Transmission Grids to Foster High Penetration of Large-Scale Variable Renewable Energy Sources – A Review of Challenges, Problems, and Solutions

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Abstract- Worldwide, integrating high shares of variable renewable energy sources (VRES) into the power grid is one of the most pressing challenges towards decarbonization and clean energy strategies. As VRES generation increases, it is imperative to support its economic deployment and use while securing the power system stability and reliability. The inherent characteristics of VRES demand expanding and modernizing the transmission grid, both infrastructure and services. In this scenario, transmission emerges as a key factor to foster such high penetration, being now the subject of renewed interest in the energy sector. Based on a thorough review of relevant literature, this work identifies, synthesizes, interrelates and explains the main challenges, problems, and solutions found in the integration of large-scale VRES, particularly, wind and solar, to the transmission grid. The main challenges considered relate to long-distance grid access, flexibility, stability and reliability, and resilience. They encompass many particular problems and solutions with elements of four defined dimensions: technology, economy, regulation, and environment-society. Out of the spectrum of conclusive ideas in this review, we highlight two of them. First, strengthening and expanding the transmission grid is the best technical solution to reach high penetration levels of VRES. An adequate transmission system is the only way to access high-quality large resources and provide abundant energy to demand centres. Second, the integration of high shares of VRES through the transmission grid needs a system-wide approach, not only VRES and transmission technologies themselves but also other related-mechanisms and actions, including all other power system components and stakeholders.

Keywords Transmission grid, large-scale variable renewable energy, integration, flexibility, stability, reliability, resilience.

1. Introduction

In the last few decades, significant and rapid changes have been undergoing in the way we produce, transmit, distribute, use, store and trade electricity. The electric power system is evolving from a vertical structure, relying on large, centralized thermal power generation with electricity flowed from large transmission-connected generation to passive distribution networks and price-insensitive consumption, towards a smart grid with a greater diversity of supply, dynamic flow between transmission and distribution-connected parties and flexibility of demand and generation. Three main drivers are guiding and accelerating this evolution of the electric grid and the energy sector in general, namely, decarbonization, decentralization, and digitalization [1, 2]. Of particular interest are decarbonization, issues of greenhouse gas emission, and energy efficiency to reduce pollution and implement a clean energy strategy.

In this energy transition to a carbon-free future, renewable energy sources (RES) are the main players called upon to lead the way. RES development and importance will continue to grow significantly in the coming years driven by declining costs, policies, government subsidies, sustainability goals, and technological advances. For instance, in the U.S., many states have renewable portfolio standards and Clean Energy Standards that mandate certain levels of renewable and carbon-free generation [3]. In the EU-27 Member States, RES made up 34 % of gross electricity consumption in 2019 [4], and in China, in early 2020, renewable energy comprised about 40% of its total installed electric power capacity, and 26% of total power generation, with solar and wind combined having more capacity than hydropower [5]. Companies are increasing their investments in and use of green power as part of their environmental programs; e.g., Google, Microsoft, Intel, Walmart, and Equinix were the top five users of renewable energy as of January 2021 [6].

Of the two main development models of power systems associated with RES generation, distributed generation and centralized generation [7, 8], we focus on the second type. This corresponds to bulk systems with large-scale RES generation usually located away from end-users, including offshore, and connected to a network of high-voltage transmission lines. In addition, we consider mainly wind and solar generation, since they will dominate growth in renewable-based electricity generation [9] and the other sources are likely to be limited in most countries [10].

To have higher levels of renewable energy penetration, governments and utilities should pay attention to careful planning, increasing flexibility, and advancing technology, and additionally to environmental, and regulatory issues as well as the many challenges brought by the characteristics of variable renewable energy sources (VRES) – wind and solar.

Early considerations of the actual and anticipated increase in renewable energy generation and its integration into the transmission network focus primarily on the risks, high costs, and system management issues associated with the expansion and adaptation of existing transmission infrastructure. They consider, in particular, policies related to transmission planning and consent processes, congestion, the nature and allocation of capacity products, and the recovery of costs associated with system development [11].

However, it was also clear that the above actions were not enough to integrate large quantities of VRES into existing transmission grids. Thus, within early works, there is literature (e.g., [12-16]) that explore different technologies that could enhance the transmission system with expanded or new capabilities. Those necessary to provide access for new renewable power plants, reliably handle VRES behaviours, and increase the system's power carrying capacity and expected dynamic power flow. The CIEE report [12] includes a long list of technologies and their development gap, and advice over the substantial costs of RD&D needed to create an effective portfolio of solutions. Authors in [13] present an interesting vision of a future smart transmission grid taking into account enabling technologies and summarize challenges and needs for future transmission grids in four areas: environment, market, infrastructure, and technologies. References [14, 15] cover synchrophasor measurement technology, and IT, data and communications paradigms. In [16], an overview of promising technologies and strategies is proposed and discussed in detail by different authors in response to the challenges of security of supply, integration of renewable generation, and the creation of integrated energy markets. References [17, 18] focus on the challenge of identifying and deciding, over the large variety of available transmission technologies, the best ones for future massive deployment of RES.

Other studies, e.g., [19, 20], continue to address the integration of RES considering the expansion of transmission networks and the necessity of planning and regulatory actions, including cost recovery, as necessary elements to allow the increment of VRES.

Since the early considerations on the transmission grid regarding the integration of large-scale RES, smart grids have gotten a lot of attention as a way to support the energy transition and the scale-up of renewable energy. Emphasis is given to the distribution grid and the flexibility and management of the demand-side and supply-side, leaving the role of transmission on a second plane.

Nevertheless, the relevance of the transmission grid is becoming apparent [21, 22] and several recent research reports and articles, e.g., [10, 23, 24], confirm that expanding and modernizing the transmission grid is imperative. These actions are necessary to access low-cost, remote RES and deliver large reductions in carbon and other air pollutants to reach energy transition goals. These studies corroborate as well that adequate transmission infrastructure and services are key for maintaining affordable and reliable electric service under any scenario for future renewable costs or carbon emissions and may incentive the creation of new jobs and lower electricity bills.

A previous study on electricity transmission [25] ends up with interesting conclusions. It points out that even in a highly decentralized scenario; a significant amount of large plants together with the bulk-power transfer capability of transmission will still be required. The transmission is necessary to provide access in the market to these plants; make sure the cheapest sources of electricity are available at all times; enable a cost-efficient transfer of power between regions with energy surplus and deficit; and maintain energy system resilience and robustness into the future.

Thus, transmission emerges as a key factor in this energy transition and power grid evolution, necessary to achieve higher levels of renewable energy penetration. Improvements to existing transmission networks, including their planning and operation, are crucial to a broader acceleration of the decarbonization of the grid and avoiding actual limitations on the use of VRES. For instance, limitations such as congestion and curtailment of large-scale VRES, curtailment of many renewable projects, or low energy prices because of congestion [26], and suboptimal investments such as the purchase of power from other sources regardless of cost and environmental impact, or approval of costly emergency projects to ensure service reliability [27].

Transmission improvements to boost the use of large-scale VRES can take several forms, e.g., new transmission lines, revisions of policies, technology upgrades, and new planning methodologies. However, to foster the penetration of large–scale VRES, transmission grids must overcome several challenges, problems, and constraints beyond technical feasibility and economic benefits, such as energy policies, climate change, market integration, and society's perception.

Against this background of energy transition and crucial changes the electricity industry is experiencing, our paper aims to summarize, interrelate, and explain the various challenges and problems that arise from the desirable and expected high penetration of large-scale VRES, particularly wind and solar, into the transmission grid and several potential solutions to address them. We consider references from the last decade for this review, including journals, conferences, and grey literature.

The main contribution of this review is to provide up-to-date information and useful knowledge regarding challenges, problems, and possible solutions found in the integration of large-scale VRES into the transmission grid. Nevertheless, it should be clear that, even though we focus on transmission, integration of VRES is a multi-entity problem involving multiple actors (e.g., VRES generators, transmission system operators, energy market operators, and regulatory bodies) and their interdependencies at different spatial and temporal scales. Thus, VRES integration involves the coordinated actions of these entities.

2. Review Motivation, Scope, Material, and Method

The requirements to target the full decarbonization of the power sector, mainly in the U.S., Europe, and China, are renewing interest in large-scale VRES and new and better transmission systems. This is consistent with several recent studies that indicate the urgency of upgrading and reforming the transmission grid.

Renewable energy integration into the power system is widely covered in the literature, from the concepts of smart grid, micro-grids, and related technologies to regulation, planning, and business models. We found that most of the work, including comprehensive reviews, focuses on specific issues, mainly related to the generation-side and demand-side of the power grid, with limited or no consideration of the transmission system. On the other hand, most articles about RES integration into the transmission grid concentrate on specific topics, even the reviews (e.g., [18], which focus on transmission technology solutions).

This trend accounts for a holistic review that summarizes the many challenges, problems, and possible solutions concerning an adequate transmission grid to foster high penetration of large-scale VRES. To the best of our knowledge, the literature lacks such an overview.

This work identifies and synthesizes relevant literature regarding this particular topic, collecting and structuring the main challenges, problems, and solutions for the integration of large-scale VRES into the transmission grid and creating an understanding of it for the reader. This is important for those interested in energy transition, policy, business strategies, and technology roadmaps for future development of transmission grids and power systems.

In this article, we consider sampling not only primary literature – books, journals, and conferences, but we refer to many high-level sources – research and technical reports, white papers, expert opinions, and fact sheets.

The approach taken in this review is the analysis of data from the references to compile, classify, and map challenges, problems, and solutions based on their nature and interrelations. This approach allows for understanding the various interactions among challenges, problems, and solutions. For instance, a solution that becomes a problem, several solutions applied to the same problem, one solution to address several problems, or a problem solved using several solutions.

We try to encompass challenges, problems, and solutions in a general scope, even though many references correspond to specific geographical realities in terms of particular power grids, technology availability, and jurisdictional issues of electricity markets, institutions, and regulation. The literature analysed and reviewed in this article corresponds to references deemed relevant to large-scale VRES integration into the transmission grid. The search focused on works that addressed the following topics: (i) challenges and requirements for integrating large-scale VRES into transmission grids; (ii) modern transmission technologies for VRES; (iii) reliability, control, and automation of transmission grids with VRES; (iv) economic, regulatory, environmental, and societal issues of transmission grid expansions and interconnections; and (vi) transmission grid security and resilience issues.

The reviewed references are classified under three categories: (a) type of reference, (b) specificness of reference (transmission or power system with a considerable treatment of transmission), and (c) main topic of reference. Fig. 1 shows the percentage distribution of references under the three categories, (a) type of reference (b) specificness and (c) main topic. The percentage values in the plots correspond to the ratio of the number of particular type of references to the total number of references. In addition, in Table 1 we compare the reviews referenced and summarize the topics covered in them based on the content explored in this paper.

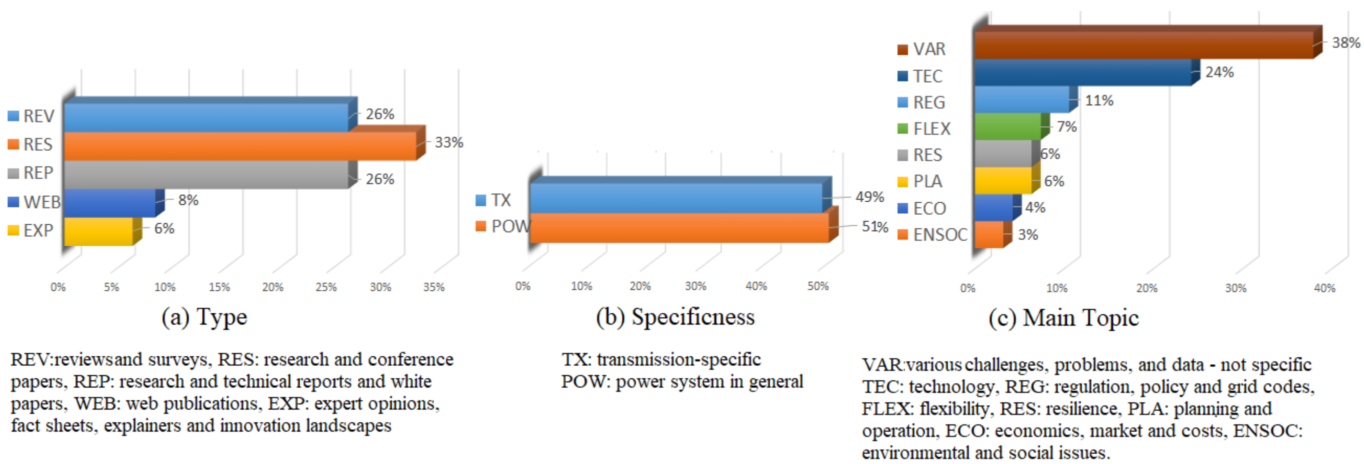

Fig. 1. Percentage distribution of references under three categories.

Table 1. Contents explored in review papers regarding the integration of VRES into transmission grids.

Perspective (Year): (T) Transmission grid (P) General power system
Content: (TE) Technology (EC) Economy (RE) Regulation (ES) Environment and society (FL) Flexibility (PO) Planning and operation (SR) Stability and reliability (RS) Resilience

		Content explored								
Ref		**TE**	**EC**	**RE**	**ES**	**FL**	**PO**	**SR**	**RS**	**Main topics**
[28]	P(2021)	*				*		*		Relationship between challenges and technological solutions for VRE integration.
[29]	P(2021)						*	*	*	Variable inverter-based RES integration, ongoing resilience research, and research related to the intersection of these two topics
[17]	P(2020)	*				*				Interrelation between challenges, VRES characteristics and solution technologies for increasing VRES penetration.
[30]	P(2020)					*	*	*		Power system flexibility - concept, characteristics, sources, and evaluation parameters. Impact of VRES penetration on stability, and methods for flexibility provision.
[31]	P(2020)			*		*	*			Status of the Indian power system (technology, regulation, and future targets) and review of relevant technical options, market mechanisms and planning approaches for flexibility.
[32]	P(2020)			*			*			Integration requirements and compliance control methods for RES plants, and solutions for compliance technology and control.
[33]	P(2019)			*			*			Marine energy installations, issues regarding their interconnection and requirements of eight European Grid Codes (overview and comparative analysis).
[34]	P(2018)	*			*			*		Challenges with current level and with future high penetration levels of photovoltaic into the grid, and existing, new and future solutions.
[2]	P(2018)	*		*						Evolution of power systems driven by decarbonization, digitalization and decentralization, and their key enabling technologies and regulatory framework.
[18]	T(2018)	*								Modernization of bulk transmission systems - regional visions, challenges, technology assessment, research and pilot projects.
[35]	P(2018)						*	*		Diverse operational challenges for dynamics, control, and automation of power systems with high RES penetration.
[36]	P(2017)	*						*		Various technical and operational issues and solutions to achieve high RES integration.
[37]	P(2017)						*			Some challenges and solutions to integrate high levels of VRES into electric power systems.
[38]	P(2016)			*		*				Transformative process to enable a flexible, stable and reliable power system based on variable energy resources.
[39]	P(2016)	*						*		Stability issues and measures to enhance performance of power systems with high penetration levels of wind power.
[40]	P(2016)			*			*			Trend of large-scale photovoltaic power plants at transmission level, related grid codes, challenges and solutions for their integration.
[41]	T(2016)						*			Experiences and management of curtailment in different countries with high levels of wind and solar power.
[42]	P(2016)	*				*	*			Flexibility needs and measures, and other elements (regulation, markets) to support VRES integration.
[43]	P(2014)						*			Power quality issues due to VRES integration.
[44]	T(2014)	*								Transmission grid extensions and transmission technologies for integrating renewable energy sources.
[45]	P(2014)				*					Qantitative assessment of social acceptance, factors of discontent for transmission infrastructure and acceptance improving strategies.
[46]	T(2013)		*	*						Analytical framework to study the challenges of integrating remote RE generation, and transmission investment schemes.

[47]	P(2013)	*					*	*		Challenges of integrating RES into smart grids, diverse storage technologies, and control strategies.
[48]	T(2009)		*							Transmission studies that include wind power to study transmission costs needed to access wind generation.
[11]	T(2008)		*	*			*			Processes and approaches to transmission system planning and operation with RES in Europe and the US.

3. Features of Large-Scale VRES and Dimensions of Challenges, Problems, and Solutions

Large-scale VRES have the following five features (Fig. 2) that make their integration into the transmission grid challenging:

Variability, intermittency, or fluctuation: it describes the change of generation output due to weather fluctuations. It makes forecasting critical for maintaining the reliability of the grid. The temporal variability of RE generation makes the supply uncorrelated with the demand pattern [49].

Uncertainty or low predictability: it describes the inability to predict the timing (on the scale of seconds, hours, and days) and magnitude of the changes in generation output [49]. As RE generation forecasts deviate in real-time operation, the uncertainty of the output creates scheduling challenges. Furthermore, sudden generation inrush from RE generators at high-resource-potential regions creates localized grid congestion [50].

Availability, geographic diversity, or location constraint: Geographic distribution of VRES is not even, and potential generation sites with high-VRE resources are generally located in specific areas that do not coincide with centers of high electricity demand. Wind and sun resources, for example, are often particularly abundant offshore and in deserts, respectively [50]. Unlike coal, gas, or oil, it is not possible to transport VRES to a grid-optimal generation site, requiring transmission lines for their delivery.

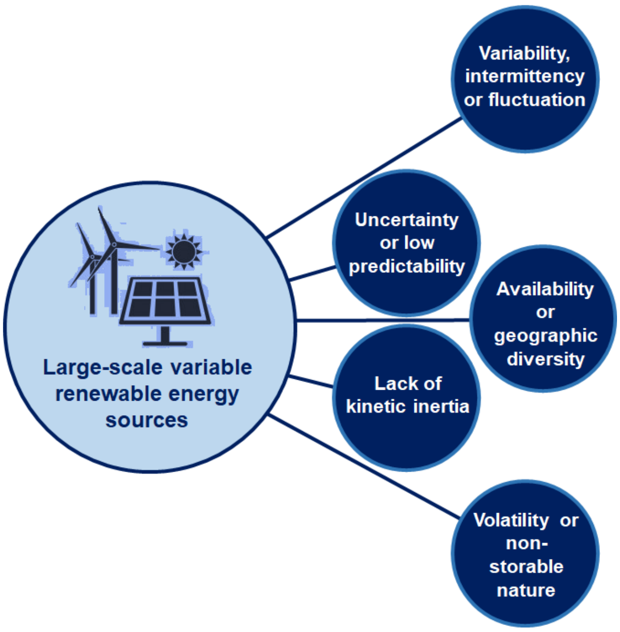

Fig. 2. Main features of large-scale VRES.

Lack of kinetic inertia or non-synchronous characteristic: RE generators are nonsynchronous and their significant penetration can cause loss of rotating inertia and damping torque, affecting the overall inertial response of a synchronous power system. This characteristic weakens the transient stability of the system and leads to voltage instability, faster frequency excursions in cases of imbalance between supply and demand, and complicates fault detection.

Volatility or non-storable nature: as opposed to hydroelectricity or biomass, wind and solar energy are not dispatchable and cannot be held in a wind or solar reservoir for future use. The fast-changing, uncertain and evanescent nature makes it volatile, requiring some sort of energy storage system as a buffering mechanism to cope with it.

Thus, high penetration of large-scale VRES increases the level of variability, uncertainty, and volatility, while reduces the inertia of the grid and limit the location availability that a system operator has traditionally managed in the past. This adds a degree of complexity and increases the demand for ancillary services and balancing energy overall.

From the overview discussed in the introduction, we can conclude that to reach some of the energy transition goals is necessary the exploitation of large-scale VRES, which in turn requires the transformation of the transmission grid to foster a safe, efficient, and cost-effective integration of them. However, this integration needs to address many challenges and problems with different solutions. To give some relational perspective, we define four interrelated dimensions as illustrated in Fig. 3 and associate the challenges, problems, and solutions with one or several of these dimensions. They refer to and include the following:

Technology - technological elements, from hardware components (inverters, controllers, cables and conductors, protection devices, sensors, meters, PMUs, communication infrastructure, others) and software components (protocols, databases, models and simulators, management systems, others) to technical tools (planning and operational tools, analyses and assessments, others).

Economy - costs associated with projects developments, allocation and recovery of costs, government subsidies, investments, operational and maintenance system costs, electricity costs, social and environmental costs, electricity market (design, implementation, and operation), energy price, and others.

Regulation - directives, actions or processes, made by authorities (standards, policies, codes, laws, restrictions, incentives, others).

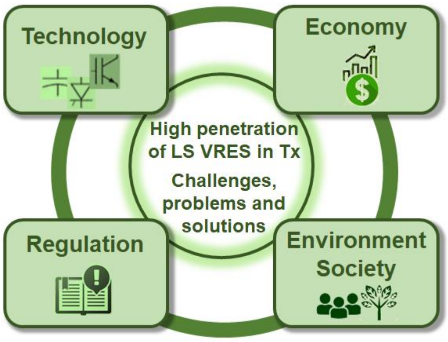

Fig. 3. The four dimensions of the challenges, problems, and solutions.

Environment-Society – elements associated with land and marine space use, public opposition to infrastructure construction or deployment of technology, environmental disruptions, health concerns, and others.

4. Challenges to The Transmission System, Problems, and Solutions

For the following discussion, we define a challenge as a demanding task that needs significant effort to be overcome or complete successfully, and a problem as something that needs attention and solution because it causes difficulties and has an impact on both directly and indirectly related things.

As seen in the previous section, variable renewable generation exhibits properties quite different from traditional generation and loads, which pose complex challenges and problems for their successful integration into the transmission grid. Some of the challenges and problems faced by the transmission grid—and the power system in general—to achieve, effectively and efficiently, a high penetration of large-scale VRES are:

- to construct a geographically dispersed grid,
- to provide timely adequate grid delivery capacity, and avoid generation curtailment and depressed or negative energy prices,
- to deal with voltage and frequency fluctuations in a very low-inertia system,
- to create adequate financial and other types of markets to trade energy, avoid economic inefficiencies, and satisfy the increased need for ancillary services, and
- to maintain system stability and reliability, and enhance security and resilience.

These challenges and problems require new or expanded capabilities for the grid. As we discussed in the following sections, new transmission technologies and other technical-economic-regulatory mechanisms offer the prospect of providing these new or expanded capabilities.

In the literature, we identified the following main challenges to the transmission system (Fig. 4) which arise from the features of large-scale VRES and encompass many particular problems and solutions from the four dimensions:

- To enable bulk power long-distance grid access to large-scale VRES
- To enhance the flexibility
- To improve the stability and reliability
- To enhance the resilience

As it will be apparent from the following discussion, many solutions concern two or more challenges or problems, and in many cases, some solutions to specific challenges or problems create other problems that demand other solutions. As the complexity of the system grows, challenges, problems, and solutions require a holistic study to reach the objective of having a flexible, reliable, secure, and resilient power grid with a high penetration of large-scale VRES.

4.1 Long-Distance Grid Access

Large-scale VRES have a not even geographic distribution and spread over wide remote areas, far from load centres. This imposes a location constraint on system planners and operators. To accommodate reliably large amounts of new such VRES, transmission infrastructure is essential. This is the only option able to interconnect distant VRES removing the location constraint and eliminating the mismatch between supply and demand centres.

Furthermore, providing access to VRES over a large area through an adequate transmission network allows cost-effectively integrating a high penetration of low-cost, high-quality resources, and helps to reduce the effects of the variability and uncertainty [49]. Large transmission grids connecting disperse resources ensure that a higher level of wind and solar output power is always available [24], reduce the average variability and uncertainty of weather and reduce the prediction errors since variability partially cancels out when considering spatially extended areas.

Nevertheless, building new transmission infrastructure or enhancing existing transmission grids brings about many problems related to the four dimensions [46]. For instance, moving more power through high-voltage systems over routes that are operating at close to capacity, difficulties in siting and building new power lines due to regulatory constraints or public opposition, extended time for approval of long lines, uncertainties in transmission network planning and operation, or problems caused by network topologies and connection schemes. In the following sections, we discuss these problems and their possible solutions.

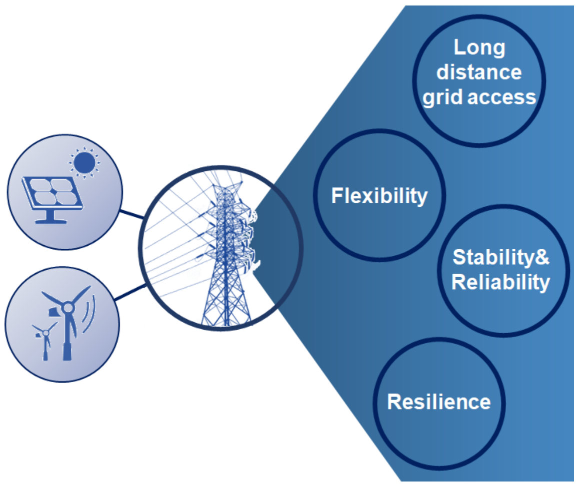

Fig. 4. Main challenges to the transmmission grid´s capabiltiy to highly integrate large-scale VRES.

4.1.1 Uncertainties in Transmission Network Planning and Operation

Large-scale VRES integration demands an evolution in transmission network planning and operation. Traditional network planning focuses on delivering capacity and considers both transmission and VRES independently. This must change, and new transmission planning approaches should point to integrated studies, including new planning algorithms to better integrate transmission constraints and the increased uncertainty resulting from the VRES [51], and focus on maximizing the permanent delivery of renewable energy and minimizing the possible development impact and conflict generated by VRES projects [52]. An interesting example is a multi-objective transmission grid-planning model based on flexibility and economy proposed in [53]. Authors show that the planning results can improve the transmission capacity and the renewable energy consumption, enhancing the flexibility, economy, and reliability of power systems.

A particular issue is the planning problem of what comes first: the VRES projects or the transmission infrastructure [50]. Generally, building new transmission lines requires availability of VRE generation, but construction of new power plants is only likely if transmission will be available. In addition, one must consider that the process of planning for and developing, new transmission can be very lengthy.

One solution to this problem is to determine competitive renewable generation or energy zones [50, 54]. These are geographic areas with high-quality VRES, suitable for development, demonstrated interest from project developers, and with a pre-determined maximum amount of renewable capacity or electricity generation over a certain period. Thus, with this information in advance about the location and expected generation capacity of these zones, the required grid infrastructure is planned and the associated costs socialized. In addition, renewable energy zones allow planners to incorporate policies and regulations that enable a VRES effective integration. Well-planned energy zones could ensure the most cost-effective and least disruptive transmission construction.

Regarding transmission planning, another issue is the cost-effectiveness trade-off between less favourable resources closer to load and higher-quality resources distant to load. Transmission planning should take this into account as well as curtailment of small shares of VRE generation to avoid congestion and oversized transmission capacity looking for a balance between the cost of VRE generation and the cost of grid connection [20, 50].

Another consideration in providing grid access to wide-area distributed VRES is to consider much larger geographic areas and/or inter-systems, including multi-states/countries transmission systems. This calls for new cooperative inter-transmission system planning and development mechanisms [10], but it faces the difficulties of regulation and policy, as well as planning coordination.

Therefore, planning frameworks should coordinate between expectations of various market participants (planners, developers, system operators, nongovernmental organizations, and others), adjacent systems and policies, consider public policy obligations, cost-benefit assessments, and accurate cost allocation, and should find the best solutions, determine beneficiaries and benefits, and ensure widespread acceptance.

To support the high penetration of large-scale VRES, transmission system operation needs to evolve and support intelligent automation at all levels. Operators must increasingly improve three areas of transmission systems operation: (i) state estimation, (ii) dynamic capability assessment, and (iii) more control of the system power flow [38]. For instance, transmission operation now has to deal with more dynamic reserves capacities and balancing management, short term forecasting of VRES and interconnected systems cross border flow management, VRES impacts on system normal and contingency flows and voltage, new ancillary services to maintain reliability, and innovative operation of energy storage systems. In addition, modern Supervisory Control and Data Acquisition (SCADA)-systems and Wide Area Monitoring Systems (WAMS) must provide advanced monitoring features, increased pervasive control, and decentralized decision-making based on two-way communication.

4.1.2 Extended Time for New Transmission Lines Availability

Times for delivering new transmission grids and interconnection projects can last between a few years to decades, depending on the administrative complexity and public opposition, given first, that the necessity of the line construction is proved [18, 50].

One of the main liabilities delaying the plan, permit, and construction time of new transmission projects is an outdated and non-effective regulation. Generally, projects require three broad classes of regulatory approvals: a certificate of public good, a siting approval, and the legal authority to take land [27]. In each case, several elements lead to delays and even cancellation of projects, requiring in many instances political intervention to ensure progress towards completion, usually having the projects already fallen behind schedule. Furthermore, in the case of inter-state or interconnections between countries, policies and regulations are more difficult to coordinate and match all interests. Therefore, it is complicated for network planners, developers, and network operators to ensure timely and accurate connection capacity for remote VRES.

Within policies and regulations, environmental and siting legislation is critical, since public acceptance or opposition is a sensitive factor that must be considered before achieving a transmission facility approval and its construction. Public opposition may come from local stakeholders and authorities where the facility is to be located, who perceive that the project may create some negative impact on the environment, or negative economic impact on land and business owners, as well as not a fair distribution of the costs and benefits affecting them.

Siting of transmission infrastructure is a particularly complex problem affected by different constraints that may limit and delay long-term regional transmission planning and construction. In [55] authors use a two-tier framework based on several datasets and statistical analyses to address the transmission line siting difficulty and its major causes for the case of power lines in the United States.

It is worth noting that, on the one hand, transmission grid expansion and modification are required for VRES integration and the success of the energy transition, but on the other hand, new transmission infrastructure frequently faces public opposition, whereas RES and the energy transition are generally perceived positively [56]. The study in [56], conducted in Switzerland (but applicable to other countries facing similar challenges), also demonstrates that high-voltage power lines are perceived positively and publicly accepted at the national level, but not at the local level. Public opposition is especially strong when new construction is required, and it is heavily influenced by the distance between energy infrastructure construction and towns, as well as the age and education of those affected.

Thus, to reduce the time for new transmission infrastructure availability and gain its acceptance, it is necessary to update policies and regulations and streamline the planning, permitting, and construction process of new transmission and interconnection projects, collaborating with local authorities and stakeholders, scientists, local experts and communities in this process. The following actions and elements may help to achieve these goals [26, 45, 57-59]:

- implementing federally identified transmission corridors;
- increasing utilization of existing transmission rights-of-way through reconductoring of existing lines, increasing line voltage, or adding additional circuits;
- converting existing AC transmission corridors to HVDC;
- undergrounding HVDC transmission lines siting alongside rail corridors; increasing network utilization by implementing flexible technology such as dynamic line rating, FACTS or storage systems;
- selecting site location, particular pylon designs and siting, and low-disruptive infrastructure that do not affect or change significantly the environment or local aesthetic;
- placing pylons further from homes and schools to help ease worries and ameliorate any health effects; compensate locals with monetary means or positive outcomes from the project;
- integrating vegetation management by selecting and planting low-growing plants in corridors ; and
- collaborating with scientists, local experts and communities to eliminate or reduce safety concerns, noise, pollution, landscape destruction, ecological change, decreased property values, the perception of diminished viewshed and procedural injustice.

4.1.3 Investment and Cost Allocation

High penetration of large-scale VRES needs new transmission infrastructure, and secure financing without access to transmission is always complicated. However, to attract investment for building transmission facilities is very challenging, since controlling and recovering the costs of building, operating, and maintaining these facilities is very difficult. Many questions must be answered — e.g., how can costs be contained, how are the costs allocated, who are the beneficiaries (direct and indirect), what are the benefits to the network users and stakeholders, how are developers compensated?

In general, classification of investment for building transmission facilities include two broad models, regulated or merchant, depending on rules about the ownership and revenues. There could be other models as concession-based.

In the regulated model, the investment is defined, promoted, and approved by the regulator authority and the new asset will become part of a regulated transmission owner (TO). The objective is to select those transmission network investments that best serve the interests of the network users as a whole. The regulator sets the allowed revenue to cover the capital and operational costs of the TO, and the TO recovers the transmission revenue from users.

On the other hand, the merchant model corresponds to investments promoted by private parties. They could be merchant entrepreneurs or network users looking to invest in a transmission infrastructure for commercial exploitation. It is important to notice that transmission investment in the merchant model requires regulatory and planning approval but its future revenue is not guaranteed by regulation. As a result, merchant investments face uncertainty and potential revenue shortfall due to risks of under-utilization and regulatory changes [60].

Costs-benefits assessment of new transmission investments is a significant element for network planners and developers to justify investments. It is crucial in the case of transmission infrastructure built to serve distant location-constrained renewable resources. For instance, consider the planning problem of what comes first, the VRES projects or the transmission infrastructure, and the cost of such investments. When considering distant VRE sites, the construction of the connection grids is cost-effective only when sufficient VRE generation capacity is built or firmly planned. However, the problem is that the generating capacity of initial VRE projects is often low. Therefore, it is necessary to find a way to pay for the transmission before the full VRE capacity is available [20, 50]. Thus, the transmission grid cost allocation and recovery for connecting remotely distanced renewable generators can be very challenging since, for example, paying for the transmission line by the generator in advance is a disadvantage, how to include future generators in this cost is controversial and even when significant shares of total investment costs go to generators, there are other beneficiaries.

Another example of such a problem is the construction of offshore wind farms. In general, costs of support structures for the large turbines, lengthy transmission cables, and extended transmission systems can be a significant obstacle, not to mention difficult weather conditions, high wind speed, and deep-water, environmental issues, rights of way, and impact on other marine stakeholders [61].

Allocation of the cost-benefit of transmission investments is also particularly critical in developing cross-border transmission network projects comprising multiple states/countries, multiple system operators, multiple incumbent transmission owners, and multiple regulators, which serve several markets and may have indirect beneficiaries. This is so, as the transmission system (widely considered a natural monopoly) is usually subject to strong regulation, and new transmission infrastructure depends on regulatory approval [50].

As shown in [62], grid extensions may have various economic effects. On one hand, grid extension may reduce the local market effects of VRES and benefit other power plants (mainly baseload technologies) providing more homogeneous and stable electricity prices and larger revenues. On the other hand, they may create inequalities among power plant owners, and disadvantages for importing regions and mid to peak load technologies.

In general, setting the beneficiaries and benefits for cost allocation purposes is a major concern since it is impossible to measure who benefits from new transmission lines and facilities and because cost-benefit allocation occurs even before construction begins. Moreover, beneficiaries and potential benefits in the long term are difficult to project because it is not known how the grid will be used in the future. Thus, to reach a fair allocation of costs-benefits is often difficult — if not practically impossible.

There are several cost allocation methodologies considering the complexity of projects, the entities involved, existing regulations, and other factors, but new infrastructure projects must assess their own requirements and use a particular cost-benefit allocation mechanism. This is fundamental since, in the absence of clear and stable cost allocation regulations or agreed-upon mechanisms, the cost-benefit allocation settling could become a severe barrier to new investment projects.

4.1.4 VRES Connection and Long Transmission Lines

Solar PV and wind generators are connected to the grid with converters, power electronics devices that offer a significant advantage regarding grid flexibility. Nevertheless, the aggregation of different renewable energy plant types onto the transmission grid comes along with unique reliability considerations at their point of connection. For instance, contrary to conventional generation, converters have no rotating mass and thus no intrinsically mechanical inertia. In addition, they contribute to limited short-circuit power and may cause harmonic oscillation problems, leading to rapid frequency variation and grid instability. Reduced inertia will also challenge the frequency ride-through capability of grid-connected power electronics, so they need to receive attention, especially during grid fault conditions [63]. Further, the increased adoption of more advanced electronic-based devices has increased the amount of data requiring higher communication capability, and faster control responsiveness for the grid.

Besides technical advances on converters, modernizing transmission system operator (TSO) connection codes is another solution to cope with the previous problems. These codes specify the various technical requirements for connecting power system resources and loads to the transmission infrastructure during normal and exceptional operating conditions [64]. Several needs have to be considered such as requiring VRE to contribute with flexibility services (e.g., primary frequency response, and voltage control), and to include Low Voltage Ride Through (LVRT) and the High Voltage Ride Through (HVRT) specifications of RES generators. These are for the generators to remain connected to the network and cope with voltage sags (LVRT) and to withstand severe overvoltage profiles (HVRT) [30]. These requirements can also help to increase the visibility and controllability of VRE resources to system operators.

Another issue with providing grid access to large-scale VRES due to their remote location is the need for increasingly long transmission lines, which results in voltage drops, higher transmission losses, and inefficient and uneconomical network connections. This necessitates increased transmission capacity over long distances as well as better planning for transmission paths and connections. Some solutions to these problems include new cable designs, optimal network topology schemes, HVDC and HVAC flexible technologies, transmission incentives, and advanced tools for the calculation of dynamic and transient network stability.

4.2 Flexibility

Flexibility is not new to power systems, but the high penetration of VRES, the transformation to VRES-full-based power systems, and the energy transition demand higher levels of flexibility. For instance, lack of power supply flexibility, which refers to the inability of controllable generating units and energy storage systems to suppress VRES output fluctuations, and lack of transmission flexibility, which refers to transmission congestion caused by a lack of transfer capability, usually leads to load shedding and renewable energy abandonment.

Flexibility is an important and complex feature of a power system that includes other properties and elements such as adaptation, reliability, generation, transmission, and consumption, operation, economics, and different time scales. There is no unique definition of flexibility, and it is constantly evolving and improving. In this regard, we use the definition provided in [64] to consider it quite complete. Power system flexibility refers to "a power system’s ability to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply."

The variable, unpredictable, and volatile nature of VRES is a key driver of new flexibility requirements, making flexibility a challenge. Furthermore, VRES themselves are flexible resources that can be exploited to provide flexibility services to address several operational issues related to modern power systems. Different flexibility requirements result from variability, uncertainty, contingencies, and congestion.

Many technical, regulatory, and economic "enablers" exist to improve grid flexibility and accelerate the integration of renewable resources. Smart grid technologies, energy storage systems, policy, regulatory, and market instruments; transmission grid expansion and interconnections across large areas; combinations of different RES; improved connection codes; joint operations of adjacent power systems, and weather forecast models are a few examples. Ref. [65], for example, provides an Austrian case study that develops a cost/benefit analysis of transmission grid expansion. The authors conclude that it is necessary to expand the system and implement innovative technologies to ensure a flexible transmission grid with capacity to support optimal VRES integration without congestion and redispatch measures, significantly reducing VRES curtailment.

Implementing and exploiting flexibility is a necessity in all aspects of the power system, from generation and transmission to distribution and demand [66, 67]. However, it is unclear how to accomplish this effectively and efficiently, particularly how to improve flexibility for VRES-grid integration and maximize its potential. The flexibility challenge is significant, and we discuss it in this section in the context of transmission grids and large-scale VRES integration.

4.2.1 Planning and Operational Flexibility

As discussed previously, planning and operation become more complex with the massive integration of large-scale VRES, which brings great uncertainty. This requires including flexibility as a key element in both, planning and operation. Nevertheless, only a small number of planning methods discussed in the literature consider the application of flexibility, and from them, a very few at transmission-level (e.g., [68, 69]).

Therefore, grid integration studies and planning processes for VRES need to consider the generation output variability and uncertainty, their impacts on the power system and the flexibility requirements to manage them. Thus, besides traditional tools such as capacity expansion models, production cost models, and designing the transmission system based on expert judgment and deterministic simulations, other elements must be included in an effective grid integration analysis and planning.

The design of the transmission network, in particular, is an important factor in determining the system's flexibility. As a result, new transmission grid-planning methodologies should consider the entire structure of existing transmission grids, as well as their scenarios describing the future evolution of the system with high penetration of VRES, evaluate the individual impacts of transmission constraints on flexibility availability, and consider strengthening the transmission network with flexibility enhancements that will provide operational flexibility. Table 2 includes some of the elements discussed in [17, 30, 54, 61, 68] to improve planning and operation flexibility in power systems with high VRES shares and limited transmission capacity.

To share flexibility resources among balancing areas, transmission grid expansion and reinforcement are necessary but not sufficient. These grid interconnections need a coordinated flexibility framework to facilitate the cooperation between transmission system operators and the consolidation of the operational flexibility they may provide [66]. Aside from the various technological means (e.g., HVDC interconnections and FACTS devices), effective coordination helps to increase transmission flexibility, enable more transmission capacity, and reduce net variability across the power system by facilitating efficient and decentralized resource sharing. Otherwise, improper use of or unwillingness to provide flexibility can lead to reliability and security problems, and even higher operational costs for balancing. A framework to coordinate flexibility may include relevant information and tools such as the cross-border transmission line limits, the available flexible resources in neighbouring areas to manage contingencies occurring in a particular area, multi-area optimal power flow, and high-resolution plant-level forecasts and nodal injection forecasts [61] for managing transmission congestion. In addition, joint operations of adjacent power systems and the interoperability of smart grids improve operational flexibility.

Table 2. Elements to enhance flexibility in planning and operation.

Planning flexibility	Operational flexibility
• Improved generation and weather forecasting. • Identification of system flexibility requirements and costs associated with large-scale VRES higher penetrations. • Flexible transmission, which refers to the extension of intra-regional and interregional transmission lines to bring in additional balancing resources to reduce net variability and enable flexibility by aggregating generation resources. • Probabilistic transmission planning (to reflect the probabilistic nature of outage and system parameters). • Coordinated generation and transmission analysis and planning. • Optimization of size and placement of flexible and renewable sources. • Use of energy storage systems.	• New transmission lines for balancing electricity generation over a wide area, facilitating exchanges with neighboring regions/countries, and linking regional and international power markets. • FACTS controllers, HVDC connections, and phase-shifting transformers to better control the power flow, utilize existing transmission systems, and increase the reliability and availability of transmission lines. • Energy storage systems as an alternative to deal with demand peaks and avoid unnecessary network expansion • Better monitoring of the transmission system to increase the system awareness and implement dynamic line rating. • Intelligent network technologies and advanced network management practices to optimize network topologies, resources, operation, and transmission usage, and to minimize transmission congestion.

Grid codes are another element to enhance operational flexibility. For example, connection codes are key mechanisms to ensure safe and reliable interconnection and may help to ensure that VRE resources can connect to the grid and contribute short-term flexibility services (e.g. primary frequency response, reactive power and voltage control).

Besides, authors in [38] make notice that three main areas of transmission systems operation required optimization for flexibility: (a) state estimation, for the accurate evaluation of the state of the system, (b) dynamic capability assessment, for accurate estimation of the operational limits, and (c) capacity for control of the system power flows. Two elements for this are real-time monitoring and dynamic control of transmission systems, which enable efficient grid operations and access to flexibility services, whereas minimizing the need for new transmission infrastructure.

4.2.2 Interconnections

Transmission grid interconnections at all levels—intra-regional, interregional, and international—would allow the development of flexible transmission grids. A flexible transmission grid provides many benefits by aggregating generation and balancing resources over larger areas, including [30, 54, 61, 70]:

- more capacity and flexibility for balancing generation and demand by facilitating power transmission from VRES-surplus areas to high electricity demand regions,
- smoothing out the aggregated variability and uncertainty of VRES, thus reducing problems associated with the intermittent generation and reducing the power forecast error of VRES,
- decrease of VRES curtailment,
- relief of energy transfer bottlenecks,
- deferral of new power plants,
- linking power markets, and
- reducing the requirements for ancillary services.

On the other hand, expanding transmission grids and providing interconnections face many difficult obstacles that include (see sections 4.1.2 and 4.1.3) obtaining regulatory approvals, controlling and recovering the costs, allocation of the cost-benefit, coordination of policies and regulations, environmental and siting legislation, and public opposition. All of these result in extended times for delivering new transmission grids and interconnections.

To counteract all of the above, instead of building new lines when possible, we may increase transmission capacity, power flow, and flexibility, and enhance existing interconnections by several means. They include reconductoring lines, increasing line voltage, converting AC transmission corridors to HVDC, implementing dynamic line rating, using high-temperature low sag conductors, FACTS and storage systems, undergrounding HVDC transmission lines, designing low-disruptive infrastructure, collaborating with the affected communities, establishing federal or international transmission corridors, and using existing interconnections as a flexibility source under new cooperative inter-transmission operations.

4.2.3 Technology as Flexibility Provider and More

Many transmission technologies are involved in the development and upgrading of bulk transmission systems to face different challenges, particularly those associated with the integration of high levels of VRES. Technologies' development, efficacy in addressing issues or opportunities, acceptance, and deployment depend on factors from the four dimensions – other technologies, existing infrastructure, policies and regulations, markets, and industry practices.

In this regard, it is noteworthy to indicate that there are barriers to the adoption of new transmission technologies [26]. Two such barriers are utility incentives based on large capital investments, like in the U.S., and reliability concerns. In the first case, utilities prefer to build new lines or reconductor lines rather than improve and optimize the existing system with technologies whose installation costs are low compared with the previous solutions. In the second case, concerns about the reliability impacts of unfamiliar, automated technologies drive utilities to persist with known solutions and be unwilling to adopt new ones.

In Table 3, we categorize those technologies designed to enable new or expanded transmission capabilities to improve not only the flexibility but also the capacity, stability, reliability, and resilience of the transmission grid.

There are several books on the subject of general or specific transmission technologies, but among the references, the interested reader can refer to [12, 16-18, 28] for more information on the transmission technologies for renewable integration. In these references, authors identify and discussed transmission technologies (not only from the technical perspective) to face different challenges, but mainly those related to the integration of VRES.

4.2.4 Market Mechanisms

Market-based mechanisms play an important role in providing balancing, managing transmission congestion, and dealing with other flexibility issues. They may also help to identify locations for new needed investments.

For example, not only the transmission system operator (TSO) carries balancing but also, partly, the electricity market. The TSO is responsible for the short-term balancing of the grid (up to the Imbalance Settlement Period) by contracting ancillary services in different markets (e.g, frequency containment reserves market and frequency restoration reserves market), while the electricity market carries the long-term balancing (intraday markets, day-ahead markets, etc.) [63].

In the future, TSOs expect to contract additional ancillary services in different markets such as inertia emulation from bulk renewable generation plants and reactive power provision [71].

Table 3. Transmission technologies for integration of VRES.

Infrastructure technologies	Real-time systems operations technologies
• Phase-shifting transformers • Passive and active filters • Real-time rating systems • AC overhead line and conductor technologies • Underground AC transmission technologies • Flexible Alternating Current Transmission System (FACTS) devices • High-Voltage Direct Current (HVDC) transmission technologies • Electric energy storage technologies • Superconducting technologies	• Disturbance detection, diagnosis, and compliance monitoring • Real-time congestion management • Real-time optimized nomogram operating tools • Ramp forecasting with renewable resources • Intelligent grid protection systems • Smart-grid system restoration with distributed renewable resources • Transmission switching for topology optimization
Transmission forecasting and planning technologies	**Technologies downstream the transmission network**
• Weather modeling • Load modeling • Uncertainty analysis and probabilistic forecasting methods for transmission planning • Probabilistic forecasting methods for congestion management • Probabilistic forecasting methods for real-time grid operations	• Smart metering for TSOs/DSOs • Distributed generation • Large-scale demand-side management • Electric energy storage technologies
Digitalization technologies	
Development, implementation, and deployment of all previous technologies are supported by advanced digital Information and Communication Technologies (ICT) with high computational power and large bandwidth communication networks, including artificial and computational intelligence.	

In addition, there will be more interregional and international coordination and cooperation on imbalance settlement and services provision to transport large volumes of electricity from low-cost production sites to where it is needed most. This may require market restructuring to implement various market mechanisms for effective and efficient exchanging of energy across multiple regions

One example is the European international energy market where power trading utilizes demand pattern differences with neighbouring countries as a source of flexibility and a balancing tool [31].

One important issue of markets is having specific price signals. The lack of accurate market prices makes it difficult to address congestion issues, locate flexibility assets where are most needed, establish exchange schedules dynamically, price power exchanges accurately, and, in the long term, incentivize investments in renewable energy and the required flexibility options [38, 50, 72].

For instance, [38] and [72] discuss the use of nodal market prices as an appropriate instrument of congestion management since they reflect local transmission conditions. Nodal market prices refer to geographically specific price signals. Both [38] and [72] indicate that granular-specific nodal prices are a powerful tool to cost-effectively address local congestion issues by flexibility available from different resources. A study referenced in [38] shows that, when comparing zonal, nodal, and uniform pricing approaches, nodal pricing scenarios resulted in the highest benefits. However, authors in [72] note that the creation of a European nodal pricing system is a complex operation with considerable political barriers, making its implementation difficult in the short term.

4.3 Stability and Reliability

Stability and reliability are two other key challenges faced by the transmission grid (and the power grid in general) that can be stressed by the high penetration of large-scale VRES.

Stability refers to the ability of a power system to return to stable or normal operation after some form of disturbance. It deals with the dynamics of the system under disturbances and its response, mainly with the control of frequency and voltage, as well as system recovery after outages.

In general, stability and control of transmission (power) systems concerns three stability conditions: steady state, transient and dynamic stability. Steady state stability refers to the capability of a system to maintain its initial operating condition after a small interruption or small and slow changes, or to reach a condition very close to the initial one when the disturbance persist. Transient stability deals with the ability of a system to return to a steady state condition after a sudden and severe disturbance. Dynamic stability involves the response of the system to small disturbances, producing oscillations, and its ability to maintain stability. Reference [35] provides an interesting discussion on the transmission system control and stability challenges imposed by renewable energy systems.

On the other hand, reliability refers to the ability of a power system to perform correctly as required and expected during a specific time duration; that is, providing the necessary electricity with the required quality to all points of demand at all times.

A blackout or power outage, in particular, is an extreme reliability issue. Disturbances or contingencies can occur at any time on the transmission system, caused by a variety of events such as an unexpected outage of a power plant or transmission line, energy constraints, natural phenomena, equipment malfunctions, or even operator error. Such disturbances can cause transmission system failures that spread across the grid and cascade to neighbouring interconnected power grids, resulting in a widespread outage with significant socioeconomic consequences. Thus, power system planning and operation must ensure that grid contingencies do not result in power outages.

The balance between electric energy production and consumption ensures the stable and reliable operation of the grid. However, the high-penetration of large-scale VRES plus long-distant transmission, expansion of capacity, and complexity to transmit this energy in dynamic situations may create serious unwanted conditions challenging the stability and reliability of the power system. Such conditions include loss of synchronism, large deviations in voltage and/or frequency, voltage collapse, flicker and harmonics, high transmission losses, transmission line overload, increased power oscillation, load shedding, and power outages, among others [35, 73, 74].

In the following sections, we discuss several important instability and unreliability concerns caused by a high penetration of VRES and various solutions to deal with them.

4.3.1 Stability and reliability concerns

Utilities typically have a number of technical concerns when it comes to integrating large amounts of large-scale VRES into the transmission network. The reason for this is that VRES integration may have a significant impact on grid stability and reliability due to both VRES inherent characteristics (variability, uncertainty, location constraint, lack of kinetic inertia) and grid inherent characteristics (e.g., actual infrastructure, topology, flexibility, and connection interfaces). For example, integrating a large number of VRES generators into a transmission network alters the steady-state and dynamic stability, putting strain on the actual infrastructure and potentially resulting in operation closer to grid stability limits [35, 74]. As a result, potential imbalances or disturbances introduced by VRES (e.g., significant changes in power flow patterns caused by weather conditions in different areas) necessitate system adaptation to the new generation. In addition, new VRES capabilities are required to ensure reliable grid operations (e.g., the ability to limit or reduce the output of variable generation to maintain system reliability during over-generation periods). As a result, several security and stability control actions are required to ensure the power system's safe, stable, and reliable operation and to prevent effects such as voltage collapse, angle instability, and undesirable power flow, among others. As VRES capacity covers a greater percentage of demand, stability and reliability concerns and requirements become more relevant [75]. The following are the main stability and reliability– related concerns for integrating high shares of VRES plants [17, 33, 35, 63, 71, 75-78].

Decreasing level of inertia. Traditionally, power system relied on grid-coupled rotating generating units to provide inertia and prevent system frequency from experiencing sudden changes, which can in turn cause stability issues. However, VRE generators provide significantly less (or none) rotational inertia in comparison to synchronous generators. Thus, the higher percentage of VRES, the lower the inertia, which may lead to faster and larger frequency excursions in cases of imbalance between supply and demand and the violation of dynamic stability regulations, resulting in turn into redispatch, curtailment of VRE generation or power being cut in certain areas.

Because of reduced inertia and higher volatility in the system frequency, the possible instability of the grid would be on a much shorter timescale (microseconds to seconds), tightening the frequency containment reserves requirement in terms of ramp-up time and the bid time interval. Therefore, to compensate for frequency deviations, automatic regulation reserves are required to respond much faster, more often and within wider operation ranges.

One solution is synthetic inertia to emulate the behaviour of synchronized spinning masses – see Table 3.

Power Quality. A large-scale renewable energy integration system comprises several components, including a large number of power electronic converters, DC lines, and smoothing reactors. Even though modern electronic converters offer lower harmonic emission and active filtering and control capabilities, resonance frequencies will inevitably occur within the system, and it may undergo harmonic oscillation, leading to grid instability, which in turn threatens the overall safety and reliability of the system, and may even result in a system outage. Thus, sub- and super-synchronous oscillation must be a matter of concern in electronic-based large-scale VRE systems. Moreover, VRE plants may have other power quality impacts on the system, such as electromagnetic transients and frequency and voltage fluctuations. All these phenomena are causes for concern, particularly for weak grids.

Insufficient reactive power provision. VRE deployment and simultaneous power transmission expansion requires higher levels of reactive power to maintain system voltage. Nevertheless, in comparison to conventional generators, VRE generators have lower reactive power output. The undersupply of reactive power reduces transmission capacity, and causes voltage drops and power lines overheat, leading to violations of dynamic stability regulations, redispatch or curtailment of VRE generation.

Decreasing level of short-circuit power. Inverter-based VRE generators have fault characteristics very different from those of conventional synchronous generators. They provide significantly less short-circuit power (fault current) in comparison to the latest and their response time depends on the programming of the inverter controller. Thus, under very high shares of inverter-based VRE generators, their short-circuit characteristics have a significant impact on protection systems and their coordination.

Generally, the large amount of fault current produced by synchronous generators is the basis for identifying certain types of faults and for time-overcurrent relay protection. However, because the fault-current contribution of inverter-based VRE generators is usually limited to 120% of their rated currents, protection relays might operate incorrectly since they will not be able to distinguish between normal overcurrent and faults based on short-circuit current levels. In addition, the fault current contribution from inverter-based VRE sources might not contain sufficient negative- and zero-sequence currents for the proper operation of directional relays.

Another issue related to this problem is the lack of sufficient detailed models for accurate short-circuit analysis with very high shares of VRES.

A low level of short-circuit power not only complicates fault detection but also increases voltage instability leading to violations of dynamic stability regulations, redispatch or curtailment of VRE generation.

Voltage instability. The dynamic change in the VRE plant's output could, in combination with other system events, cause unexpected and fast-changing conditions resulting in voltage instability. These events may include high consumption of reactive power at heavy load areas, improper locations or interactions of FACTS controllers, and power plant distance from load centres.

Voltage instability may seriously endanger the operation of transmission systems since it may result in progressive rise or collapse of voltage at nodes, loss of loads, or tripping of transmission lines and other elements, leading to cascading outages and large blackouts. Besides, voltage instability is a factor limiting the power transfer.

Fault ride-through capability. It refers to the desired capabilities for a power generator to ride through a voltage or frequency disturbance and its performance during and in post-fault conditions. Inverter-based VRE systems have limited fault tolerant capability. Thus, VRE plants may or may not be able to remain connected to the network for a certain period during disturbances, such as voltage sags or swells. Nevertheless, VRE plants are expected to contribute to manage faults, provide grid recovery from them and sustain the regulation of voltage and frequency, requiring then control methods to provide fault ride-through capability.

Spinning reserve. This refers to an extra reserve of available online power plants used to compensate for power shortages or frequency drops due to load changes and unexpected events (e.g., generators or transmission line outages or sudden drops in output power of VRES). Spinning reserves are necessary to ensure stability and reliability. Then, considering the variability and uncertainty of VRES, it is essential to have the availability of sufficient levels of fast-responsive spinning reserve in systems with a high share of VRES plants. Moreover, in such systems, in the absence of traditional generators, it is necessary that VRES power plants and energy storage systems provide the spinning reserve.

Forecasting and analysis. The most important scheduling input for weather-dependent VRE generators comes from weather forecasting data. Resource forecasting is critical for VRE power plants because variability and uncertainty have an impact on the power system's stability and reliability. More sophisticated tools and simulation models are required for forecasting VRE plant output over different timeframes (e.g., frequency, duration, and resolution) and simulating the physical behaviour of the electric grid under various scenarios. Accurate short-term VRE generation forecasting can improve not only unit commitment, operational planning, and dispatch efficiency, but it can also reduce reliability issues and, as a result, the amount of operating reserves required in the system. In addition, long-term weather forecasting may assist to the allocation of appropriate balancing reserves ensuring safe and reliable system operations.

Interference between transmission and distribution systems. It is a common practice to control and treat transmission and distribution systems independently from each other and asses their dynamics separately. However, the integration of renewable power plants impose changes in this practice due to several conditions. For instance,

- integration and operation of VRES power plants in the transmission level can affect the control of distribution feeders due to changes of power flow, new points of power injection and topological changes in the grid;
- the integration of renewable distributed generators into the distribution system can influence the dynamics and control of the transmission system by, for example, triggering reverse power flow from distribution back to transmission, causing stability issues that might lead to incorrect operation of frequency and voltage regulators;
- control and stability issues in assets such as energy storage units interconnected at the distribution level that are controlled by the transmission system operator.

Stability Models. They require further development to include accurate models for converter-based VRE generation and additional elements (e.g., synthetic inertia equipment) for conducting transient stability constrained optimal power flow and other studies in systems with high shares of VRES.

Unplanned power flows in interconnected transmission systems [79]. Unplanned power flows are a source of instability and congestion. They are mainly a consequence of increased penetration of VRES generation in a transmission grid that has insufficient capacity and lack of control infrastructure for routing the energy to far demand centres and the insufficient coordination of cross-border markets. An effective tool to deal with this problem are the phase-shifting transformers [80].

4.3.2 Solutions to Tackle Instability and Unreliability Problems

Grid instability and unreliability have significant technical, social, and economic impacts, making it critical to provide solutions that stabilize the grid and guarantee a reliable service. As indicated above, high VRES penetration raises a new paradigm in the configuration and operation of power networks, bringing stability and reliability concerns and challenges. In the following, we briefly describe the main solutions available to face such challenges. It is worth noting that we already discussed several of these solutions in previous sections, but they related to long-distance connection and flexibility challenges.

Integration requirements. Integration requirements, compliance technology, and control methods are essential components for improving the grid operation, stability, security, and reliability of any transmission (power) grid with a high proportion of large-scale VRES. References [32, 75] provide interesting overviews of essential requirements, compliance technology, and control methods for VRES integration toward grid stability and reliability. References [81, 82] have examples of these control methods and compliance technologies. The authors in [81] discuss a control strategy for integrating a hybrid renewable energy system. The strategy uses two stages, each with its own set of functions: converter control and grid control. In [82], the authors propose a high-frequency isolated dc-dc converter with low active snubber circuits to connect renewable energy systems. Based on a prototype, the experimental results validate the feasibility of the design as well as the converter's wide input voltage range, efficiency, and safety.

The technical requirements for integrating VRES into the bulk power system are determined not only by the design and capabilities of the connected VRE power plant but by other factors including the grid profile and the electricity market, as well as the penetration level of VRES.

The requirements are commonly set in regulations introduced by TSOs to guarantee that VRES plants' performance is similar to traditional power plants' and to facilitate their successful integration. VRES plants are required to enhance voltage and frequency stability, withstand various disturbances, and improve the power quality, reliability, and security of the grid. Table 4 lists the main requirements imposed on the VRE plants for their integration and some solutions to comply with them. Ref. [83] provides an interesting case study of some of the requirements listed in Table 4 for the connection of large utility-scale renewable power plants. It discusses the requirements of the South African Renewable Energy Grid Code Version 2.8 and includes some practical testing methods to determine compliance.

Congestion Management. Transmission grids may be constrained to accommodate new VRE capacity not only at the point of connection, but also through the paths of power delivery from the VRE connection to demand centres. With the high penetration of VRES and deregulated markets, existing transmission networks are compelled to operate close to system security and operating constraints. When transmission networks fail to transfer power based on the load demand, congestion occurs. Congestion is a serious threat to security, stability, reliability, and the economy, severely affecting the power system. For instance, congestion in transmission networks may cause blackouts, affect current and future transactions in the energy market, and raise prices in some areas of the energy market. Thus, modern congestion management methods with control actions are necessary to avoid and relieve congestion in the transmission system and use the available power efficiently without violating any system constraints. There are several methods (some based on market operations, others not) for managing congestion. Their implementation uses ICT tools like Artificial Intelligence (AI), Big Data, sensor networks, and real-time communications. These methods include:

- network capacity allocation protocols based on users/transactions necessities or priorities,
- methods based on nodal and zonal pricing or optimal power flow,
- taking out congested lines and re-dispatching of lines,
- operation of tap setting transformers, phase shifting transformers, and FACTS devices,
- load or source curtailment, generation rescheduling, topology optimization, and
- methods based on transmission sensitivity factors and available transfer capability.

Furthermore, grid reinforcement (e.g., transmission expansion) is typically required to alleviate severe grid congestion [84].

FACTS and HVDC. Flexible AC Transmission System (FACTS) and High Voltage Direct Current (HVDC) technologies based on fast-response power electronics opens up new opportunities for network controllability and better utilization of existing transmission systems enabling grid access of large-scale VRES and bulk power long-distance transmissions.

These technologies play an important role by reducing transmission losses, increasing reliability and availability of transmission lines, providing controllable interconnections among regions (facilitating open electricity markets), improving the dynamic and transient stability, and increasing reliability and resilience overall in the face of the variability and uncertainty of VRES. Among several benefits to the transmission system, we may indicate [44, 59, 85]:

- shortening of the electric distance in transmission systems
- enabling a line to carry power closer to its thermal rating
- reducing transfer reactances in bulk transmission corridors which increase significantly the transient and voltage stability
- providing continuous control of capacitive or inductive reactance
- minimizing high short circuit contributions
- regulating and controlling inter-area and local power oscillations, flicker, voltage unbalances and voltage variations
- providing frequency regulation and damping of dynamic oscillations and transient stability swings
- enhancing conditions to avoid congestion of transmission lines
- providing dynamic, fast-response reactive power to cope with contingency conditions
- controlling active and reactive power flows
- submarine applications (HVDC)

FACTS technology include several devices such as Static VAR Compensator, Synchronous Condenser, Static Synchronous Compensator, Thyristor Switched Series Capacitor, Thyristor Controlled Series Capacitor, Static

Table 4. Essential requirements for integration of VRE plants towards stability and reliability of the power grid.

Requirement	Solutions
Voltage regulation and reactive power control VRE plants have to respond to voltage fluctuations at their point of interconnection (POI) and provide voltage stability.	VRE generators with an automatic voltage regulation system. Use of active power, terminal voltage or reactive power to regulate the power factor at the POI. Provision of reactive power, at the POI, over the full voltage and frequency range under normal and fault operating conditions.
Frequency regulation and active power control VRE generators need to deal with frequency variation.	VRE generators with advanced frequency control system to manage their active power yield with respect to the frequency variations. These control systems require automation, use of real-time data, and communication with some central operation system to share information about dispatch schedule, regulation capacity, and power control commands. Some solutions also integrate energy storage systems.
Fault ride-through RES plants need voltage ride-through and frequency ride-through capability to avoid destabilizing the grid after fault events and after the loss of generation or load events.	VRE plants should withstand a fault and remain in operation during the fault and perform auxiliary services (e.g., injection/absorption of the reactive current) to ensure voltage and grid stability. Different solutions, based on hardware (e.g., improved topology of crowbar circuits, static synchronous compensators, dynamic voltage restorers, energy storage systems) and software (e.g., enhanced control methods based on fuzzy controllers, redesign control schemes of the inverters, flexible advanced algorithms) are available.
Spinning reserves Generation units must have the capability to provide increasing power output with high flexibility and high sensitivity to the system frequency.	High shares of VRE power plants require the capability of quantifying, dynamically and proportionally, the spinning reserves for the expected VRE output. Modern automated control systems and optimization techniques have to consider the variability and uncertainty of VRE sources. Models, algorithms, and simulations must include the impact of related factors (e.g., power and reserve cost, expected cost of power outages) on the optimal spinning reserve capacity.
Active and reactive power control	Advanced automated control systems using real-time data and communication systems must provide VRE plants with the capability to limit active and reactive power production in response to signals from the system operator.
Synthetic inertia VRE generators do not provide inertia to the system.	Inverter control strategies may provide synthetic or artificial inertia. This requires advanced control methods and additional hardware. Some solutions include energy storage systems (flywheels, supercapacitors, batteries), de-loading control strategies, and hidden inertia emulation controllers.
Monitoring and supervisory controls	Metering, SCADA and communication systems to provide real-time dynamic high-resolution monitoring and dynamic performance monitoring, together with control actions.
Power quality	Regulation and standardization can guarantee limitation and stabilization of harmonics, flickers, and voltage unbalances due to VRE power plants.
Protection systems Inverter-based VRE generators provide significantly less short-circuit power than conventional generators, affecting the protection systems.	Programming and coordinating the fault current capacity of inverters Using synchronous condensers to provide the inertia and fault characteristics of synchronous generators. Developing and implementing more advanced protection schemes that use current differential or other methods to detect and clear faults instead of traditional overcurrent protection schemes. New short-circuit impedance models for inverter-based VRES and advance tools to provide accurate short-circuit analyses.
Forecasting and analysis High variability of VRES makes weather and power generation forecasting crucial for stability and reliability.	Advanced algorithms, analysis tools and integration methods are necessary to deliver forecasts and information to system operators and integrate automatic response systems. Advanced algorithms based on Artificial Intelligence and Big Data for weather and power generation forecasting and analysis, with forecasts more accurate with increase time granularity for short-term predictions and high confidence levels.
Blackstart Power plants need to restore operation without relying on the external power transmission network after outages.	Blackstart plans must account for the capabilities and constraints of VRES and other generation sources, energy storage technologies, and power electronics interfaces. A blackstart with electronic-based VRES requires the ability to provide large in-rush currents that grid components need for a cold start, provide capacitive charging currents of un-energized transmission lines, maintain voltages within acceptable limits, and blackstart support for a sufficient period not to jeopardize system restoration.

Synchronous Series Compensator, and Unified Power Flow Controller. This last device is a great solution for dynamic load flow management. It reacts extremely fast and allows for both series and parallel line compensation, balance load flow, bypassing overloaded line sections, dynamic reactive power compensation and voltage control, using lines to physical limits without the need for safety margins, and even dampening disturbances such as oscillations and harmonics. Ref. [86] provides an interesting comparative analysis of the performance evaluation of a Static VAR Compensator (SVC) and a Thyristor Controlled Series Compensator (TCSC) using Artificial Intelligence. The optimization problem considers optimal allocation of FACTS devices for transmission loss reduction alongside maintaining the voltage magnitude of all the buses within the lower and upper bounds of the grid system.

When using FACTS and HVDC technology for stability and reliability, as well as effectively improving system performance, the need for analysis and control of operational parameters and interactions among different devices, as well as adequate allocation of such devices to avoid adverse responses, interactions, and operation, is an important issue. For instance, one device may influence and interfere with others in nearby zones, requiring local control and coordinated control between zones to avoid such conflicts.

Grid integration studies. Those studies concerning stability and reliability are critical, and particularly important for increasing VRES penetration along with the required transmission and capacity expansion. Integration studies aim to model and simulate actual power system operations, including response to real time disturbances, recovery time, fault tolerance, voltage and frequency stability, contingency response and decision processes made in committing power resources. All previous, considering detailed, transmission-constrained models, production-operation-cost models and statistical analyses of net load variations.

Artificial intelligence (AI). As indicated before, AI is a powerful tool that can enable fast and intelligent decision-making, resulting very valuable for a practical and smooth integration of large share of VRES and improving security, efficiency, stability and reliability in the grid.

AI technology applications encompass automated data processing in real time using advanced stochastic and statistical methods, monitoring and detection of disturbances and emergency or failure conditions, forecasting and analysis (weather, VRES output, transmission and load), congestion management, implementation of fully automated countermeasures to guarantee stability and reliability, among others.

There are several examples of ongoing initiatives using AI with IoT for Grid stability and reliability. Some of them are SmartNet (European Union), IBM Watson (United States), Fraunhofer Institute (Germany), DCbrain (France) [87] and PrognoNetz (Germany) [88]. All of them take advantage of AI capacity to process efficiently large volume of data to implement and enhance many applications including monitoring, ancillary services, decision making, grid analysis and management, metering, failure detection and prevention, forecast, and others.

Coordination between transmission and distribution systems. With the large integration of VRES at all levels, it is critical not to neglect or simplify the interaction between the transmission system and the distribution system [77]. With the emergence of renewable distributed generation and energy storage systems, distribution systems have become active and flexible. This requires the use of active models, unlike traditional models, in the dynamic behaviour analysis, with corresponding dynamic equivalents connected to the transmission network. For example, in [89], the authors propose a unified power flow algorithm for overall analysis of upper and lower networks considering the mathematical relationship of voltage and reactive power between transmission and distribution systems.

In addition, it is essential to upgrade the functions of security and stability analysis in real-time and have a real-time exchange of information between the transmission and distribution management systems for different power applications to cope with the increasing complexity, dimensionality, and uncertainty of larger power systems with high shares of VRES.

Market-based mechanisms. They are an interesting tool to enhance the reliability of the power system. For example, through balancing markets, reserve markets, ancillary services markets and other mechanisms, it is possible to match demand and supply in real-time, and manage transmission congestion, further enhancing the reliability.

Energy storage (ES). It is a valuable mean to compensate the variability and uncertainty of VRES generation and provide a tool to meet reliability needs and increase the use of transmission capacity. This is possible by capturing excess generation (avoiding curtailments) and dispatching it as needed when VRES power is low or not available, or under other conditions (e.g., congestion of transmission lines or faults). ES can enhance the reliability and resilience of the grid through short-term and long-term storage applications [78] for peak-shaving, transmission capacity management, power quality regulation, power injection during contingencies for stability, frequency response or other reliability standards at the transmission level, base-load bulk power management, and grid support by load levelling and load shifting.

Actual ES technologies at transmission-level include pumped hydroelectric, compressed air electric storage, flywheels, and batteries. They have the advantage of fast response (few minutes or less), but the purpose of the storage and the timescale of response may differ from seconds to hours depending on the application.

One interesting application is the so-called virtual power lines (VPLs) [90]. They are battery-based ES systems connected at certain points of the grid to support the existing network infrastructure and enhance the performance and reliability of the system. They could increase the import and export capabilities of existing interregional transmission lines and provide other services. VPLs are an alternative to expensive upgrades to the transmission infrastructure for VRES integration.

Up to date, ES on a utility-scale basis is not common, and has several regulatory and economic concerns. For instance, it is not clear its categorization – some legislation consider it as generation and forbid transmission utilities from owning it – or whether it will be allowed in a particular regulatory environment. Besides, utilities are not sure how investment in ES technologies will be treated and how costs will be recovered.

4.4 Resilience

Resilience, in general, refers to the capacity to withstand, adapt well to and recover quickly from adversity, threats, or significant sources of stress. Thus, in the context of the evolution of power systems to a decarbonized clean energy future with a high share of VRES and a high level of automation, the everyday more dependent critical infrastructure sectors and economy on electricity and the increasingly uncertain risk environment with potentially catastrophic events, resilience becomes a fundamental feature of power systems. As extreme and unpredictable severe weather events (e.g., heat waves, deep freeze), natural disasters (e.g., wildfires, earthquakes, geomagnetic disturbances) and malicious human-made – cyber and physical – attacks increase in frequency and intensity, resilience challenges to power systems arise and become more critical.

In this sense, a resilient power grid must be able to anticipate, withstand, adapt to and quickly recover from large, infrequent catastrophic events (including deliberate attacks, accidents, or natural incidents) and reduce the magnitude and duration of the effects of such events on the system degradation.

The transmission network is particularly important for the resilience of the power system. Without transmission, load centres and critical services cannot receive energy from generation plants. As a result, a robust transmission system will have a significant impact on supporting overall system resilience in response to a wide range of threats. For example, an enhanced transmission grid can lower the vulnerability to generators' and transmission lines' contingencies, provide more transfer capacity and access to more diverse (technologically and geographically) energy resources, provide stability and reliability under severe disturbances, and facilitate more connecting options and services support across regions during emergency situations. The study [91] explores and highlights the importance of transmission in grid resilience and describes how policies and investments concerning strengthening the transmission system will further enhance (cost-effectively) the resilience of the power system.

It is important and interesting to notice the differences between reliability and resilience. While reliability is a well-known and intensively applied concept, resilience is still developing. Resilience is related to reliability but broader; it further incorporates more extreme adverse conditions or scenarios than reliability and encompasses forecast, robustness, response, and recovery as fundamental features. One particular difference is the nature of the disturbing event. Reliability considers low-impact high-frequency events, while resilience deals with high-impact low-frequency events. In the first case, to quantify the preparedness of the system one can use deterministic methods with reasonably accuracy, but in the second case, probabilistic methods are necessary because of the randomness of the events. Reference [29] is an interesting survey addressing several aspects of resilience in power systems, including its relation to the integration of VRES.

One key issue is the investment in resilience. Currently, in contrast to reliability, investments in resilience and their prioritization face several obstacles [92, 93]. They include:

- absence of common used or standardized metrics for measuring grid resilience,
- resilience is typically associated with low-frequency events (disasters),
- there is not an established method for quantifying and estimating the costs and benefits of resilience investments,
- current assessment of resilience solutions do not systematically characterize the effects of available solutions,
- the responsibility for building, maintaining and improving grid resilience concerns multiple entities and jurisdictions,
- risk assessment have to consider many social, cultural, and environmental issues with qualitative and quantitative values.

4.4.1 Risk Factors for Resilience

Within the current context of evolution of power systems with everyday more VRES generation, open markets, interconnections, and adoption of disruptive technologies in all stages for monitoring, control, and automation, summoned up to emerging catastrophic threats (both natural disasters and malicious attacks), there are significant risk factors threatening the resilience of power systems. Some of the risk factors are:

Transmission systems and VRES are susceptible to weather conditions, and with the actual climate-change, extreme weather events with greater intensity and frequency are more likely. In addition, VRES locations and long transmission grids are vulnerable to longstanding natural disasters.

Exposed facilities and elements of the grid. Transmission towers and lines, large power transformers, and electricity substations and transmission control centres are easily identified and vulnerable to physical attacks. Particularly, transformers have the additional issue of long replacement times due to their specialization and reliance on third parties manufacturers.

Deploying smart grid technologies. These include many types of intelligent electronic devices and communication systems as part of supervisory, control and automation systems, which can provide new vectors for cyber-attacks. Hackers may disrupt the grid by producing erroneous or false signals, blocking communication, disconnecting equipment, stealing information, etc.

The fast evolution of cyber security threats and vulnerabilities, while deployment of defensive measures is very slow. This last is due to several issues, including limited capacity for detecting anomalies and intrusions, and sharing this information across organizations; presence of significant legacy systems, and utility-specific IT and operational technology system configurations; lack of security-specific technological and skilled personnel resources; challenges associated with multi-jurisdictional threats and consequences, and slow strategies to provide security updates.

The current approach to maintain grid security and resilience. This approach generally focus on addressing threats on each component within the grid independently rather than looking at the whole and considering the interconnections and interactions between components.

Lack of information on cyber-physical threats, hazard events, mitigation practices and comprehensive vulnerabilities assessments, and its exchange among responsible entities. Exchange of information faces several barriers related to classified information, liability and privacy concerns from industry, limited data and predictions on resulting impacts, and lack of details concerning the coordination and interdependencies of various systems and actors involved in regional and interregional energy system operations.

References [92] and [93] address a range of possible risks (due to different threats and vulnerabilities) for maintaining and planning for resilient and secure grids. In addition, they assess current approaches to manage and improve grid security and resilience, and consider elements to evaluate better strategies and enhance the resilience of the overall system.

4.4.2 Instruments to Enhance Resilience

Traditionally, the electricity industry manage the inherent vulnerability of the grid through redundancy and hardening of critical equipment, and major disruptions through restoration plans. However, these measures do not completely avoid outage risks and for the evolving power systems, they seems not enough for providing the necessary resilience to avoid or mitigate the negative effects of a large-scale outage. Thus, the challenge of resilience needs novel instruments to address it, including some of the following [29, 58, 92-94].

Transmission ties. Transmission upgrades, expansion and interconnection would increase transfer capabilities and reduce outages during extreme events, such as unusual weather conditions, fuel shortages, and multiple or sustained generation and transmission outages. Expanding and interconnecting the power grid would cancel out local fluctuations in the supply and demand of electricity, strengthen alternate paths for power to flow to distribution systems, provide access to diverse sources of power in an emergency, and may lessen the impact of any single grid-component failure.

Underground transmission cables. They can significantly reduce potential damage from climate impacts and save recovery costs. They are less vulnerable to climate hazards such as high-speed winds, wildfires, floods and landslides, than above ground cable systems.

Blackstart-enabled renewable generation. With the new technology, VRES plants may provide blackstart with the potential to offer more resilient options than the traditional fuel-based units. After an outage, utility-scale VRE plants could blackstart the transmission and distribution system, thus powering the load.

Energy storage. ES systems can provide the “shock absorber” capacity to withstand stresses with little or no loss of performance. ES systems can avoid or mitigate outages by, for example, supplying the power during outages, providing outage ride-through support for critical facilities and services or supporting generation blackstart. To take advantage of ES, it has to be an integral part of the core infrastructure and grid operations.

Uncertainty analysis. New algorithms and analytical procedures are required to incorporate the complexity and size of the system with the uncertainties of VRES generation and loads, to assess the uncertainty of risk of natural disasters and cyber security threats in resiliency analysis, and to support contingency monitoring as well as monitoring, coordination and control of protection.

Big data management and analytics. The higher the number of devices and the greater the complexity of the system, the higher the resolution, precision and analytics of the data required for monitoring, operation, control, and protection of the system. In consequence, data management and analytics need more powerful information and computational infrastructure and algorithms to handle huge data volumes and security against cyber-attacks. In addition, compatibility is a necessary feature for the analytic and security engines for grid operators across regions and systems.

Cyber-physical security. Security of data process and exchange is a main concern. The cyber-physical security needs to detect, identify and respond fast enough to threats and try to protect the system, and recover from any disruption, with minimum time and cost.

Information collection and sharing. Collecting, analysing and sharing information between entities regarding cyber-physical threats and all-hazard events are necessary actions to enhance resilience, prioritize resilience investments, and assess quantitatively risks, and structural and social vulnerabilities. Systems and procedures must provide data quickly and securely.

Artificial intelligence. AI with its methods and tools using information of the system status and critical infrastructure resources can significantly improve resilience by enabling preventative and fast response proactive actions, comprehensive monitoring and accurate detection of malicious operation conditions, evaluation of resilience more acutely, and implementing automatic and autonomous response to threats and disruptive events. For instance, AI could help to

- estimate pre-fault low-probability high-impact critical security conditions,

- improved weather and renewable forecast accuracy,
- model renewable scenario generation and its capability to back up the power system operation with extreme harmful events,
- simulate extreme events using pure artificial signals,
- preliminarily validate a resilience enhancement strategy,
- anticipate damage to energy system equipment,
- predict outages and lack of service associated with threats as well as recommend optimal mitigation strategies, and
- automate the search of alternative topologies during degraded conditions with limited connectivity.

Technologies for automation. These include sensing, control, information and communication technologies and tools that can allow transmissions operators to react more quickly and effectively to system disturbances. For instance, these technologies can enable

- situational awareness based on real-time and high resolution measurements,
- wide-area visibility to detect disturbances and prevent or quickly recover from outages,
- control of flows to manage an event as it unfolds,
- isolation of damages and active re-routing of power flows,
- control of the network topology on operational timescales,
- modification of the properties of transmission lines,
- more extensive control, and decentralized decision making,
- self-healing capabilities, and
- continued operations with the use of redundant and diversely routed communication networks.

Proactive transmission planning. Resilience must be part of transmission planning and incorporated to operations. Planning needs to address the prevention or mitigation of loss or disruption and the restoration of critical transmission infrastructure and its services. In addition, comprehensive disaster or safety plans to act immediately before, during, and after a disruptive event are necessary, particularly for utilities in regions susceptible to extreme weather and natural disasters. These plans should include coordination with local governments, private and public sectors to direct response and recovery efforts, drills as part of the employee training, and emergency response plans for critical facilities (e.g., hospitals, police, fire stations, and communication facilities).

Optimal allocation of VRES and energy storage. This must be part of the transmission planning. During extreme events, distributed VRES generation and ES devices may provide greater access to energy sources for both load and non-blackstart units. In [95], the authors propose a multi-objective optimization model for sizing and siting battery storage units and photovoltaic generation in the transmission network. The model aims at improving capacity accessibility and grid operation performance in the face of unpredictable extreme events. In addition, optimal allocation and sizing of VRES and ES devices help to improve the grid-scale integration of renewables, alleviate transmission congestion, reduce real power loss, and enhance system reliability.

Policy reforms. They can create incentives mechanism to encourage actions to adopt resilience measures, address risk factors, and enhance systems' resilience to climate change and cyber-physical attacks; enable ancillary services and other types of markets; strengthen generation, transmission and building codes regarding resilience, and drive utilities to include resilience in their planning and operational regimes at all levels - local, regional and interregional.

5. Conclusion

Based on the review of pertinent literature, this paper study the integration of large-scale VRES into the transmission grid. Thereby, this paper evidences the critical role of transmission in paving the way for the massive integration of VRES into the power grid, and identifies, describes and interrelates the main challenges and problems arising from the integration of VRES to transmission grids, and the multiple solutions to address them.

The four main challenges to the transmission system, which arise from the characteristics of large-scale VRES, relate to long-distance grid access, flexibility, stability and reliability, and resilience. Each challenge encompass many particular problems and solutions, which in turn include many elements from different dimensions – technology, economy, regulation and environment-society.

From the study, we highlight the following conclusive general ideas.

- High VRES penetration brings many concerns and challenges, thus compelling a new paradigm in the planning and operation of power networks. Particularly necessary is the modernization and expansion of the transmission grid, which is key to integrate and exploit (reliably, efficiently, and cost-effectively) large-scale VRES and broader accelerate decarbonization of the grid and achieve energy transition goals.

- Transmission improvements to boost the use of large-scale VRES include many elements within an ample spectrum from technology to economic and regulation mechanisms. For instance, grid and flexibility technologies, control grid technologies, new lines and inter-regional connections, storage systems, proactive planning and regulation, operating coordination, clear and stable cost recovery methodologies and regulations, policy frameworks, market mechanisms, improved connection codes, advanced computing and advanced weather forecast models.

- Upgraded and new transmission infrastructure is needed to access VRES in remote regions or offshore, cope with some of the characteristics of large-scale VRES – variability, uncertainty, and availability, diversify the resource portfolio, provide ramping capability and ancillary services, facilitate new market models and their implementation, and reduce or eliminate grid congestion and VRES curtailment. In general, the transmission grid is key to enhance the flexibility, economy, reliability and resilience of power systems with high shares of VRES.

- To foster high penetration of large–scale VRES, transmission grids must overcome several challenges, problems, and constraints beyond technical feasibility and economic benefits, such as energy policies, regulation, climate change, market integration, public opposition, and restrictive environmental and siting legislation. Not urging the modernization of the transmission grid and dealing with its problems and constraints will threaten the achievement of the energy transition goals, and limit the reliable and effective integration of high shares of large-scale VRES into power systems.

The main contribution of this review is to provide a holistic view of the transmission grid and the integration of large-scale VRES with up-to-date information and useful knowledge regarding challenges, problems, and possible solutions over a wide spectrum nature and their interactions, not only technology but regulation, planning, operation, economy, environment and society.

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References

[1] S. Colle, EY Global Power & Utilities Leader, As the countdown to a new energy world intensifies, who will beat the clock?, 2019. Accessed on: 04.05.2021. [Online] Available: https://www.ey.com/en_gl/power-utilities/as-the-countdown-to-a-new-energy-world-intensifies-who-will-beat-the-clock

[2] M. Di Silvestre, S. Favuzza, E. Riva, G. Zizzo, “How Decarbonization, Digitalization and Decentralization are changing key power infrastructures”, Renewable and Sustainable Energy Reviews, Vol. 93, pp. 483-498, October 2018.

[3] Center for Sustainable Systems, University of Michigan. 2020. “U.S. Renewable Energy Factsheet.” Pub. No. CSS03-12. September 2020.

[4] Eurostat Statistics Explained, Renewable energy statistics, “Share of renewable energy more than doubled between 2004 and 2019”, Accessed on: 03.31.2021. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics#Share_of_renewable_energy_more_than_doubled_between_2004_and_2019.

[5] China Energy Portal, "2020 Q2 electricity & other energy statistics". Accessed on: 03.31.2021. [Online]. Available: https://chinaenergyportal.org/2020-q2-electricity-other-energy-statistics/

[6] U.S. EPA portal, Green Power Partnership National Top 100 (2021). Accessed on: 03.31, 2021. [Online]. Available: https://www.epa.gov/greenpower/green-power-partnership-national-top-100#:~:text=As%20of%20January%2024%2C%202022,7%20million%20average%20American%20homes.

[7] K. Cleary and K. Palmer, Renewables 101: Integrating Renewable Energy Resources into the Grid, Future of Power Explainer Series - Resources for the Future, April 15, 2020.

[8] T. Trondle, J. Lilliestam, S. Marelli, S. Pfenninger, “Trade-Offs between Geographic Scale, Cost, and Infrastructure Requirements for Fully Renewable Electricity in Europe”, Joule, Vol. 4, pp. 1929–1948, September 2020.

[9] IRENA-International Renewable Energy Agency, “Global energy transformation: A roadmap to 2050”, Abu Dhabi, 2019.

[10] P. Joskow, “Transmission Capacity Expansion Is Needed to Decarbonize the Electricity Sector Efficiently”, Joule, Vol. 4, No. 1, pp. 1-3, January 2020.

[11] C. Decker, International Approaches to Transmission Access for Renewable Energy - A report for Ofgem, Regulatory Policy Institute, UK, 2008.

[12] CIEE (California Institute for Energy and Environment), Transmission Technology Research for Renewable Integration, Energy Research and Development Division Final Project Report, 2008.

[13] F. Li, W. Qiao, H. Sun, H. Wan, J. Wang, Y. Xia, Z. Xu, and P. Zhang, “Smart Transmission Grid: Vision and Framework”, IEEE Trans. on Smart Grid, Vol. 1, pp. 168–177, 2010

[14] A. Bose, "Smart Transmission Grid Applications and Their Supporting Infrastructure," in IEEE Trans. on Smart Grid, Vol. 1, pp. 11-19, June 2010.

[15] L. Vanfretti, D. Van Hertem, L. Nordström and J. O. Gjerde, "A smart transmission grid for Europe: Research challenges in developing grid enabling technologies," 2011 IEEE Power and Energy Society General Meeting, pp. 1-8, 2011.

[16] G. Migliavacca (Editor) Advanced technologies for future transmission grids. Springer-Verlag London, 2013.

[17] S. Sinsel, R. Riemke, V. Hoffmann, “Challenges and solution technologies for the integration of variable renewable energy sources—a review”, Renewable Energy, Vol. 145, pp. 2271-2285, January 2020.

[18] G. Arcia-Garibaldi, P. Cruz-Romero, A. Gómez-Expósito, “Future power transmission: Visions, technologies and challenges”, Renewable and Sustainable Energy Reviews, Vol. 94, pp. 285-301, October 2018.

[19] M. Madrigal and S. Stoft, Transmission Expansion for Renewable Energy Scale-Up Emerging Lessons and Recommendations, Energy and Mining Sector Board. Discussion Paper No.26, The World Bank, June 2011.

[20] M. Milligan, B. Kirby, T. Acker, M. Ahlstrom, B. Frew, M. Goggin, W. Lasher, M. Marquis, and D. Osborn, Review and Status of Wind Integration and Transmission in the United States: Key Issues and Lessons Learned, NREL Technical Report NREL/TP-5D00-61911 March 2015.

[21] T. Pepper and A. Flavin, “Streamlining Power Transmission Siting To Help Renewables”, JDSUPRA,

Accessed: 25.11.2020. [Online]. Available: https://www.jdsupra.com/legalnews/streamlining-power-transmission-siting-25011/

[22] P. Behr, Power lines: The next 'Green New Deal' battlefront? Energywire, Accessed: 25.11.2020, [Online]. Available: https://www.eenews.net/articles/ power-lines-the-next-green-new-deal-battlefront/

[23] P. Brown and A. Botterud, The Value of Inter-Regional Coordination and Transmission in Decarbonizing the US Electricity System, Joule, Vol. 5, no.1, pp.115-134, 2020.

[24] C. Clack, M. Goggin, A. Choukulkar, B. Cote & S. McKee, Consumer, Employment, and Environmental Benefits of Electricity Transmission Expansion in the Eastern U.S., ACEG, October 2020.

[25] National Grid plc, Future of Electricity Transmission, discussion document, July 2018.

[26] R. Walton, "Propelling the transition: New and better transmission is key to zero carbon; here's what's driving it". Utility Dive, Filed under Transmission and Distribution. Accessed: 25.11.2020, [Online]. Available: https://www.utilitydive.com/news/propelling-the-transition-new-and-better-transmission-is-key-to-zero-carbo/582331/

[27] L. Reed, M. Dworkin, P. Vaishnav, M. Granger, "Expanding Transmission Capacity: Examples of Regulatory Paths for Five Alternative Strategies", The Electricity Journal, Vol. 33, issue 6, July 2020.

[28]Erdiwansyah, Mahidin, Husin, Nasaruddin, Zaki and Muhibbuddin, "A critical review of the integration of renewable energy sources with various technologies", Protection and Control of Modern Power Systems, Vol. 6, 2021.

[29] P. Cicilio, D. Glennon, A. Mate, A. Barnes, V. Chalishazar, E. Cotilla-Sanchez, B. Vaagensmith, J. Gentle, C. Rieger, R. Wies, et al. "Resilience in an Evolving Electrical Grid", Energies, Vol. 14, 2021.

[30] S. Impram, S. Varbak N. Bülent, "Challenges of renewable energy penetration on power system flexibility: A survey", Energy Strategies Reviews, Vol. 31, September 2020.

[31] P. Das, P. Mathuria, R. Bhakar, J. Mathur, A. Kanudia, A, Singh, "Flexibility requirement for large-scale renewable energy integration in Indian power system: Technology, policy and modeling options," Energy Strategy Reviews, Vol. 29, pp. 1-17, April 2020.

[32] A. Al-Shetwi, M. Hannan, K. Pin, M. Mansur, T. Mahlia, "Grid-connected renewable energy sources: Review of the recent integration requirements and control methods," Journal of Cleaner Production, Vol. 253, pp. 1-17, Apr. 20, 2020.

[33] E. Robles, M. Haro-Larrodea, M. Santos-Mugica, A. Etxegarai , E. Tedeschi, "Comparative analysis of European grid codes relevant to offshore renewable energy installations", Renewable and Sustainable Energy Reviews, vol. 102, pp.171-185, March 2019.

[34] T. Olowu, A. Sundararajan, M. Moghaddami, A. Sarwat, "Future Challenges and Mitigation Methods for High Photovoltaic Penetration: A Survey". Energies, 11, 1782, 2018.

[35] A. Sajadi, L. Strezoski, V. Strezoski, M. Prica, K. Loparo, "Integration of renewable energy systems and challenges for dynamics, control, and automation of electrical power systems", WIREs Energy Environ. 2018.

[36] B. Kroposki, B. Johnson, Y. Zhang, V. Gevorgian, P. Denholm, B. Hodge, and B. Hannegan, "Achieving a 100% Renewable Grid", IEEE Power & Energy Magazine, pp. 61 – 73, march/april 2017.

[37] B. Kroposki, "Integrating high levels of variable renewable energy into electric power systems", Journal of Modern Power Systems and Clean Energy, Vol. 5, pp. 831–837, 2017.

[38] G. Papaefthymiou and K. Dragoon, "Towards 100% renewable energy systems: Uncapping power system flexibility," Energy Policy, Vol. 92, pp.69-82, May 2016.

[39] D. Flynn, Z. Rather, A. Ardal, S. D'Arco, A Hansen, N. Cutululis, P. Sorensen, A. Estanquiero, E. Gómez, N. Menemenlis, C. Smith and Y. Wang, "Technical impacts of high penetration levels of wind power on power system stability", WIREs Energy and Environment, Vol. 6, 2016.

[40] A. Cabrera-Tobar, E. Bullich-Massagué, M. Aragüés-Peñalba, O. Gomis-Bellmunt, "Review of advanced grid requirements for the integration of large scale photovoltaic power plants in the transmission system", Renewable and Sustainable Energy Reviews, Vol. 62, pp. 971-987, 2016.

[41] L. Bird, D. Lew, M. Milligan, D. Flynn et al., "Wind and solar curtailment: a review of international experience," Renewable and Sustainable Energy Reviews, Vol.65, pp. 577-586, Nov. 2016.

[42] E. Martinot, "Grid Integration of Renewable Energy: Flexibility, Innovation, and Experience", Annu. Rev. of Environment and Resources, Vol. 41, pp. 223–251, 2016.

[43] M. Sandhu and T. Thakur, Issues, Challenges, Causes, "Impacts and Utilization of Renewable Energy Sources - Grid Integration", Int. Journal of Engineering Research and Applications, Vol. 4, pp.636-643, March 2014

[44] S. Oyedepo, A. Agbetuyi, M. Odunfa, "Transmission Network Enhancement with Renewable Energy", J. Fundam. Renewable Energy Appl., Vol. 5, March 2014.

[45] J. Cohen, J. Reichl, M. Schmidthaler, "Re-focussing research efforts on the public acceptance of energy infrastructure: A critical review", Energy, Vol. 76, pp. 4-9, 2014.

[46] K. Hasan, T. Saha, M. Eghbal, D. Chattopadhyay, "Review of transmission schemes and case studies for renewable power integration into the remote grid", Renewable and Sustainable Energy Reviews, Vol. 18, pp. 568-582, February 2013.

[47] S. Zafar, K. Nawaz, S. Naqvi and T. Malik, "Integration of Renewable Energy Sources in Smart Grid: A Review", The Nucleus, Vol. 50, pp. 311-327, 2013.

[48] A. Mills, R. Wiser, and K. Porter, The Cost of Transmission for Wind Energy: A Review of Transmission Planning Studies, Berkeley National Laboratory, Feb. 2009

[49] APS, Integrating Renewable Electricity on the Grid, A Report by the APS Panel on Public Affairs, 2018.

[50] S. Mueller, The Power of Transformation - Wind, Sun and the Economics of Flexible Power Systems, OECD/IEA, Paris, 2014.

[51] E. Lannoye, D. Flynn and M. O'Malley, "Transmission, Variable Generation, and Power System Flexibility," in IEEE Trans. Power Systems, Vol. 30, No. 1, pp. 57-66, Jan. 2015.

[52] The Nature Conservancy, Optimizing California's Transmission System for Renewable Energy, Executive Summary of a technical analysis and report prepared by Energy + Environmental Economics, 2018.

[53] Z. Chen, Y. Hu, N. Tai, X. Tang and G. You, "Transmission Grid Expansion Planning of a High Proportion Renewable Energy Power System Based on Flexibility and Economy", MDPI Electronics Vol. 9, 966, 2020.

[54] S. Cox and K. Xu, Integration of Large-Scale Renewable Energy in the Bulk Power System: Good Practices from International Experiences, Technical Report NREL/TP-6A20-74445 March 2020.

[55] S. Vajjhala and P. Fischbeck, "Quantifying Siting Difficulty: A Case Study of U.S. Transmission Line Siting", Resources for the Future, Discussion paper RFF DP 06-03, February 2006.

[56] P. Lienert, B. Suetterlin, M. Siegrist, "Public acceptance of the expansion and modification of high-voltage power lines in the context of the energy transition", Energy Policy, Vol. 87, pp. 573-583, 2015.

[57] L. Reed, M. Granger, P. Vaishnava, and D. Erian, "Converting existing transmission corridors to HVDC is an overlooked option for increasing transmission capacity", Proceedings of the National Academy of Sciences, Vol. 116, No. 28, pp. 13879–13884, July, 2019.

[58] A. Maxwell, "Supporting Renewables & Resilience with Better Transmission", NRDC, June 17, 2020 Retrieved 21 November 2020.

[59] M. Henderson, D. Novosel, and M. Crow, Electric Power Grid Modernization Trends, Challenges, and Opportunities, IEEE, Nov. 2017.

[60] D. Volk, Electricity Networks: Infrastructure and Operations - Too complex for a resource? Insights Series 2013, International Energy Agency, OECD/IEA, 2013.

[61] IEC, Grid integration of large-capacity Renewable Energy sources and use of large-capacity Electrical Energy Storage, White paper, 2012.

[62] K. Schaber, F. Steinke and T. Hamacher, "Transmission grid extensions for the integration of variable renewable energies in Europe: Who benefits where?" Energy Policy, Vol. 43, pp. 123-135, 2012.

[63] R. van Gerwen, Y. Sun, M. Eijgelaar, T. Bosma, E. Dugstad, Future-Proof Renewables - Implications of a high percentage of solar and wind in the power system, Group Technology & Research, White paper, DNV-GL, 2018.

[64] IEA, Status of Power System Transformation 2019 Power system flexibility, IEA, Paris, 2019.

[65] B. Burgholzer, H. Auer, "Cost/benefit analysis of transmission grid expansion to enable further integration of renewable electricity generation in Austria", Renewable Energy, Vol. 97, pp. 189-196, 2016.

[66] P. Denholm, K. Clark, and M. O'Connell. 2016. On the Path to SunShot: Emerging Issues and Challenges in Integrating High Levels of Solar into the Electrical Generation and Transmission System. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65800.

[67] IRENA, Solutions to integrate high shares of variable renewable energy (Report to the G20 Energy Transitions Working Group (ETWG)), International Renewable Energy Agency, Abu Dhabi, 2019.

[68] M. Anzari, S. Pirouzi, M. Kazemi, A. Naderipour, M. Benbouzid, Renewable Generation and Transmission Expansion Planning Coordination with Energy Storage System: A Flexibility Point of View. Applied Science, Vol. 11, 3303, MDPI, 2021.

[69] dena-REPORT, Transmission Grid Planning in systems with high shares of Renewable Energy - Planning the future energy system in China, Deutsche Energie-Agentur GmbH (dena), 2019.

[70] Ud.S. Energy Information Administration, Assessing HVDC Transmission for Impacts of Non-Dispatchable Generation, June 2018.

[71] G. Feller, Renewable Energy's Impact on Power Systems, T&D World eNewsletters, Nov 26, 2019.

[72] R. Verzijlbergh, L. De Vries, G. Dijkema, P. Herder, "Institutional challenges caused by the integration of renewable energy sources in the European electricity sector", Renewable and Sustainable Energy Reviews, Vol. 75, pp. 660-667, 2017.

[73] S. Sreedharan, R. Ghorbani, S. Sepasi, W. Ongsakul and J. Singh, "Simultaneous Optimization of Renewable Power at Transmission and Distribution Grid", Procedia Technology, vol. 21, pp. 24-32, 2015.

[74] M. Ni, F. Xue and Z. Meng, Chapter 2 Integration of Large-Scale Renewable Energy: Experience and Practice in China, P. Du et al. (eds.), Integration of Large-Scale Renewable Energy into Bulk Power Systems, Power Electronics and Power Systems, Springer International Publishing AG, 2017.

[75] ESMAP (Energy Sector Management Assistance Program), “Grid Integration Requirements for Variable Renewable Energy.” ESMAP Technical Guide, World Bank, Washington, DC. 2019.

[76] Y. Li, H. Liu, X. Fan, X. Tian, “Engineering practices for the integration of large-scale renewable energy VSC-HVDC systems”, Global Energy Interconnection, Vol. 3, No. 2, pp. 149-157, April 2020.

[77] H. Gerard, E. Rivero, D.Six, “Coordination between transmission and distribution system operators in the electricity sector: A conceptual framework”, Utilities Policy, Vol. 50, pp. 40-48, February 2018.

[78] L. Rácz, D. Szabó, G. Göcsei and B. Németh, "Grid Management Technology for the Integration of Renewable Energy Sources into the Transmission System," 2018 7th International Conference on Renewable Energy Research and Applications (ICRERA), pp. 612-617, 2018.

[79] A. Singh, T. Frei, N. Chokani and R. Abhari, “Impact of unplanned power flows in interconnected transmission systems – Case study of Central Eastern European region,” Energy Policy, Vol. 91, pp. 287-303, 2016.

[80] M. Pistora, K. Maslo, “Impact of Embedded Renewables on Transmission and Distribution Network”, 10th International Conference Control of Power Systems 2012, May 15-17, 2012.

[81] F. Ayadi, I. Colak, I. Garip and H. I. Bulbul, "Impacts of Renewable Energy Resources in Smart Grid," 2020 8th International Conference on Smart Grid (icSmartGrid), pp. 183-188, 2020.

[82] S. Ikeda and F. Kurokawa, "Isolated and wide input ranged boost full bridge DC-DC converter for improved resilience of renewable energy systems," 2017 6th International Conference on Renewable Energy Research and Applications (ICRERA), pp. 290-295, 2017.

[83] S. Sewchurran and I. E. Davidson, "Guiding principles for grid code compliance of large utility scale renewable power plant integration onto South Africa's transmission/distribution networks," 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), pp. 528-537, 2016.

[84] A. Schroeder, P. Oei, A. Sander, L. Hankel and L. Laurisch, “The integration of renewable energies into the German transmission grid—A scenario comparison,” Energy Policy, Vol. 61, pp. 140-150, 2013.

[85] R. Sajadi, M. Kolacinski and K.Loparo, "Transient voltage stability of offshore wind farms following faults on the collector system," 2016 IEEE Power and Energy Conference at Illinois (PECI), pp. 1-5, 2016.

[86] G. Ajenikoko, O. Olabode, G. Ojo, "A Comparative Analysis of Performance Evaluation of SVC and TCSC for Transmission Loss Reduction on Nigerian 330 kV Grid System Using Self-Adaptive Firefly Algorithm," International Journal of Smart Grid-ijSmartGrid, Vol. 1, No. 1, pp. 26-33, 2017.

[87] IRENA Innovation landscape brief: Artificial intelligence and big data, International Renewable Energy Agency, Abu Dhabi, 2019.

[88]KIT Energy Center, Artificial Intelligence Improves Power Transmission, Press Release No. 055, April 24, 2019.

[89] K. Li, X. Han, W. Li and R. Ahmed, "Unified power flow algorithm of transmission and distribution network," 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), pp. 257-261, 2017.

[90] IRENA, Virtual power lines, International Renewable Energy Agency, Abu Dhabi, 2020.

[91] M. Chupka and P. Donohoo-Vallett, Recognizing the Role of Transmission in Electric System Resilience, report prepared for WIRES, The Brattle Group, Inc., 2018.

[92] QER, Transforming the Nation’s Electricity Sector: The Second Instalment of the QER, Chapter IV: Ensuring Electricity System Reliability, Security, and Resilience, January 2017.

[93] M. Dyson and B. Li, “Reimagining Grid Resilience”, Rocky Mountain Institute, 2020.

[94] IEA, Power Systems in Transition, IEA, Paris, 2020.

[95] B. Zhang, P. Dehghanian and M. Kezunovic, "Optimal Allocation of PV Generation and Battery Storage for Enhanced Resilience," in IEEE Transactions on Smart Grid, Vol. 10, No. 1, pp. 535-545, Jan. 2019.