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Research Article

Emerging Issues and Challenges in Integrating of Solar and Wind

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Abstract: The anticipated expansion of renewable energy, particularly solar and wind power, is reshaping the landscape of global power systems. This article explores emerging issues and challenges associated with the integration of these fluctuating renewable energy sources, focusing on their impact on existing grid infrastructure and the evolving requirements for grid growth and development. As countries work to achieve ambitious renewable energy targets, the variability of solar and wind energy introduces significant complexities in terms of ensuring system stability and reliability. These complexities are further compounded by the need for extensive grid expansion, modernization, and adaptive operational practices. The article provides a comprehensive overview of the key challenges in integrating variable renewable energy (VRE) while also outlining the critical grid requirements needed to support a stable, flexible, and resilient energy system amidst rapid growth. It highlights the importance of adopting innovative solutions to manage the variability of renewable sources, ensuring that grid expansion is synchronized with the accelerated deployment of renewable technologies.

Keywords: Variable Renewable Energy; Solar PV; Wind Power; Grid Development.

1. Introduction

The expansion of solar photovoltaic (PV) and wind energy requires strategic, proactive integration to fully leverage their capabilities. From 2018 to 2023, the installed capacities of both solar PV and wind energy experienced substantial growth, more than doubling over this period [1]. This surge was mirrored by a significant rise in their share of electricity generation. As governments worldwide identify these renewable energy sources as essential components for achieving energy sector decarbonization, their capacities are anticipated to continue accelerating [2]. This expansion is underpinned by a favorable policy environment and the considerable cost reductions recently realized in solar PV and wind technologies, positioning them as vital contributors to future energy systems [3].

To fully capitalize on the increasing capacities of solar PV and wind energy, it is imperative to integrate them efficiently into power systems. Unlike traditional energy sources, solar PV and wind—

forms of variable renewable energy (VRE)—bring variability on the supply side, which is dependent on fluctuating weather patterns. While power systems have long adapted to fluctuations in demand, managing VRE demands a comprehensive enhancement of system-wide flexibility [4]. This involves not only leveraging dispatchable power generation and upgrading grid infrastructure but also advancing energy storage technologies and implementing responsive demand-side strategies. Successful integration will lead to the secure and cost-effective use of renewable energy, while minimizing the need for expensive system stability measures and reducing fossil fuel dependency [5].

Postponing the implementation of essential integration measures could undermine as much as 15% of projected solar PV and wind energy generation by 2030, resulting in substantial setbacks to decarbonization efforts [6,7]. This delay would not only compromise renewable energy deployment but also reduce the power sector's carbon dioxide (CO_2) emission reductions by up to 20%. If integration measures are not synchronized with scenarios that align with national climate objectives, up to 2,000 terawatt-hours (TWh) of global VRE generation could be jeopardized by 2030, thus threatening the achievement of energy and climate commitments worldwide [8,9]. Figure 1 illustrates global of solar photovoltaic and wind power during both high and low phases of variable renewable energy integration in the Announced Pledges Scenario, 2022-2030.

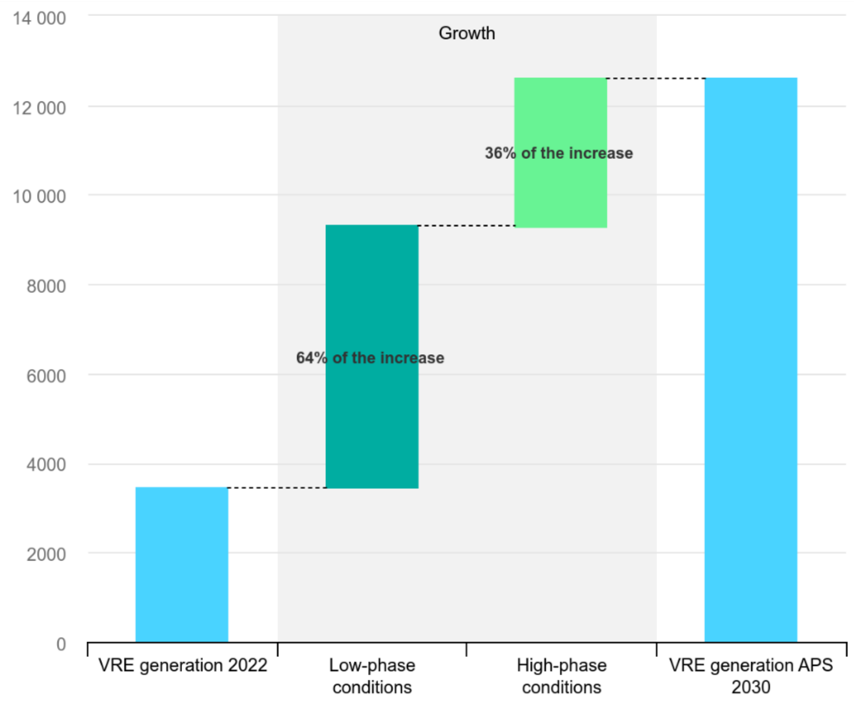

Figure 1. The global of solar photovoltaic and wind power during both high and low phases of variable renewable energy integration in the Announced Pledges Scenario, 2022-2030.

This risk, equivalent to the combined VRE generation of China and the United States in 2023, emerges from increased curtailment, both technical and economic, as well as delays in connecting projects to the grid [10-13]. Consequently, without timely integration, the global share of solar PV and wind in the electricity mix would reach only 30% in 2030, rather than the 35% achievable under optimal conditions. Any reliance on fossil fuels to compensate for this shortfall would undermine emission reduction efforts, leading to a power sector emissions reduction that is up to 20% less effective [14-16].

Discussing the literature on emerging issues and challenges in the integration of solar and wind energy is crucial, as it provides a foundational understanding of the complexities and evolving dynamics of renewable energy systems. The literature review sheds light on the technical, economic, and regulatory barriers that hinder effective integration, such as grid stability, intermittency of resources, and the need for advanced energy storage solutions. Table 1 presents a comprehensive overview of recent studies on the integration of solar and wind energy across various regions.

Ref.	Year	Highlights	Type of VRE	Region
[17]	2024	▪ Optimizing the installed capacities of wind and solar energy increases the mean capacity factor while simultaneously reducing variability. ▪ Integrating wind and solar resources offers a significant improvement in managing the tradeoff between energy output and variability across all timescales. ▪ The benefits of such optimization appear to be largely overlooked in the EU reference scenarios. ▪ By optimizing renewable energy deployment across Europe, energy output can be increased by 22%, with variability reduced by 26%.	Wind & solar	Europe
[18]	2024	▪ Hybridization with solar PV reduces power output variability in offshore wind farms. ▪ Selected three offshore wind farms in Europe and China for retrofitting with solar PV to improve output stability. ▪ Identified the optimal solar subsystem capacity to minimize overall power variability. ▪ Resource availability and characteristics contribute to performance differences between the European and Chinese offshore sites.	Wind & Solar	Europe & China
[19]	2024	▪ Polygeneration from renewable energy enables the integrated production of cooling, heating, electricity, water, hydrogen, and oxygen. ▪ Dynamic system modeling conducted using transient simulation software TRNSYS®, with optimization performed through GenOpt linked with TrnOpt. ▪ Utilized multiple prime movers, including EGTC, PV panels, WECS, fuel cells, electrolyzers, and absorption chillers for efficient energy conversion. ▪ Key performance metrics include: EGTC efficiency at 68%, solar fraction of 0.78, WECS efficiency at 52.24%, PV at 10.90%, and electrolyzer efficiency at 95.7%.	photovoltaic panels, wind energy, fuel cell	Pakistan
[20]	2024	▪ Explored the utilization of solar and wind energy for remote regions in Iran. ▪ Analyzed three distinct energy scenarios using cost minimization models. ▪ Findings emphasize the prioritization of renewable solutions over conventional energy infrastructure. ▪ Addressed challenges related to electricity access in remote and underserved areas. ▪ Demonstrated the feasibility and optimality of small wind turbines for meeting local energy demands.	solar & wind energy	Iran
[21]	2024	▪ An empirical model which utilizes the Weibull distribution and Monte Carlo methods. ▪ Battery storage and Vehicle to Grid operations support the power smoothing process of the power grid. ▪ A modeling approach for integrating renewable energy sources. ▪ Integrating Vehicle to Grid operations into renewable energy sources.	solar & wind energy	Australia
[22]	2024	▪ Assessed wind and solar resources to identify optimal sites for hybrid energy systems (ES).	Hybrid ES	Chittagong

	▪ Designed a hybrid system integrating solar PV panels with wind turbines for enhanced energy generation. ▪ Evaluated different system components to determine their impact on overall performance. ▪ Implemented Vertical Axis Wind Turbines (VAWT) alongside PV panels for improved efficiency and flexibility. ▪ Utilized HOMER Pro and PVsyst simulations to analyze technical and economic feasibility.	

This article contributes to the discourse on VRE integration by arguing that integration challenges should not be perceived as inherent barriers to the growth of VRE, especially in systems at early integration stages. At these nascent phases, the system-wide impacts of VRE are minimal, and there exist numerous cost-effective, scalable measures to facilitate integration. These measures offer confidence to countries with low VRE penetration that potential integration challenges are manageable. By aligning the deployment of foundational integration strategies with the expansion of VRE, nations with currently modest renewable capacity can substantially accelerate their clean energy objectives. This coordinated approach is essential to harnessing the full potential of VRE technologies, which contribute not only to decarbonization but also to enhancing energy affordability and reducing reliance on fossil fuels.

2. Anticipated Expansion in Renewable Energy

Over the past decade, the installed capacity of renewable energy has seen substantial growth, more than doubling, with solar and wind power driving nearly all of this expansion [23-25]. Moreover, this growth is expected to continue at a rapid pace, especially with global commitments, such as the pledge to triple renewable energy capacity by 2030, necessitating even faster acceleration. Figure 2 deconstrues countries in phases of variable renewables integration, 2023-2030.

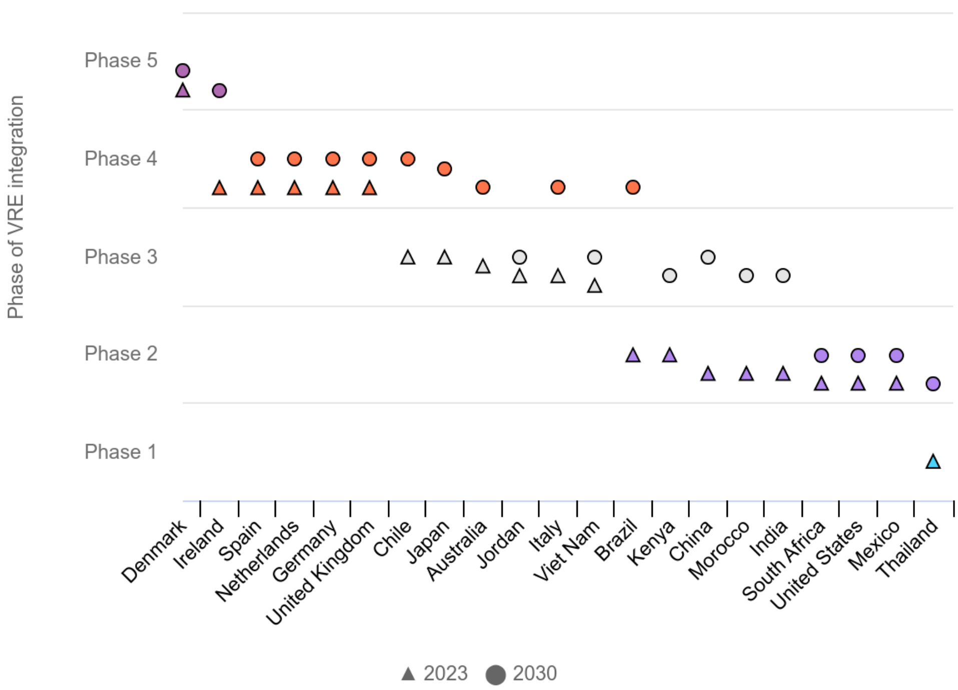

Figure 2. Countries in phases of variable renewables integration, 2023-2030

According to analysis from multiple studies, if this commitment is realized, solar photovoltaic (PV) is projected to contribute approximately two-thirds of the new renewable capacity by 2030, with wind accounting for about a quarter. Additionally, other low-emission technologies, including nuclear and hydropower, are expected to expand by around 25% and 30%, respectively. This trend contrasts with the expected decline in fossil fuel-based generation capacity, which is anticipated to decrease by nearly 25% by 2030, marking a significant shift away from coal, natural gas, and oil toward cleaner energy sources [26-29].

National ambitions are playing a crucial role in supporting multilateral goals for the power sector, particularly in the deployment of renewable energy. Under the Paris Agreement, countries submit nationally determined contributions (NDCs) that outline their intended targets and actions for reducing greenhouse gas emissions. By October 2023, more than 110 countries had set renewable energy targets for the power sector by 2030, signaling a strong commitment to green energy. Of these, 63 countries specified targets as percentages, including not only European and North American nations but also countries from diverse regions such as Kenya, Australia, Chile, and Brazil [30-34]. Within these commitments, 24 countries have set renewable shares ranging from 25% to 59%, 14 countries target between 60% and 89%, and 12 nations have made ambitious commitments to achieve between 90% and 100% renewable energy in their power sectors. These varied commitments illustrate a global momentum towards decarbonizing energy systems, highlighting the complementary role of domestic policies in achieving broader international renewable energy goals.

3. The Incorporation of Variable Renewable Energy

The effective integration of variable renewable energy (VRE) is crucial for maximizing the potential benefits that come with increased capacity. Integration refers to the process of securely and cost-efficiently incorporating solar and wind energy into existing electricity systems. Achieving timely integration, aligned with the growth in solar and wind capacity, is essential to ensuring that investments in VRE yield their intended outcomes. Without synchronized integration, the anticipated benefits in terms of system reliability, cost reductions, and emission reductions may not be fully realized [35,36].

Industry stakeholders increasingly identify integration difficulties, such as grid connection delays and congestion management, as substantial impediments to investment in solar and wind energy. Such issues introduce delays and uncertainty, complicating the approval and connection of projects, which in turn undermines the overall business case for renewable energy development. In 2023, it was reported that over 3,000 GW of renewable power projects were waiting in connection queues, while congestion management volumes and associated costs have continued to rise in regions such as Europe and the United States. These trends indicate potential setbacks not only in the construction timeline of VRE projects but also in the delivery of the generated energy once operational, thereby affecting cost recovery according to planned business models [37,38]. The uncertainty and risk of delays diminish investor confidence, ultimately impeding the growth of renewable energy capacity even as demand for clean energy escalates.

The fluctuating and unpredictable nature of energy production from solar and wind power is primarily due to changing weather conditions, which are inherently challenging to forecast with high accuracy. Wind power output varies based on changes in wind speed and direction, while solar power is influenced by sunlight intensity, which can be significantly impacted by factors like clouds and fog. These weather elements are often localized and can change rapidly, making precise predictions difficult. While existing power systems are designed to accommodate some degree of variability and uncertainty in demand, the distinct characteristics of solar and wind introduce greater supply volatility and wider uncertainties [39-41]. This heightened variability places strain on the ability to manage power systems using traditional operational methods, necessitating more advanced approaches to integrate these renewable sources effectively.

Regions rich in solar and wind resources are often geographically distant from areas where electricity demand is highest, creating what is known as a locational mismatch. This mismatch is particularly evident for utility-scale VRE plants, which are frequently located far from urban and industrial centers where consumption is concentrated. To effectively transmit electricity from these remote locations to the areas of high demand, the development or enhancement of transmission infrastructure is necessary. However, expanding transmission capacity is often a complex endeavor, requiring extensive planning and funding, which leads to long lead times that can delay the integration of renewable energy into the grid [42-44].

The rollout of VRE contrasts sharply with traditional power generation, which is typically dominated by large, centralized power plants. VRE deployment, on the other hand, often takes a decentralized form. For example, rooftop solar systems are characterized by their small scale and widespread nature, while utility-scale renewable power plants are generally smaller compared to conventional power facilities. This decentralization leads to a proliferation of numerous power-generating units of varying sizes, configurations, and ownership models, making it challenging to fully oversee or manage their collective operation [45-47]. This complexity is particularly evident at the level of distribution grids, where many of these diverse power plants are connected, posing additional challenges for grid stability and control.

Eventually, solar and wind power plants connect to the grid as non-synchronous generators, unlike conventional power plants such as hydro, coal, nuclear, and gas-fired units, which utilize the rotating machinery of synchronous generators. Instead, solar and wind technologies primarily use electronic power converters, which inherently lack the grid-stabilizing properties, such as inertia, that are naturally provided by synchronous generation [48,49]. The absence of these stabilizing characteristics can create significant challenges for maintaining grid stability, particularly in terms of frequency control and voltage support. To effectively address these challenges, system management must be adapted to accommodate the unique characteristics of non-synchronous generation.

4. Requirements for Grid Development

Expanding, modernizing, and upgrading electricity grids is vital to enable solar and wind energy to meet the growing electricity demand effectively. Grid infrastructure must expand and be reinforced to connect new solar and wind power plants, ensuring that generated electricity can be efficiently transported to consumers and that the balance between supply and demand is maintained securely. Furthermore, an enhanced grid supports the integration of solar and wind by enabling geographical smoothing of their generation, thereby improving overall power system flexibility. Analysis from several studies indicates that, to stay on track with national energy and climate commitments, global annual investments in grid infrastructure must double by 2030 [50-52].

For example, in the United States, congestion management costs escalated dramatically from USD 6 billion in 2019 to almost USD 21 billion by 2022, translating to more than USD 4 per megawatt-hour (MWh) of electricity consumed. Other countries, such as Germany and Great Britain, have similarly faced substantial multi-billion-dollar annual congestion costs, resulting in an average cost of around USD 8 per MWh consumed. Moreover, delays in grid development significantly increase the risk of power outages, which already inflict a global cost of at least USD 100 billion annually, equivalent to 0.1% of the world's GDP. These rising costs and risks underscore the critical importance of timely grid investments to ensure reliable and affordable energy systems [53,54].

Accelerating grid expansion and upgrades is essential for countries, not only to facilitate the integration of VRE but also to provide broader benefits, such as enhancing electricity access and supporting the growth in overall demand. Given that grid development is a lengthy process, it is also necessary to implement complementary solutions with shorter lead times to effectively enhance the integration of solar and wind energy [55-57]. These interim measures can play a pivotal role in ensuring that renewable energy deployment remains on track while long-term grid infrastructure is being developed.

Power systems worldwide have made remarkable progress in adopting VRE, with expected capacity additions poised to drive VRE contributions to unprecedented levels. In a sample of 133 countries, which collectively account for 99% of global electricity generation, only around 15 countries had an annual VRE generation share of 10% or more in 2018. By 2023, that number nearly doubled, reflecting rapid adoption. By 2028, almost 70 countries are expected to achieve a VRE share of at least 10%, while those surpassing 30% VRE penetration are set to grow from just four in 2018 to over 20 by 2028 [58-63]. This trend underscores that higher VRE penetration will no longer be limited to pioneering nations; instead, it will become a widespread phenomenon for many power systems across the globe. This illustrates the rapid pace of transformation in electricity systems worldwide, with solar PV and wind emerging as central components of this ongoing energy transition.

5. Emerging Issues and Challenges

From a system performance and resilience standpoint, the primary challenges emerging with the integration of VRE at high levels are the need to ensure system stability and to meet growing flexibility requirements across all timescales. Historically, large hydro and thermal generators have been the backbone for providing stability and flexibility. However, as fossil-fuel-based plants are phased out, new approaches must be adopted to secure these essential functions, ensuring that power systems can adapt effectively to the increasing share of VRE without compromising reliability or resilience.

Stability in power systems refers to the ability to restore equilibrium after a disturbance, such as maintaining frequency and voltage within acceptable ranges following an outage. In traditional power systems, large rotating masses of conventional generators have played a crucial role in maintaining stability by damping the effects of disturbances. With the transition from large generators to variable renewable energy (VRE), it has become necessary to source stability from a broader range of assets, including dedicated stability equipment, batteries, and even VRE plants. Moreover, adapting operational practices is essential to ensure that power systems continue to effectively manage disturbances in this evolving energy landscape.

The stability of large power systems relies on three fundamental characteristics—collectively known as system strength: physical inertia, a stiff voltage waveform, and high fault currents. Traditionally, these characteristics have been provided by synchronous generators, but as VRE continues to grow, alternative sources must be utilized to maintain these features. Unlike conventional generators, VRE units, along with storage systems and HVDC interconnectors, connect to the grid through power converters.

These converters are capable of providing a wide range of system services, including voltage regulation, frequency control, and adaptive responses to grid events, which can enhance grid efficiency. However, despite their adaptability, converter-connected resources do not inherently supply the system strength attributes. Consequently, as VRE increasingly replaces traditional power units, challenges emerge in maintaining all aspects of system strength, requiring careful management and new approaches.

Effectively addressing the stability and flexibility challenges at high levels of VRE integration requires more than straightforward operational adjustments. It often necessitates deploying dedicated assets specifically designed to enhance system stability and flexibility. Additionally, it is crucial to ensure that resources from both the supply and demand sides actively contribute to system needs and support VRE integration. While many of these technological solutions are commercially mature and ready for deployment, some are still in the developmental phase and yet to reach full maturity.

6. Conclusion

Integrating solar and wind energy into global power systems is crucial for advancing toward a sustainable and decarbonized energy future. However, this journey is not without challenges. Delays in implementing integration measures pose a serious risk to the anticipated growth of renewable energy, potentially undermining up to 15% of expected solar and wind generation by 2030 and reducing carbon reduction potential by as much as 20%. Achieving ambitious renewable energy targets requires alignment between integration efforts and national climate goals, as failure to do so could put up to 2,000 TWh of VRE generation at risk. Moreover, the anticipated rise in solar PV and wind capacity is promising, with solar expected to account for two-thirds and wind one-quarter of new renewable capacity by 2030. However, successfully harnessing this growth will depend heavily on resolving the locational mismatch between renewable generation sites and consumption centers. Addressing this requires the expansion and enhancement of transmission infrastructure, a complex undertaking often constrained by long lead times in planning and funding.

However, the escalating costs associated with congestion management, especially in regions like the United States, Germany, and Great Britain, further highlight the urgency for investment in grid development. Delays not only increase financial burdens but also heighten the risk of power outages, underscoring the necessity of proactive measures to ensure grid stability and resilience. Despite these challenges, global power systems have made notable strides in adopting variable renewable energy, with the number of countries achieving significant VRE shares growing rapidly. By 2028, the proliferation of VRE integration across nearly 70 countries demonstrates that renewable energy is becoming a global standard, not just a feature of a select few frontrunners. To fully realize the potential of solar and wind energy, it is imperative to address the emerging challenges related to grid infrastructure, integration, and operational practices, ensuring a reliable and effective transition to a cleaner energy landscape.

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