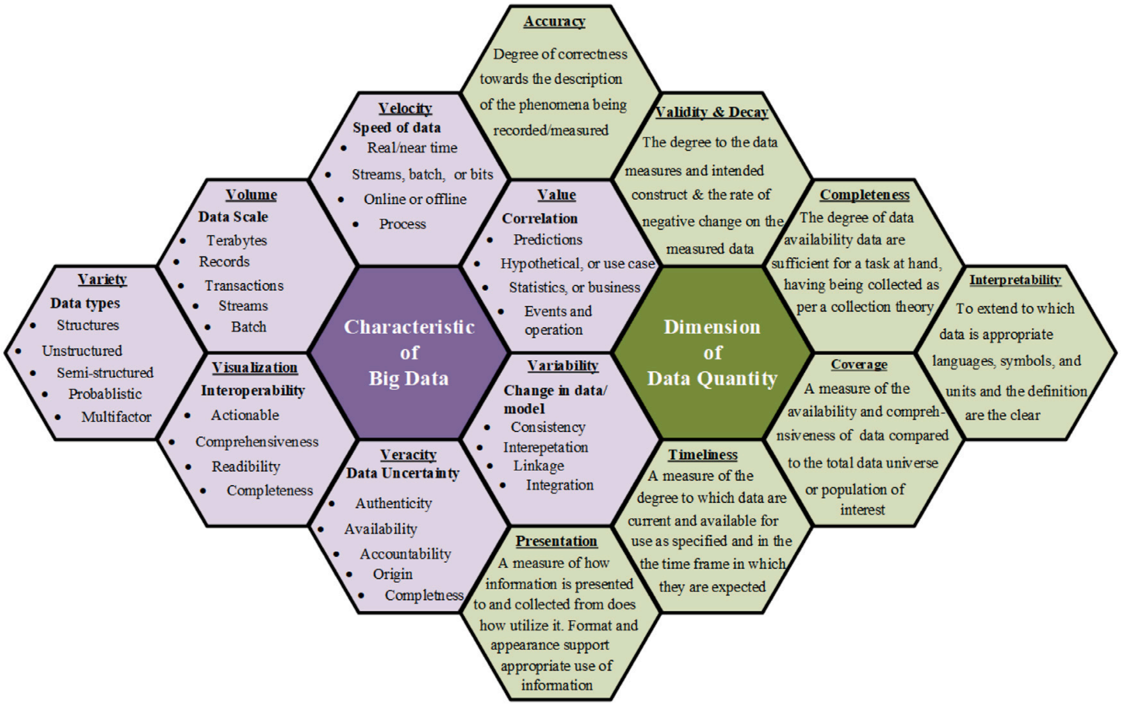

Fig. 4. Quality and characteristic of big data [157–159].

many of the solutions associated with renewable integration, energy storage, and other elements of smart energy systems. The transformation towards SG will lead to the formation of big data which requires additional requirements to be considered (Fig. 4). Most of the innovative solutions available in the literature (Table 3) require state-of-the-art communication and information collected through smart meters, sensing devices, home area networks (HAN) etc., for their actual implementation. Many technologies of smart communication exist and are under development coupled with information technologies to facilitate a resilient flow of bulk data, albeit having their operational and integrative challenges (Table 5). While many technologically innovative solutions are existent to realize an ideal smart grid architecture for facilitating an effective utilization of hlrenewable, the concern for security as well as interoperability between these technologies exists in terms of practical application to the existing grid infrastructure that requires steady transformation and development while reliably supplying the load. Therefore, security and interoperability are driving factors that quantify the practicality of the existing as well as developing communication and information technologies directed towards smart grid development from the perspective of consumer acceptance and ease of operation for the power system planners.

Meticulous energy management requires complex data processing and optimization, to mitigate failures and other unpredictable anomalies of SG with a rapid processing and response unit being additionally needed [167]. Therefore, considering a large national-level SG with millions of communication nodes, a large number of controllers are to be placed for local regulation. This can potentially reduce the complexity of the problem. But mostly locally integrated smart grid systems require a regional as well as governing SG framework to a provide protective and regulatory framework to the smart grid in the form of attack resistance, self-healing, market legislation, secure energy transaction, and financial recovery from outages. Finally, a global SG framework to target future policy and strategies in terms of energy and technology diversification and transformation [168–170].

The factorization to validate the efficacy of various different technologies of communication and information infrastructure while maintaining an appropriate quality-of-service between the devices and the components associated with metering, power lines, generation, control, monitoring in terms of user-end interface, enhanced utilization, DG management, grid regulatory adherence, reduction in greenhouse gas emission is based on the technological interoperability. Considering the associative high cost related to SG establishment, optimal and reliable asset utilization is pertinent. Therefore, effective approaches to systematically identify the margins of reliable operations with dynamic monitoring systems to observe these margins.

The huge amount of information pertaining to the data associated with the smart sensors, PMUs, and meters is posited to be sampled in the smart grid network. Therefore, appropriate identification and selection of data optimization is pertinent to remove unwanted redundant data, so that meaningful interoperable data can be collected for the entire electricity network. The historical data of the users and system operation is pertinent for analyzing the overall smart grid behaviors to effectively implement billing, install protection devices, and maintain the power quality and reliability of the electric power supply. Hence, maintaining secure and reliable communication for such large data is challenging. Suggestions have been presented for incorporating data mining, information retrieval interfaces, and machine learning algorithms to obtain and maintain representative data. Moreover, some data sets might have a high degree of similarity or correlation. For instance, Smart meter readings are similar when no activity is taking place at a specific user. Therefore, data information can be significantly reduced for such readings. In addition, tools for the database are required for appropriate user interface as well as for two-way communication in terms of organizing, storing and retrieving the data.

The underlying dynamics of the smart communication system with the integration of distinct technologies are unpredictable. For instance, both the operation of connecting/disconnecting the electric vehicle to/from the grid and the respective motion of the electric vehicle may lead to a change in the communication topology. In this respect, the dynamics of the smart grid have not been fully explored. Therefore, systematic protocol design and dynamic resource allocation algorithm are pertinent to respectively deal with unpredictable topology reconfiguration and to support the network dynamics. For example, the communication protocol is designed to support the topology configuration during disconnection–reconnection of the electric vehicles and

Table 5
Technical specification and summary of the communication technologies.

Technology		Spectrum	Data-rate	Range	Network application	Limitations
PLC	Wired	1-30 MHz [160,161]	2-3 Mbps [160,161]	1 – 3 km [161]	AMI, fraud detection	Vulnerable to noise
DSL	Wired		ADSL – 1- 8 Mbps HDSL – 2 Mbps VDSL – 1—100 Mbps	1.5 – 5 km	AMI and HAN	Efficiency decrement is proportional to distance
Fiber Optics	Wired		155 Mbps – 40 Gbps	5 – 10 km	AMI, WAN, sensors, and fraud detection	Very high investment cost
GSM	Wireless	900-1800 MHz [160,161]	2G – 14.4 Kbps [160] 14 kbps [161,162] 2.5G – 171kbps [162] 3G - +2Mbps [162] 4G – 300 Mbps	1–10 km [160–162]	AMI, ADR, HAN, EV, ADR, DER, HAN	Comparatively low data rate
WiMax	Wireless	25 GHz, 3.5 GHz, 5.8 GHz [160,161]	70 Mbps [163] 72 Mbps [162] 75 Mbps [160,161]	9 km [162] 10–50 km (LOS) 1–5 km (NLOS [160] 48 km [163]	AMI, fraud detection, WAN, ADR	Technology is under research. Low market presence
Satellite	Wireless		1 Mbps		GPS, time synchronization, and monitoring transmission lines and substations	Can be affected by weather conditions and also suffers from a long round-trip delays
3G	Wireless	1.92–1.8 GHz 2.11–2.17 GHz [160]	384 kbps–2Mbps [160,161]	1-10 km [160]	AMI, ADR, NAN, WAN	High communication cost High computational cost
GPRS	Wireless	900-1800 MHz [160,161]	170 kbps [160,161]	1- 10 km [160]	AMI, ADR, HAN	Comparatively low data rate
Zigbee	Wireless	2.4 GHz [160,161,164] 868–915 MHz [160,161]	250 Kbps [160,161,163–165]	10-20 m [164] 30-50 m [160,161] 10-100 m [163,165]	AMI, HAN, Load management	Comparatively low data rate and range. Faces interoperability issues with data sharing in diversified communication network.
Bluetooth	Wireless	2.4 GHz [164]	20 - 250 Kbps [165] 721 Kbps [163] 1 Mbps [164]	1-100 m [163–165]	Load monitoring	Short communication range and low data rate
Z-wave	Wireless	900 MHz [164]	9.6-100 kbps [164]	30 m [166] 100 m [164]	remote control applications in HAN.	Limited coverage

appropriate algorithms to optimally allocate resources and enhance communication performance. On this front, current power grid protocols utilize simple data communication systems that are based on Supervisory Control and Data Acquisition Systems (SCADA) [191]. Therefore, the problem arises during the updating process of protocols to the ones in the future smart grid. For instance, considering the case of TCP/IP in the end-to-end communication system, even though an application might not be supporting TCP/IP natively, it can still be interoperated through encapsulation, gateways, or tunneling. However, this is deliberately not considered for practical application as an encapsulation of SCADA protocols with TCP/IP protocols generates an additional overhead [192].

Cloud computing has been predicted to be the next-generation computing paradigm. It provides several advantages in transference risk,

Table 6
Selected list of attacks and their countermeasures in SG security.

Ref.	Countermeasures	Attacks targeted	SG components
[171]	Methodology for message authentication	Spoofing, sniffing, and message authentication	Advanced metering infrastructure (AMI) of SG that includes smart meters, vehicle-to-grid devices, PMU, meter data management systems of meters, and data collectors
[172]	Centralized data management, authentication, hash encryption methodology for smart meter integration to the SG to maintain confidentiality and data integrity.	Impersonation, substation security, session key exposure	
[173]	Smart meter integration and registration into the SG network with key generation	Impersonation, substation security, session key exposure, and meter manipulation	
[174]	Logistic regression for compromised smart meter detection	False data injection	
[175]	Estimation technique and transmission policy for malignant code detection	Attack on time synchronization of devices	
[176]	Analytical simulation to detect DDoS attacks on smart meters.	DDoS attacks	
[177]	Implementation of mixed Nash equilibrium for securing the communication network of PMU and smart meters through developing a hybrid routing protocols	Data manipulation and device availability	
[178]	Data management scheme and encryption technique for electric vehicle hardware performance confidentiality between the vehicles as well as the charging stations	Data confidentiality, theft, and data authenticity	
[179]	Virus detection method based on support vector machine (SVM) technique	Availability, and data integrity, overloading of the CPU and memory exhaustion	Information technology devices of SG that includes server systems, routers, network nodes, storage, memory, CPU, hardware, wireless communication, and authentication server frameworks
[180]	Formulation of security guidelines for protection of network topology using game theory	Authenticity, confidentiality, device malfunction, integrity, and desynchronization	
[181]	A Message authentication technique for protection communication between devices	DDoS, availability, Jamming of the device, data falsification through delay, and desynchronization	
[182]	Cloud computing and blockchain technique for secure single sign-on for improved user security	Confidentiality, integrity, authenticity, and vulnerability	
[183]	Password and identification integrated management based on blockchain	Confidentiality, integrity, authenticity, and vulnerability	
[184]	Protection device-to-device communication in wireless network using game theory	Jamming and availability of the device	
[185]	Game theory approach for optimal load shedding using Nash equilibrium states	Availability, cyber–physical attacks	Operational technology devices of SG that includes generators, transmission lines, transformers, load system, state estimators, controllers, physical components of the system, and wide area protection, monitoring, and control systems
[186]	Feedback linearization control methodology for resiliency of SG stability towards cyberattacks	Availability and integrity	
[187]	Markov model formulation based on game tree theory for SCADA system protection against attacks	Confidentiality, availability, and integrity	
[188]	Analysis of attacks on state estimations in SG using mixed integer linear programming	Security, integrity, malfunction, desynchronization, vulnerability, and availability	
[189]	A dynamic game approach for security against on power systems by learning attack patterns using reinforcement learning	Desynchronization, availability, credibility, and vulnerability	
[190]	Differential game theory for transient stability of distributed generation systems against cyber attacks	Vulnerability, availability, and authenticity	

ubiquitous network access, and self-service [193]. Cloud computing frameworks have huge storage space facilitated by cloud providers. Therefore, the incorporation of cloud computing in the smart grid will allow the operators to deal with information management services and outsource the generic information functions to the cloud. This is especially a techno-economic solution for smaller utilities. Furthermore, the problem of interoperability and data compatibility between the heterogeneous elements of the smart grid that lead to the formation of an "island of operation", can be easily solved in a cost-efficient manner with cloud computing storage facilities. The study in [194], states that cloud computing technology has the potential to formulate usable de facto standards while facilitating extensibility and interoperability. Nevertheless, many security and privacy issues need to be addressed.

The authors proposed some solutions associated with designing multi-tenant data topology, cryptographic hashes, and pseudonymization. However, it seems unlikely that a utility will outsource all its information management to the cloud. Therefore, considering these advantages and disadvantages research and innovation are required to identify which characteristics of cloud computing should a service provider sell and what management functions can be qualified to be outsourced considering security and privacy concerns.

Interoperability between different protocols, heterogeneous configurations, and technologies plays a pivotal role in a rapid and smooth transition towards the foundation of the smart grid. This task proves to be challenging and requires innovative solutions in accordance with each element of the smart grid. Even though the classic layer model, such as the open systems interconnection model, provides a promising solution for this problem, this model has some drawbacks. For instance, in wireless network systems, the performance of the TCP is very bad. This is due to the fact that it cannot differentiate between packet loss and wireless fading resulting from network congestion [195–199]. This requires innovative solutions such as optimization and cross-layer design. Therefore, innovations in cross-layer approaches are required to maintain the ease of establishing smart grid infrastructure. Accordingly, an in-depth analytical study is needed to establish the advantages and drawbacks of the cross-layer approach with quantification and identification of the trade-offs associated with an interoperable communication network in a smart grid.

Maintaining an effective "two-way" flow of commutation and electricity while maintaining a reliable, secure, and techno-economic operation of SG leads to a huge amount of data for each end-user and communication point ranging from generation, transmission, and distribution is needed. A balance between the preservation of privacy and information accessibility is pertinent. On one hand, higher accuracy and smarter decisions are based on the higher amount of demand information that the users allow the utility to access. While on the other hand, more accessibility to information for utility operators means more chances of privacy leaks. Therefore, trade-off and tolerable privacy violation quantity need to be identified to define an effective management system.

Advanced smart grid infrastructure means expanded communication and increased system complexity that easily makes the system vulnerable to cyber-attacks. The availability of millions of nodes in the smart communication network makes it unpredictable to anticipate the cyber-attack severity and quantity [200]. One possible solution is the division of the grid structure into several exclusive interconnected sub-systems thereby reducing the complexity and limiting the level of attacks. This communication solution is conceptually analogous to the terminology of microgrids in power systems. However, a complete solution is needed that takes into consideration both autonomous and interconnected communication networks.

An ideal inter-operable communication network leading to real-time monitoring, swift two-way communication, and enhanced sensing does increase the system interconnection and interaction but also increases the likelihood of cyber-attack on the power generation and distribution system. Utilities are the most targeted and infiltrated despite having comparatively more effective cyber-security infrastructure [201]. The cybersecurity of a power system is a pressing engineering issue. Cyber-attacks may lead to system failure by displaying fraudulent data and suppressing error alerts and warnings [202]. For cyber defense, data transfer between IEDs and control centers is crucial [203]. Quantifying the physical effects of an assault is difficult. To mitigate cyber threats, it is important to understand how a particular dataset affects the power delivery limit. However, the ability to assess the effect on utility is hindered by ambiguous or nonexistent mathematical models of interaction sub-networks [204] with accessibility and privacy being difficult to reconcile as the incremental degree of information exposure while being proportional to improved decision-making is also proportional to reduced data security.

SCADA systems are being extensively utilized for the operation, control, and monitoring of the system. They are systematically implemented by power plants, chemical treatment facilities, and dams for their operations. SCADA deployment improves monitoring and reaction to failures; it also enhances the control capabilities but it remains susceptible to numerous types of cyber-attacks due to its reliance on connectivity, consequently making the utility system vulnerable. For instance, the Stuxnet event is an example of a cyber-attack that was carried out against SCADA systems [205]. Some of the common approaches to infiltrate SCADA systems are through network connections, computers, and terminals. Therefore, resilience is essential not only for dealing with cyber-attacks but additionally for counteracting the interruptions that result through physical disruption to these equipment which might also occur from natural disasters or any sort of physical attack on the infrastructure. Therefore, as systems become increasingly interconnected with one another and the internet, the number, and methods of attacks are certain to increase.

Furthermore, two solar inverter security flaw namely, Meltdown [217] and Spectre [218], were identified that in combination with the cache side channel becomes a powerful attack [219]. Aurora attacks may affect AGCs, influencing the closing/opening operation that may consequently result in desynchronization or potentially damage the targeted generators [207]. This attack may be initiated even without extensive knowledge of the target system [220]. False frequency deviation data may also be used to attack AGCs, resulting in load shedding [207]. The interdiction attack was one of the first known transmission system attacks, in which components of a transmission scheme are forced to trip by incorrect or modified data [221].

In accordance with the studies presented in [222], similar assaults may also be used against wind farms by exploiting the weakness of SCADA or EMS. Substations play an important role in cyber-vulnerability since the shut-down of a few substations may trigger blackouts in a power system [207]. Investigations done in [223], postulate that even with various firewalls and protective procedures in place, the entire control of a substation may be hacked. False communications from attackers may cause voltage controllers to be misconfigured, leading to voltage fluctuation and system instability [224]. The same thing can happen with switching signals, where malicious signals can be used to guide a transmission system into worse or unstable operating conditions, resulting in voltage and frequency instability, cascading failures, and malicious use of ESS for destabilization [214]. False data may also accomplish load redistribution in other busses without increasing the overall load of the system, allowing the attacker to go undetected, and such assaults can have a substantial impact on the reliability and stability of the grid [225].

Similarly, PMUs are a crucial component in today's power grid. The AMIs of microgrids and smart grids connect all of the smart meters in the network, data storage, and analysis facilities [226]. Each of these components may be used to launch cyber-attacks, making utilities more vulnerable than ever. GPS is used by PMUs to provide the time stamps necessary for synchronized functioning in a networked system since it offers a greater understanding of the system's characteristics. This reliance on GPS time stamps, however, can be utilized to generate false alerts by injecting false data in place of real data sets. This is referred to as "spoofing" [227]. On the other hand, hardware and cost limits mean that smart meters only have basic security features [207]. Data and energy theft pose significant challenges to AMIs [228]. They are also vulnerable to being overloaded with malicious data, which may disrupt or paralyze the whole network allocated to metering [229]. Such assaults may also have an impact on a grid system's load frequency control [230]. Energy market data may potentially be manipulated to generate illegal profits [231]. It should be highlighted that many attack techniques do not need extensive knowledge about the targeted system, and attackers may launch operations that result in major blackouts using just publicly accessible data [232]. A summary of numerous cyber-attacks associated with SG is listed are Table 6 with

Table 7
State-of-the-art reviews on different technological and perspectives of security, standards, and threats in SG.

Ref.	Description	Year
[206]	Review and classification of types of communications technologies and security measures used in HAN and NAN.	2013
[207]	Classification and solutions to cyber-attacks on the operational technologies of SG	2016
[208]	Summary of policies and framework of smart metering structure around the world	2016
[209,210]	Classification security threats in advanced metering infrastructure, their types, and countermeasures	2015 2018
[171,211]	Review and summary of numerous SG security standards on IEC/ISO, IEEE, GB, and NIST. Surveying the selection and evaluation criteria with detailed discussion on each standard and its definition	2011 2018
[212]	Overview of cyber security threats, classification of network layers, and update on related research with countermeasures	2020
[173]	Detailed description and countermeasures to security attacks in the IoT and operational technologies	2021
[213]	Standardization of EV and charging stations with detailed description of state-of-the-art developments and management systems	2021
[214]	Technical classification cyber–physical attacks in SG in terms of mathematical model for false data injection and state estimation attacks	2021
[215]	Principles, standards, recommendations, and constraints on cyber-security and cyber–physical systems in SG	2022
[216]	Summary, identification, and descriptive explanation on SG security covering the advanced metering infrastructure, information technology, and operational technologies with update of research on countermeasures.	2022

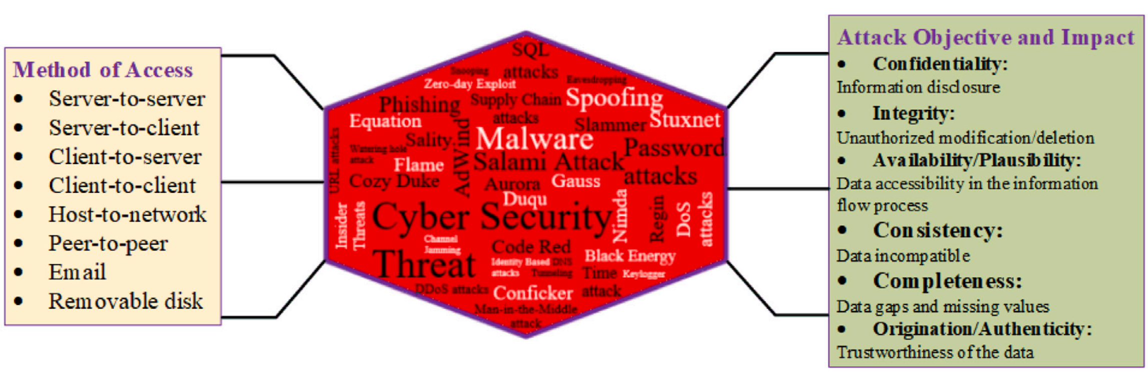

Fig. 5. Visualization of smart grid security access points and impacts.

Table 7 presenting the tabulation of numerous standards, reviews, and descriptions of benchmarks associated with the elements of smart grid systems. A visualization of numerous security attacks with their means of infiltration into the network and impact on the systems is shown in Fig. 5. The Table 8 presents a complete review of the many strategies that have been employed to mitigate the effects of SGs on distribution networks. Advanced Metering has emerged as a significant participant in the field, providing real-time monitoring and demand response capabilities. However, it encounters obstacles like as substantial initial expenses and issues around privacy. The potential of Distribution Automation to improve dependability and defect detection is noteworthy, notwithstanding the challenges associated with integration and cybersecurity threats. Furthermore, the implementation of Energy Storage and Microgrids exhibits potential in enhancing the resilience of the grid. However, the widespread adoption of these technologies can encounter obstacles due to the considerable initial expenses involved and the regulatory complexities that arise. The provided table functions as a great resource for stakeholders who are navigating the complex terrain of smart grid deployment. It enables them to assess the pros and cons of various techniques, so facilitating informed decision-making towards achieving a sustainable and efficient energy future.

6. Summary of problems resolved by SGs

The Table 9 provides an overview of the multiple challenges that are being addressed by SGs in the contemporary energy sector. SGs

Table 8
Pros and cons of SGs impact on distribution networks.

Approaches	Advantages	Disadvantages	Refs
Advanced Metering	The system offers real-time monitoring, precise billing, and demand response features.	Substantial capital cost, privacy issues, security risks.	[233,234]
Demand Response	The benefits include a decrease in peak. Demand, an enhancement in grid dependability, and cost reductions for users.	Low levels of customer engagement, possibility for disruption.	[235–237]
Distribution Automation	Increased dependability, shorter downtimes, and accurate problem diagnosis.	High financial expenses, difficulty in emancipation cybersecurity threats.	[238–240]
Distributed Generation	Enhanced energy utilization, lower distribution losses, grid stability.	Impact on grid stability, difficulty of integration, and intermittent power supply.	[20,241]
Smart Sensors and IoT	Enhanced monitoring, data-driven decision-making, improved system visibility.	Security vulnerabilities, privacy concerns, data overload.	[242,243]
Predictive Analytics	Early fault detection, improved maintenance planning, enhanced reliability.	Data accuracy challenges, complex modeling, computational requirements.	[244,245]
Cybersecurity Measures	Protection against cyber threats, safeguarding sensitive data, system integrity.	Ongoing maintenance, resource-intensive, evolving threat landscape.	[246]
Grid Resilience Strategies	Enhanced ability to withstand and recover from disruptions, improved reliability.	Implementation costs, regulatory barriers, potential trade-offs.	[247,248]

employ several tactics, such as demand response and load balancing, to effectively manage energy distribution and mitigate peak loads, hence addressing energy efficiency concerns. Renewable sources are effectively integrated through the management of intermittency and the enhancement of grid flexibility, with a vital role played by certain entities. The enhancement of reliability is achieved by implementing fault detection mechanisms, establishing self-healing networks, and employing predictive maintenance strategies. The optimization of power quality is achieved by the regulation of voltage, the reduction of distortions, and the stabilization of frequency. The significance of cybersecurity is acknowledged in the implementation of encryption, intrusion detection, and authentication methods inside SGs, in order to protect against potential digital attacks. Consumer empowerment is attained by means of real-time monitoring, smart metres, and variable tariffs, which serve to incentivize customers to actively engage in the management of their energy consumption. The chart shown underscores the significance of SGs in safeguarding grid resilience through the implementation of strategies such as disaster recovery planning, microgrids, and redundancy systems. These measures are crucial for sustaining uninterrupted power delivery in demanding situations. Collectively, these components emphasize the all-encompassing characteristics of SGs in tackling the complex issues associated with contemporary energy management. The presented Table 10 provides a comprehensive statistical analysis of SG implementations on a global scale, including a full breakdown of key parameters across many nations. The presented data serves as a great resource for policymakers, investors, and researchers who are interested in gaining insights into the worldwide landscape of smart grid efforts. Additionally, it facilitates the ability to do cross-country comparisons. The data provided in this presentation contributes to a comprehensive comprehension of the economic, environmental, and societal consequences associated with the implementation of smart grid technology. This information is valuable for informing strategic decision-making processes on future projects and the development of policies.

7. Discussion

The conceptual framework of an ideal smart grid ensures numerous enabling functionalities that mitigate the challenges required to mitigate the impact of renewable transience, that systematically deteriorates the over grid's power quality. In fact, certain functionalities of smart grid such as bi-directional power flow and ease of reliable as well as secure communication is a necessity not only to circumvent the impact of abrupt renewable transience but also to initialize and successfully establish a deregulated energy market with functional peer-to-peer trading. In this context, smart grid is known to facilitate transparency, direct, and optimized asset utilization it also serves as a necessary framework to establish and maintain a commercializable and seamless transition towards renewable and sustainable energy development.

Even though SGs prove to be a promising technology, a meticulous blueprint is needed to be designed to ensure an advanced projection in the process of initiation, planning, and development to execute a practical and satisfactory intelligent energy system. Energy storage systems are an important auxiliary support that will inevitably facilitate the auxiliary support needed for renewable integration. Hence, effective identification of each energy storage technology towards each power quality factor is evidently pertinent. At the same time, alternative solutions to energy storage systems are necessary. For instance,

Table 9
Overview of various aspects of SGs and the specific problems.

Smart grid topics	Specific problems addressed
Energy efficiency [11,229,249]	Demand Response: Reduce peak load and manage energy consumption during high-demand periods. Load Balancing: Optimize distribution to match real-time demand, minimizing wastage and improving efficiency. Grid Optimization: Enhance overall grid performance for better utilization of resources.
RE Integration [17,48,250]	Intermittency Management: Smoothly integrate and manage the intermittent nature of renewable energy sources. Storage Integration: Improve storage solutions to store excess energy generated by renewables. Grid Flexibility: Enhance the grid's ability to adapt to varying levels of renewable energy generation.
Grid reliability [5,124,251]	Fault Detection and Isolation: Quickly identify and isolate faults to minimize downtime. Self-Healing Networks: Automatically reroute power to restore service in case of disruptions. Predictive Maintenance: Anticipate equipment failures and schedule maintenance to prevent unplanned outages.
Power quality [146,197,252]	Voltage Regulation: Maintain consistent voltage levels to ensure the quality of power supplied. Harmonic Reduction: Minimize harmonic distortions to enhance the quality of electricity delivered. Frequency Regulation: Stabilize and regulate the frequency of power supply for better reliability.
Cybersecurity [253]	Data Encryption: Secure communication channels to protect sensitive data transmitted within the grid. Intrusion Detection Systems: Detect and respond to potential cyber threats to the smart grid. Authentication Mechanisms: Implement robust authentication methods to prevent unauthorized access.
Consumer empowerment [254]	Real-time Monitoring: Enable consumers to monitor and manage their energy consumption in real time. Smart Meters: Provide consumers with detailed information to encourage energy-efficient behaviors. Tariff Flexibility: Implement flexible pricing structures to encourage energy consumption during off-peak hours.
Grid resilience [67,106,255]	Disaster Recovery Planning: Develop strategies to quickly restore power after natural disasters. Microgrid Implementation: Create self-sufficient microgrids to maintain power during grid-wide failures. Redundancy Systems: Integrate redundant systems to ensure continuous power supply in case of failures.

Table 10
Stats of SG for different countries.

Country	Region	Ref	Number of SG Projects	Total Budget (USD)	Payback Period (Years)	Energy Savings (%)	CO2 Emission Reduction (%)
USA	North America	[256]	50	2.5 M$	5	15	20
China	Asia	[257]	80	4.1 M$	4	18	25
Germany	Europe	[258]	30	8.8 M$	6	12	15
Brazil	South America	[259]	20	3 M$	5	10	18

the implementation of coordinated active–reactive power management through PV inverters combined with an energy storage system proves to be effective as the voltage stability is regulated more efficiently as compared to conventional solutions. In this case, energy conversion losses are obviated, and the storage life cycle is preserved. However, the participants, such as prosumers, independent power producers, and utilities, should be compensated for contributing to the power quality of the grid.

The flexibility of the power system is identified as an important parameter for forming numerous distributed generations based on different generation technologies. Considering that the smart infrastructure will consist of numerous renewable-based microgrid systems that are interconnected to the smart grid framework, Most microgrids tend to have the configuration of plug-and-play, so any islanding or isolation of power generation will inherently affect the whole system. A high number of renewable-based microgrids, though beneficial for the environment, will inevitably reduce power quality and increase the probability of grid failure. In this respect, the flexibility of the smart grid should be able to facilitate these variations. This introduces the potential for research and innovation towards the identification of flexible parameters and power elements in SGs, such as the ramping rate of renewable, flexible energy storage systems, the reactive power capability of smart PV inverters, and flexible energy markets.

Energy storage alternatives must be investigated simultaneously. PV inverters and energy storage systems can coordinate active–reactive power management to improve voltage stability, reduce energy conversion losses, and extend store lifespans. However, prosumers, independent power producers, and utilities must be fairly compensated for improving grid power quality. Diverse distributed generating technologies require power system flexibility. Smart infrastructure includes linked renewable-based microgrids, whose plug-and-play nature might cause system-wide issues if the power supply is isolated. While many renewable-based microgrids are environmentally friendly, they can potentially affect electricity quality and system reliability. Flexible parameters and power aspects, including renewable ramping rates, adaptive energy storage systems, reactive power capabilities of smart PV inverters, and flexible energy markets, must be researched and developed to respond to these fluctuations in the SG. RES intermittent and unpredictable nature and scalability make them incompatible with conventional grid standards.

Finally, grid standards need to be revised and introduced. For instance, current black start process consists of protocols considering a centralized and controllable generation system. However, with the introduction of renewables, energy market as well as bi-directional communication and information flow, the protocols need significant updates to consider the uncontrollable variability of renewables. In addition, protocols for large scale grid monitoring in concurrence with demand side response should be considered along with appropriate utilization of energy storage technologies for short- and long-term grid requirements. Since, energy is generated and consumed from numerous points in the power grid, the contingency towards reliable information flow in black start process needs to be suitably defined while maintaining security, privacy, and independency of the contributors in the smart grid. Such standardization leads to the enhancement of grid resiliency and flexibility.

Similarly, standardized protocols need to be defined for demand side management considering real-time communication between the prosumers and the operators as it directly contributes between optimal management of the grid's resources and the power balance. In similar, context, with introduction of prosumers and numerous small-scale renewables, proportional information access points will be increased with the need to enable real-time monitoring and control, especially for the operators in contingency situations. Therefore, the degree of cyber security threats and vulnerabilities increases requiring updated protocols for maintaining data integrity and safeguard during the data exchange between the distributed components.

Inverters facilitate seamless integration of renewable and a major grid redefinition if inverter-dominated grids. The degree of controllability over variable renewable energy sources in increased especially in terms of voltage and frequency control, fault ride-through capabilities, and grid support functions. Therefore, grid standardization of appropriate sizing, control theories, allocation, and utilization towards different challenges need to be appropriately defined, especially for black start process, islanding, and energy market. Considering these points, one of the major challenges in black-start process is establishment and selection of protocols in order to maintain a coordinated control and automation between the centralized or bulk utility generators and the distributed small scale generation systems. Therefore, regulatory framework needs to be defined for adapt to support decentralized generation, enabling fair compensation for distributed energy producers and facilitating grid access.

8. Conclusion

This paper outlines the requirements that are introduced with the need for smart grid formulation, renewable integration challenges, large-scale deregulated energy markets, challenges towards power system planners, and reservations of consumers to highlight some of the drivers hindering smart grid formation with associated research progressions. The introduction of RES that has the potential to be upgraded with contemporary communication and information technologies and effective design and planning collectively formulates the present global visualization of SGs. SGs are complex systems, and hence their deployment should be well organized and planned before their initiation while considering their efficacy for future technological and economic expansions.

We examine SG requirements in terms of renewable and grid perspective. Integrating RES, negotiating large-scale deregulated energy markets, and power system planner issues are discussed. We also presented consumer misgivings, important constraints that hinder SG implementation, and research advances. Integration of RES, ripe for improvement through modern communication and information technologies, and careful design and planning provide the worldwide blueprint for SGs. Given their importance for future technical and economic progress, these complex systems must be systematically designed and planned before installation considering security, interoperability, and grid standards. SGs have immense potential, but a good blueprint is essential for commencement, planning, and development. A comprehensive approach is needed to implement an intelligent energy system that meets current and future demands. Energy storage systems help integrate renewables; therefore, choosing the right technology for each power quality element is critical.

Considering the current technological level of the existing grids and their components, the unpredictability and transience of RES within a small-time frame combined with their scalability cannot be appropriately supported mainly in terms of the grid standards. Numerous solutions and analyses performed to effectively mitigate these challenges require state-of-the-art communication technologies and information systems. The successful integration of renewables at the generation as well as distribution levels ultimately depends on the transparency, security, and protocols of the information and communication technologies, and their direction of grid expansion will be governed by the interoperability among the elements of the smart grid system.

Most of the applied information and communication innovation is suitably aimed at improving energy efficiency, demand-generation balance, maximizing the utilization of energy assets, emission control, and operational cost reduction based on several different innovative approaches, technological solutions, and operational management strategies. Therefore, motivation and promotion of smart grid technologies are needed for customers to buy into the ideas of advanced energy management structures. However, from the perspective of system planners, developers, and end-users, such solutions primarily need a standardized protocol, reliability assurances, flexibility, and suitability for diversification that are inclusive as well as exclusive to smart energy, smart communication, and smart information solutions so as to achieve the present objective of renewable integration along with the potential to accommodate both the long- and short-term prospects of future targets associated with the electrical energy sector. Effective solutions require cutting-edge communication and information systems. Communication technology must be transparent, secure, and protocol-driven to integrate renewables. Interoperability between SG elements determines grid extension.

In this context, security and privacy are important aspects of smart grid technologies that require regulatory governance. Considering the high cost of renewables and smart grid infrastructures, and though the smart grid in theory provides adequate protection, utilities tend to neglect these functionalities to reduce costs and increase profits, which includes the risk of privacy leaks. For instance, when the utility outsources the smart information system to third parties, although such decisions enable a higher degree of information and communication flexibility with increased interoperability, the utility loses controllability and might risk the privacy of the customers. Accordingly, interoperability is another key factor that quantifies the success of SGs as well as reduces potential future redundant investments. Firstly, considering numerous geographical, social, and heterogeneous networks that are visioned to be interconnected and various technological options in energy systems, information, and communication for the smart grid infrastructure, a global standardized framework is pertinent to guide the establishment of interoperable SGs. This ensures effective collection, processing, analysis, optimization, and exchange of data that is pertinent to incorporating and enacting the main objective of SGs, that is, self-healing, reliable, cost-effective, flexible, and sustainable energy systems.

Declaration of competing interest

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

Data availability

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

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