International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 14, Issue 7 [July 2025] PP: 45-60

Renewable Energy Variability and Grid Stability: A Global Perspective

1st K Sivasankar
M.E Power System, First Year (2024-25)
Adhiyamaan College of Engineering
Hosur, Tamil Nadu, India

2nd Dr. S. Muthukrishnan
Professor EEE Department
Adhiyamaan College of Engineering
Hosur, Tamil Nadu, India

Abstract:
While integrating wind and solar energy into power systems has been explored extensively, the unpredictable nature of these energy sources still lacks comprehensive solutions despite their fast-growing use. Recent research has shifted from traditional methods of analyzing variability to more advanced approaches, such as real-time monitoring and machine learning-based predictive models. This study investigates the different sources and types of variability in renewable energy generation, highlights the challenges involved, and explores strategies used across the globe to reduce these fluctuations in power grids.
A summary of ten countries effectively handling energy variability in their grids is provided. The review indicates that the most successful cases relied on advanced energy storage systems, modernized grid infrastructure, and a diversified energy mix as core technical and economic strategies. Furthermore, the study proposes a seven-point conceptual framework involving all stakeholders in the energy sector to enhance the integration of variable renewable energy (VRE) into power systems. Key strategies identified include long-duration energy storage, the development of virtual power plants (VPPs), smart grid technologies, cross-border electricity connections, power-to-X solutions, and overall grid flexibility.
This comprehensive review is a valuable resource for researchers and industry professionals aiming to build a reliable, stable, and renewable-energy-focused grid system.
Keywords: *variability; grid flexibility; variable renewable energy; power-to-X; smart grid*

Date of Submission: 02-07-2025 Date of acceptance: 12-07-2025

I. Introductions:

The integration of variable renewable energy (VRE) sources such as wind and solar into grid-connected power systems offers significant potential along with critical challenges. As the global push for clean energy gains momentum, increasing the share of VRE in electricity generation helps lower greenhouse gas emissions and boosts energy security [1]. However, due to the inherently intermittent and unpredictable nature of these resources, several challenges arise concerning grid reliability, operational stability, and effective energy delivery [2].

Key technical issues include fluctuations in generation output, real-time supply-demand balancing, and the control of frequency and voltage across the grid [3]. To address these problems, several countries have adopted a range of technical and policy-based solutions, such as energy storage technologies, advanced forecasting methods, responsive demand programs, and grid modernization using smart infrastructure [4]. These approaches aim to build grid flexibility and resilience while enabling a greater share of renewables to be integrated effectively.

Although the deployment of solar and wind technologies has seen exponential growth in many regions, the variability and uncertainty they introduce into power systems have not been studied as thoroughly as their technological adoption [5]. This study aims to bridge that gap by analyzing the effects of solar and wind variability on traditional power grids, exploring mitigation strategies, and proposing a scalable framework that can adapt to changing technologies and market dynamics.

Matching renewable generation with electricity demand is relatively straightforward when both rise and fall simultaneously. However, when renewable output peaks while demand dropsor vice versa,the cost and complexity of balancing the system increase significantly [6]. Adding to the challenge is the weak correlation between solar/wind generation and real-time demand, which leads to imbalances and potential instability within the grid [5].

The challenges posed by solar and wind variability occur across multiple time scales, making their integration more complex as their share increases. While low levels of renewable penetration (e.g., below 30%)

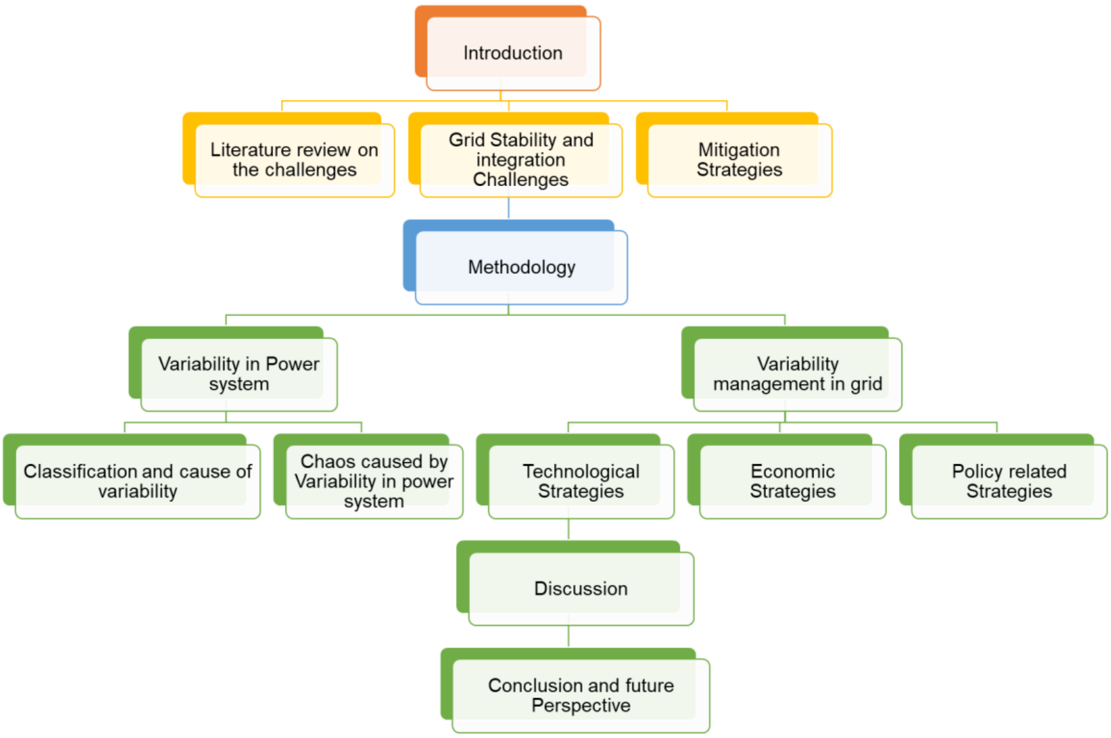
are often manageable, higher shares tend to introduce operational chaos and necessitate new control strategies and infrastructure upgrades [4].

Despite progress in integrating VRE into power networks, key challenges remain in maximizing efficiency, balancing supply and demand, and maintaining grid stability and quality. Seasonal variation, fluctuating output, and limited predictability of VRE sources present difficulties in harmonizing renewable energy with conventional grid operations [2].

This paper aims to evaluate the long-term potential of VRE integration in developing sustainable, dependable, and adaptable power systems. It addresses the following research goals:

- To analyze the technical and economic barriers to integrating VRE, such as intermittency, voltage and frequency regulation, power quality concerns, and the need for ancillary services [3].
- To identify effective mitigation techniques, including high-resolution forecasting, battery energy storage, and responsive demand strategies [4].
- To assess the role of grid modernization and flexible infrastructure in supporting high shares of renewable energy [1].
- To review ten global examples of successful variability management and develop a conceptual framework suitable for evolving technology and policy trends [5].
- To explore the future of VRE-based grids in delivering sustainable and reliable energy systems [6].

The structure of this study begins with an introduction, followed by a literature review that outlines the foundations of the topic. The methodology is then detailed, followed by a discussion on the sources and impacts of variability in power systems and corresponding strategies for mitigation.



II. Review of Related Literature

The integration of Variable Renewable Energy (VRE) into power systems presents critical challenges related to intermittency, reliability, and infrastructure adequacy, necessitating a multifaceted approach to ensure grid stability and energy security. Several scholars have explored these dimensions, offering diverse perspectives and solution strategies.

Juma D[7]. (2023) emphasizes the necessity of power system flexibility to complement VRE capacity expansion. Their study explores the adverse effects of intermittency on grid stability and underscores the importance of efficient energy distribution mechanisms to manage variability.

Xu T [8]. (2022) delve into the implementation limitations of VRE, particularly highlighting how variability impacts demand-supply balance, voltage regulation, and overall grid stability. Their work stresses the need for adaptive strategies to handle technical disruptions arising from fluctuating generation patterns.

Similarly, Zaheb H [9] (2023) investigates the role of optimal grid flexibility in integrating VRE, identifying key constraints such as aging infrastructure, insufficient generation capacity, frequent outages, and minimal RE contribution to the energy mix. Their analysis reinforces the need for investment in infrastructure and reliability upgrades.

In the Indian context, Joshi [10] (2023) provides a comprehensive review of the institutional frameworks governing VRE forecasting, proposing six strategic methods to improve forecast accuracy and integration. Their study supports policy-driven, data-informed approaches for managing VRE deployment at scale.

Shafiullah [11] (2022) narrows their focus to solar PV systems, detailing the technical, operational, and market barriers to grid integration. They advocate for the use of energy storage systems (ESS) and advanced control technologies as effective means of mitigating VRE-related volatility.

Lastly, Fang [12] (2024) contributes a forward-looking perspective by presenting a grid expansion planning model that incorporates chronological variability and uncertainty of renewable generation. Their model addresses both short- and long-term planning needs, integrating operational flexibility constraints to support high VRE penetration scenarios.

The study fell short of investigating the enhancement methodologies and establishing strong strategies for the effective integration of EVs and RES in the power grid.

A comprehensive literature review summarizing the number of published papers and research focus in recent years is presented in Table 1.

Author/Reference	Year	Topic	Focus
Juma D. [7]	2023	Power System Flexibility: A Necessary Complement to Variable Renewable Energy Optimal Capacity Configuration	Impacts of intermittency on grid stability and efficient energy distribution.
Xu T.[8]	2022	The implementation limitation of variable renewable energies and its impacts on the public power grid.	Impacts of variability on demand and supply, stability, and voltage fluctuations.
Zaheb H. [9]	2023	Optimal Grid Flexibility Assessment for Integration of Variable Renewable-Based Electricity Generation.	Aging infrastructure, inadequate generation, power outages, minimal RE production, and loss of loads.
Joshi, M. [10]	2023	Institutional Framework of Variable Renewable Energy Forecasting in India.	Review of institutional frameworks for VRE forecasting that advocate large-scale integration in India by applying the best practices. Presents 6 methods of enhancing the VRE forecasting framework in India
M. Shafiullah M. [11]	2022	Grid Integration Challenges and Solution Strategies for Solar PV Systems.	Focused on the challenges and solutions of integrating PV into grid-connected systems, addressing technical, operational, and market problems while emphasizing methods like ESS and advanced control as solutions to variability.
Y. Fang [12]	2024	Electric energy system planning considering chronological renewable generation variability and uncertainty.	Proposal on grid expansion-planning model that integrates operational flexibility constraints addressing both long and short-term variability and uncertainty for high VRE penetration.

The research contributions of this study are summarized as follows:

- An up-to-date comprehensive literature review on the impacts of the variability of renewable energy integration into power grids, the chaos caused, and the different successful mitigation methods applied in some ten selected countries' grids worldwide.
- A review of the key technological, economic, and policy mitigation strategies; analytical, data-driven, machine learning methods for managing variability from both the demand and supply side.
- A seven-point proposed conceptual policy framework for smoothing out variability in VRE grid-connected power systems involving all energy stakeholders, with lessons drawn from the successful cases, has been presented.
- The work highlights the essentiality of long-duration energy storage, grid-forming inverters, virtual power plants, smart grid/infrastructure, and incentivizing support as key takeaways for reliable, resilient, and carbon-free grids.

This work is different in that it focuses on a holistic review of VRE sources and their impacts on power systems grids, providing useful insights concerning the challenges, mitigation strategies, frameworks, and prospects over a broad scale, including the technological, economic, and policy aspects. A clear understanding of the inherent variability of solar and wind resources integration from this study will serve as a lift from the pitfalls of some VRE grid-connectedprojectsaroundtheglobe,pavingthewayforefficientgriddecarbonization.

III. Methodology

1. An Overview of Global VRE Installations

Variable renewable energy (VRE) sources are types of energy that come from natural processes that change over time. The main VRE sources are wind and solar. Other renewable sources like hydro, ocean, and tidal energy don't change as much, and their changes mostly happen over seasons. Wind and solar are different because their energy output depends a lot on the weather. They can change very quickly—every few seconds, throughout the day, or between seasons—making them hard to predict. Solar energy relies on sunshine, while wind energy depends on wind speed and direction. These changes make it difficult to keep the electricity supply stable. Even so, wind and solar are clean, don't produce carbon emissions, and are becoming more affordable [13]. Using them in power systems is important for reducing pollution and moving toward cleaner energy.

In a report from October 2023, the International Energy Agency (IEA) said that if countries meet their clean energy goals, solar and wind will make up over 80% of new power capacity in the next 20 years. This is a big increase from less than 40% in the past 20 years [14]. Other researchers agree and add that wind and solar will make up about 90% of the changes needed to reach net-zero carbon emissions by 2050. Solar energy is leading the change, providing more than twice the new electricity compared to coal in 2023 and the first half of 2024 [15].

In the European Union, coal power dropped by 24% in the first half of 2024 compared to the same time in 2023. That's a reduction of 39 terawatt-hours (TWh). This made up more than half of the 71 TWh drop in fossil fuel use around the world. At the same time, wind and solar power in the EU grew by 13%, adding 45 TWh. This pushed their share of total electricity to 30% in 2024, up from 27% in 2023—an all-time high [16]. Globally, solar power grew by 307 TWh in 2023, a 23% increase. Wind energy increased by 206 TWh or 9.8%. Solar made up 5.5% of all electricity produced worldwide in 2023, reaching 1631 TWh [17]. To meet future goals, solar PV needs to grow by 35% by 2029–2030, while wind energy needs to double. Solar capacity could reach 10 terawatts (TW) by 2030 in the best-case scenario [18].

Wind power has been used for a long time and is now growing fast worldwide. Countries like China, the U.S., and Germany are leaders in wind energy. However, by 2021, solar panels started to have more total capacity than wind, about 30% more. Even so, wind turbines still produce more power per unit than solar panels, with about twice the output [19]. In 2023, the wind industry saw record growth, with a 50% jump in new installations. This happened despite problems like economic troubles, wars, and supply chain delays. A total of 117 GW of new wind power was added to grids, showing how strong and adaptable the wind sector is [20]. This brought the world's total wind power capacity above 1 TW in 2023, growing by 13% from the year before. Most of this came from onshore wind, which grew by 54%, adding 106 GW. Major countries also saw drops in emissions as more wind energy was used [21]. The historical and projected solar PV and wind power capacity in the renewable2023maincase(2024–2028)andNetZeroEmissionby2050scenario(2018–2030) are shown in Figure 3below.

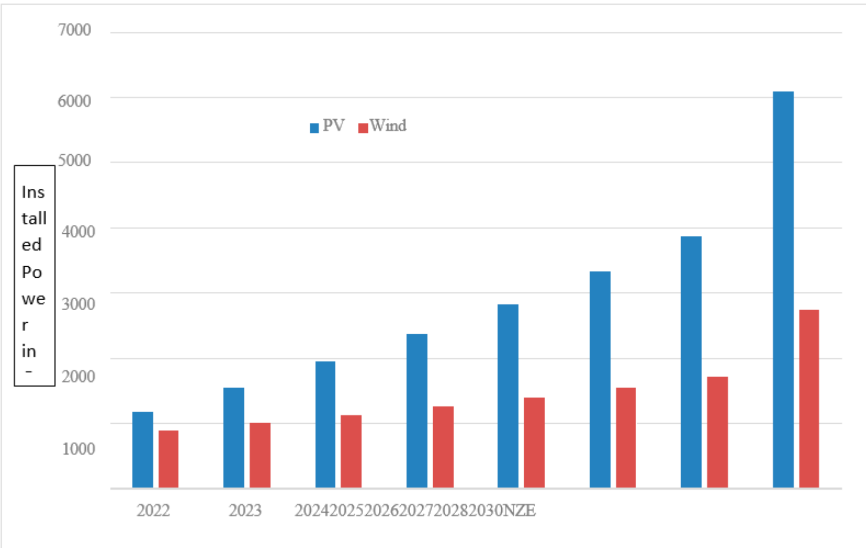


Figure 1. Installed capacity of solar PV–wind parks based on IEA data (main scenario, NZE scenarioby 2050) [14].

At the national level, China and the United States remain the biggest markets for onshore wind installations, followed by Brazil, Germany, and India. These top five countries accountedfor82%oftheglobalnewinstallationsin2023,constitutingacombinedsurge of 9% compared to the previous year.After two years of modest growth, onshore wind installations in China surged in 2023, recording over 69 GW commissioned. In the US, developers installed more new wind plants, leading to a total addition of just 6.4 GW of onshorewindcapacity,markingthelowestfiguresince2014[22].

Variabilityin Power Systems

In power systems, variability means changes, either short-term or long-term, in how much electricity is produced and used. These changes happen because of shifts in electricity demand, weather changes, and the unpredictable nature of renewable energy sources like solar and wind [23]. Unlike traditional power plants that give steady energy, solar and wind power depend on the weather, which makes their energy output go up and down.

Researchers in [24] explain variability as how much values change or spread out when you look at data. This makes it hard for grid operators to keep the system stable and balanced, as they need to make sure the electricity supply always meets demand. The ups and downs from VRE (Variable Renewable Energy) sources make it more difficult to smoothly add them into power grids.

Recent studies are focused on better understanding and measuring these changes to help improve how power grids are managed. Wind and solar energy naturally change with weather, which causes big swings in power supply. This is especially challenging in areas that rely heavily on renewables [25]. One study suggested that using a “finite-time correlation” method could help detect large changes in voltage, which may help improve power system stability if used correctly [26].

Researchers in [27] developed a model using support vector regression (SVR), a type of machine learning, to track things like power production, equipment failures, and weather conditions to better predict energy output. This could make power systems more reliable.

New, smart, and affordable technologies—like AI-based forecasting tools, long-term energy storage, and electricity connections between continents—offer strong ways to reduce the problems caused by variability. These are discussed further in Section 5.

The unpredictable nature of solar and wind creates problems when connecting them to electricity grids. However, many countries have found ways to reduce these issues using tools like energy storage, connecting power networks across borders, controlling energy use on the demand side, and making grids more flexible and responsive [28]. These methods have helped keep power systems reliable and running smoothly.

Important tools that help stabilize the grid when using a lot of renewable energy include grid-forming inverters, big battery storage systems, real-time forecasting models, and smart grids. Several countries have made great progress in handling the problems caused by VRE sources. The successful methods used in these countries are shown in Table 3.

All these real-world examples show how well solutions like battery storage, cross-border grid connections, and smart control systems can reduce variability. But there is still a strong need for more research and innovation in this area to make renewable power even more reliable.

Table2. Top10successfulcasesofwell-managedvariabilityinsomepowergridsaroundtheworld.

Nation/Region	GridProject(Case)	MajorHallmark	Method/SuccessFactor	References
Denmark	EnergyIsland (Bornholm)	windenergy	Highwindcapacity,flexible network, interconnectedwith neighbouringnationssuchas GermanyandSweden	[29,30–32]
Germany	Energiewende	Highsharegrid, integrationwithsolar andwindenergy	Demandresponse,EnergyStorage System(ESS),Smartgrids,and decongestedpowerproduction	[33,34,35]
Spain	The Spanish power system network	Large-scale renewable energy integration with over 40% in 2020	Dynamic power grid management, grid interconnections with nearby countries, peak storage capacity (e.g., pumped-hydro storage system)	[36,37]
California-United States of America	California Independent System Operator (CAISO)	High integration of solar and wind power	Power grid innovations, VRE forecasting models, energy storage, and demand response programs	[29,11,38]
South Australia (Australia)	South Australia’s Renewable Transition	60% variable renewable energy incorporated into the grid from solar and wind plants	Battery storage (e.g., the Hornsdale Power Reserve), smart grid-forming inverters, Virtual power plants, and Rigorous regulatory aids	[39,40,41]
United Kingdom	National Grid Electricity System	Injection of offshore wind,	Use of advanced forecasting, flexible demand, battery storage, and grid stability measures	[38,43,44]

	Operator's energy transition	interconnections with Europe		
Norway	Norway's Hydroelectric Power Integration	Supplying 98% of its electricity from hydropower plants	Interconnecting with nearby nations (e.g., Denmark and Sweden), hydropower for adaptability	[43,45,46]
Iceland	Hydropower mix and Geothermal exploit	100% renewable energy from geothermal and hydroelectric plants	Using stable and dispatchable sources of renewable energy (hydropower and geothermal) to balance fluctuations in demand	[47,48]
TX, USA	ERCOT (Electric Reliability Council of Texas)	High share grid integration of wind and solar energy, with over 30% renewable energy injected in 2020	Dynamic market-oriented balancing, enhanced forecasting models, and high amounts of power sharing with nearby grids	[29,49,50]
India	Renewable Energy Management Centers (REMCs)	High share grid integration of wind and solar energy, with over 30% renewable energy injected in 2020	Renewable Energy Management Centers (REMCs) for real-time forecasting and scheduling, the implementation of Green Energy Corridors to enhance transmission infrastructure, and pilot projects in battery energy storage systems (BESS) and smart grids	[10]

1.1. Causes of Variability

Variability in power systems means changes that can happen for many different reasons, either directly or indirectly. The main causes are changes in how much electricity is made or used. But technical problems like power losses, overloaded lines, or equipment failure can also make the situation worse. Below are some of the main causes of variability when renewable energy is added to power grids:

- **Fluctuationsinpowerdemand**
  Electricity use changes during the day, week, or year because of things like weather, how busy businesses are, and when people use more power. These changes in demand affect how the grid works [51].
- **Powerplantoutages**

  Power plants can suddenly stop working because of repairs, breakdowns, or fuel shortages. This can cause quick changes in how much electricity is available [51].
- **Transmissionlinelosses**
  When electricity travels over long distances, some of it is lost. These losses can cause changes in how the grid performs, especially when electricity is sent far from where it's produced.
- **Environmentalfactors,weather,andintermittencyofrenewables**

  Wind and solar power depend on the weather. Things like clouds, storms, temperature, and wind speed affect how much power is made. Since these weather patterns change a lot, they make it hard to keep the power supply steady [52].
- **Variablefuelavailability**
  Even traditional power plants can be affected when fuel supply changes, prices go up or down, or there are delivery problems. This affects how much energy they can produce.
- **Limitedenergystoragecapacity**

  Energy storage systems like batteries or water storage (pumped hydro) help balance the grid. But they can only store a certain amount of energy, and when they're empty or charging too slowly, this can cause power system variability [53].
- **Systemfrequencyvariability**

  The grid needs to keep its frequency (usually 50 or 60 Hz) within a narrow range. If energy supply or demand changes too quickly, the frequency changes too. This can lead to problems and needs quick action to fix [54].
- **Inter-regionalenergyexchange**

  Countries sometimes trade electricity with each other to balance supply and demand. But the amount of electricity available from other regions can also change, which adds to variability [55].
- **Systemcommunicationandcontroldelays**

  If there are delays in detecting or responding to problems in the grid, it can cause or worsen variability. Fast and accurate control is needed to keep the system stable [56].

These causes show just how challenging it is for grid operators to keep the system balanced and reliable, especially as more renewable energy is added to the network.

1.2. Types of Variability

Variability is usually grouped into three main types:

(i) short-term variability – changes that happen within minutes or hours,

(ii) long-term variability – changes over days, seasons, or years, and

(iii) spatial and temporal correlation – how weather patterns affect different areas at the same or different times.

In power grids that use renewable energy, variability comes from both the supply side (energy generation) and the demand side (energy usage). Grids with solar and wind energy (called VRESs) must deal with changes from both ends. How much power is being made and how much is being used?

Short-term flexibility is especially important because demand and renewable energy output change a lot during the day. In places with a lot of solar panels, power systems need to adjust quickly because of sudden drops in solar energy, especially when the sun goes behind clouds or during early evening when demand is still high but solar power drops [24].

For example, on cloudy days, solar panels produce much less energy than on sunny days, which causes fast changes in power output. Similarly, wind speed can change from hour to hour, which also causes the amount of wind energy to go up and down.

1.3. Types of Supply-SideVariability

Temporalvariability

Daily variability means that the amount of renewable energy produced changes at different times of the day. For example, solar power depends on sunlight, which is strongest around midday and weaker in the early morning or late afternoon. At night, solar panels don't produce any electricity at all. Wind power also changes during the day and night, depending on local wind patterns. In some places, wind might be stronger at night, while in others, it may blow more during the day. This makes it hard to predict exactly how much energy will be available throughout the day.

Seasonal variability refers to changes in renewable energy production across different seasons of the year. For instance, wind energy is usually more powerful in the winter months, when wind speeds are generally higher. On the other hand, solar energy tends to be more effective in the summer months, when days are longer and there is more direct sunlight. These seasonal patterns can vary based on geographic location and regional climate [57].

Weather-reliantvariability

Solar variability: Solar generation of energy relies heavily on weather conditions. Cloudy days may reduce PV output, and clear days might give an increase in output.

Wind variability: Strong windy days result in high yields of wind power production, while calm days with little or no wind lead to low power production. Localized weather activities can affect power generation since wind patterns are stochastic [58].

Topographicalvariability

Renewable energy production varies according to site location. For instance, wind power production yields are greater at seashores or mountainous sites, while solar may be efficient in zones closer to the equator.

Inter-annualvariability:

Long-term variability can span from one year to another, causing solar and wind resources to change due to prolonged climate change. Thus, impacting the power supply scenarios [57].

SpatialVariability

Renewable energy (RE) production in the same region or nation often varies because of zonal humidity, distribution of renewable energy resources, or land characteristics.

1.4. TypesofDemand-SideVariabilityGridFrequencyVariabilityandVoltageVariability

Frequency instability: Sharp variations (ramping) in renewable energy injections could result in unstable grid frequency, which may decrease or increase depending on the regional frequency limits (50 Hz or 60 Hz).

Voltage instability: Solar and wind energy sources are often integrated at various bus bars on the grids and can lead to voltage fluctuation if the voltage stability analysis studies are not effective [59].

EnergyStorageandDispatchVariability

Energy storage intermittency: Storage systems in VRE are effective mitigation strategies for variability in

power systems' networks; however, they become types of variability due to their charging and discharging cycles. They introduce variations in the grid based on the quantity of energy in stock.
Energy Dispatch variability: Renewables are fundamentally non-dispatchable. Meet- ing demand stresses the network, and balancing demand with supply introduces variability, particularly during periods of low production [60].

TransmissionandDistributionVariability
Transmission congestion: Variations in renewable energy (RE) generation could result in congestion when there is optimum production from the sources but insufficient transmission infrastructure to manage the available excess power. This situation leads to instability, energy loss, and network deficiency [61].
Voltage Regulation in the Distributed System: In zones or regions with a proliferation of rooftop installations, the distributed system of power production could have voltage regulation challenges, especially whenever solar yields go above load demand and reverse power flow back into the network.
The types of variability surveyed in the previous sub-section have led to a lot of chaos in grids around the world, some of which are presented in the next section.

1.5. ChaosCausedbyVariabilityinSomeGridsintheWorld
Variabilityinrenewableenergypowersystemshasbroughtaboutchaos,whichhas grown into a significant problem as electrical grids adapt to sophisticated technologies.This studyemphasizestheintricacyofchaosintheelectricalgridswhichmanifestinmanyforms.
Theauthorsin[62]stressedthatitisimperativetoconsiderharmonicdistortion,voltage imbalance, the capacity of transmission/distribution equipment, overvoltage, flickering, andundervoltageassomeofthechaosresultingfromstochasticloadsandgenerationthat create negative impacts on power quality and should be eliminated.
Thereference[63]reportsthatvariabilitycausestransientchaos,whichhasbeena phenomenonofmulti-stabilitywitnessedontheBritishpowergridandischaracterized bythepresenceofmultiplecoexistingattractorsthatresultinunpredictablereactionsto disturbances.This intricate behavior is shaped by the topological configurations of the network, especially in areas featuring complex basin landscapes.
AnothercaseofchaosisthatoftheTexasgridwherevariabilityhasledtooperational failuresasaresultofforecastingerrorsinenergyproduction. Theelectricitysystemhad experiencedtheeffectsofrandomnessandvariabilityduetoemergingstochasticassets[64]. The authors proposed a probabilistic steady-state analysis driven by inspirations from statistical worst-case circuit analysis to assess the likelihood of operational violations originating from stochastic resources.
The variability inherent in RE production, such as fluctuations in wind velocity or changes in solar irradiance, introduces considerable uncertainty in terms of the output power.Consequently,powersystemsoperatorsareoftenrequiredtosustainareasonable quantity reserve of backup generation capacity to ensure system stability amid these variations in renewable energy output. For instance, in the case of Denmark and the United Kingdom, where wind power plays a pivotal role in electricity generation, the grid must maintainsomereservestoaccommodaterapidvariationsinwindconditions,therebycomplicating operational management and huge costs incurred for standby generators. Furthermore, variability in these cases has increased the demand for reserves, leading to a dependency on fuel-based reserves, which risk elevating carbon emissions [65].

1.6. VariabilityManagementinVREGrid-ConnectedPowerSystems
TheproductionandintegrationofVRESintopowergridsposesomereal-timeopera- tional challenges to system operators, system designers, and researchers. These challenges spanfromtechnology,economics,andtogovernmentalenergypolicies.Generally,current VREresourcesutilizepowerelectronicdevicesorinverterstointerfacewiththenetwork rather than synchronous generators [66].At a point when a greater proportion of VRE injected goes above 50%, the system functions as an inverter-controlled network and such a system has exceptional qualities that change the operation of the grid components [64]. The keychallengeconfrontingpolicymakersandtheenergymarketsistoinstallandmaintain reliable carbon-free power grids that accommodate variable renewables while limiting holistic cost upgrading security and unwavering quality. This section summarizes some ofthekeychallengesandattemptstoprovidetechnological,economic,andpolicy-related solutions as shown in Table 4.
The technological strategies proposed in Table 3refer to techniques that employ novel components or systems

such as smart meters, relays, inverters, smart transformers, and so on. The economic strategies touch on methods of power grid management or monetary incentives such as contractual reserves, price-oriented balancing, and energy consumption. Policy approaches are decisions in line with norms and regulatory structures such as grid modernization guidelines, balancing requirements, etc.

Table3. Mitigationstrategiesofvariabilityinpowersystems.

Challenges	Mitigation	Category	Reference
Variabilityanduncertainty	-Deploying accurate innovative forecasting models or platforms -Installation of energy storage system	Technological	[61,38]
	- Implementing five-minute dispatch and greater balancing norms as in California and Germany - Curtailing of excess energy from VRE generation as in China and Germany - Dispersed installation of RE resources	Policy	[33,34]
Solutions to Chaos Caused by Variability			
Reverse current flow	-Installation of under-current detectors (relays) to signal grid inverters in case of current flow violations - The dynamic line rating (DLR) method is used on the Italian grid	Technological	[67,70]
Non-synchronization	-Use smart inverters (SI) to transfer maximum unsheathed power to the grid regardless of frequency, amplitude, and phase variation - Use of Proprotional integral (PI)/Phase lock Loop (PLL) controllers	Technological	[71,72]
Frequency instability	-Installation of smart inverters (SI) to eliminate frequency tripping - Reduction of active power close loop regulation - Use of virtual synchronous machines - Five-minute energy dispatching	Technological	[73,74,75]
Generator rotor instability	-Use of fault ride-through criteria with quality time variation.	Technological	[70]
Voltage instability (swell, sag, or dip)	-Installation of SIs to eliminate voltage tripping - Use of smart transformers (ST) techniques to link DC storage battery plans. - Use of OLTCs to shape voltage profiles - Running of synchronous condensers - Grid reconfiguration especially transmission lines disposition - Use of dynamic voltage restorer (DVR)	Technological	[19,54,74,76]
Grid protection	-Installation of smart protective relays -Use of adaptive protective systems (APS) as in the Canadian distribution network	Technological	[77,78]
Low level of inertia	-Least quota of synchronous generators in a traditional grid (Virtual Synchronous Machine) -Running synchronous condensers -Use of smart grid-forming inverters - Superconducting magnetic energy storage (SMES)	Technological	[79]
	-Contracting for more faster-operating reserves	Economic	[80]
Transient issues	-Introduction of Distributed Flexible AC Transmission (DFACT) devices at the point of common coupling (PCC) - Use of thyristor-controlled series capacitor (TCSC) - Fast valving (turbine FACT solution)	Technological	[77,61,81,82]
Harmonic distortion	-Use of DFACTs - Active Power Filter - Smart converter control	Technological	[83,84]

IV. Discussion

The integration of variable renewable energy sources (VRES), such as wind and solar, into power systems is an ongoing challenge. A number of strategies have been developed to manage the variability and intermittency associated with these renewable sources. However, these solutions are not one-size-fits-all. They need to be tailored to the specific needs and realities of each region, taking into account climatic conditions, the state of grid infrastructure, and the particular energy landscape. Despite these challenges, there are several promising strategies and technological solutions that have been demonstrated in various regions. This summary provides an overview of key approaches to mitigate the issues associated with VRES integration, with a focus on flexibility, energy storage, advanced power electronics, virtual power plants, sector coupling, and an innovative planning model for system integration.

1. Grid Flexibility and Demand Response

One of the most effective strategies in managing the variability of renewable energy is increasing grid flexibility through demand response programs. Countries such as Germany and China have led the way in implementing flexible grid systems that can adapt to fluctuations in renewable energy output. This flexibility is achieved through the use of smart grids, advanced metering infrastructure (AMI), and demand-side management. For instance, consumers are encouraged to adjust their electricity usage based on real-time supply conditions. When renewable generation is high (e.g., during sunny or windy periods), demand can be increased, and when generation is low, demand can be reduced. This flexibility can also be supported by traditional power plants that can rapidly ramp up or down to meet fluctuations in renewable energy supply.

In addition to this, grids in countries like China benefit from dispatchable energy sources, such as coal and hydroelectric plants, which provide the long-term flexibility needed to accommodate seasonal changes in both demand and renewable energy production. As power grids are modernized and upgraded with more flexible infrastructure, the need for expensive, polluting, peaking plants can be reduced, making the entire system more efficient and cost-effective.

2. Energy Storage Systems (ESS)

Energy storage is another key strategy for mitigating the intermittency of renewable energy. Storing excess energy generated during times of high renewable output and releasing it when demand exceeds supply or when renewable generation drops can help stabilize the grid. Battery energy storage systems (BESS) have shown great promise in balancing supply and demand. Large-scale energy storage systems, such as pumped hydro storage or large-scale battery banks, can absorb short-term variability in renewable energy and provide backup power during periods of low production.

To scale this strategy, significant investments in advanced storage technologies are required. Additionally, widespread financing models and policy support are necessary to make energy storage economically viable on a large scale. Energy storage systems are particularly effective in regions with high shares of VRES and are considered essential for increasing the resilience of grids dominated by renewable energy sources. Furthermore, the integration of power-to-X technologies, such as power-to-gas (hydrogen) and power-to-heat, can further enhance the functionality of energy storage systems and increase their capacity to support grid stability.

3. Grid-Forming Inverters and Advanced Power Electronics

Grid-forming inverters and advanced power electronics are crucial technologies that enable the integration of renewable energy sources with minimal disruption. These technologies are particularly valuable in enhancing grid stability, especially in isolated or weak networks that do not rely on traditional rotating machines (such as large turbines in conventional power plants).

Grid-forming inverters allow for the seamless integration of high shares of renewable energy without compromising important grid parameters like voltage quality and frequency. These technologies also help mitigate the effects of low system inertia, which is a common challenge in grids with high renewable penetration. Smart inverters and other power electronics solutions are becoming increasingly important for providing frequency and voltage control, ensuring that the grid remains stable even in the face of a variable renewable energy supply.

4. **Virtual Power Plants (VPPs)**

Virtual power plants (VPPs) represent another promising strategy for integrating variable renewable energy into the grid. A VPP aggregates decentralized, distributed energy resources (DERs) like small-scale solar, wind, batteries, and flexible demand loads into a single, dispatchable resource. These resources can be remotely controlled and managed, enabling them to provide grid services such as frequency regulation and demand response.

By clustering decentralized energy sources, VPPs help to mitigate variability and improve grid stability. They also allow for the participation of smaller, distributed energy resources in energy markets, offering new opportunities for energy trading and sharing. However, to effectively scale VPPs, robust communication technologies and advanced remote management platforms are required. These systems must be able to handle real-time data flow, ensure cybersecurity, and guarantee interoperability between different components of the grid.

5. **Sector Coupling (Power-to-X)**

Sector coupling is a concept that integrates renewable energy with other sectors, such as heating, transport, and industry. The power-to-X strategy allows for the conversion of renewable electricity into other forms of energy, such as heat or hydrogen, which can be stored and used in different sectors. This approach not

only helps to balance supply and demand but also reduces the overall carbon footprint of the energy system by integrating renewables with sectors that are typically harder to decarbonize.
For example, power-to-heat systems can use excess renewable energy to generate heat for district heating networks, while power-to-gas technologies can convert renewable electricity into hydrogen, which can then be stored and used as a fuel. This approach adds flexibility to the energy system and helps reduce variability by making use of renewable energy in multiple forms and sectors.

6. **Innovative Expansion Planning Models**
An innovative expansion planning model that incorporates operational flexibility constraints can help effectively manage both long-term and short-term variability in renewable energy supply. This model optimizes investment decisions for production and transmission infrastructure, ensuring that grids are capable of accommodating increasing shares of renewable energy.
The model also considers the variability of renewable energy sources and includes mechanisms for re-dispatching power to address changes in supply and demand. By incorporating flexibility into the planning and operation of the grid, it becomes easier to integrate renewable energy without compromising system reliability or performance.

7. **Key Takeaways and Future Directions**

Despite the many challenges posed by the integration of variable renewable energy sources into power systems, several promising strategies and technologies have emerged. These strategies, such as grid flexibility, energy storage, advanced power electronics, virtual power plants, and sector coupling, can significantly reduce the impact of renewable energy variability and help create more stable, resilient, and sustainable grids.

However, many regions still face challenges due to outdated grid infrastructure and the need for significant investment in modernization. To mitigate the impacts of variability in solar and wind energy integration, it is essential to invest in technologies like energy storage, forecasting tools, and advanced grid infrastructure, as well as to develop effective regulatory frameworks and policy support. Cross-sector collaboration, particularly with the transportation sector, can also help improve energy flexibility on a global scale.

The future of renewable energy integration will require continued innovation in technology, regulatory frameworks, and market mechanisms. As countries move forward with ambitious renewable energy goals, the effective integration of variable renewable energy into power systems will be crucial for achieving sustainability and energy security.

In conclusion, while the integration of VRES presents both challenges and opportunities, the strategies outlined above offer pathways to a more flexible, resilient, and sustainable energy future. Continued research, technological development, and global collaboration will be key in addressing the variability and intermittency of renewable energy sources and ensuring the stability of power systems worldwide.

Table 4. A proposed conceptual framework for boosting VRE integration into the grids.

S.no	Policy	Concept	Application Note
1	Policy and regulatory support	Develop a clear policy framework	Governments should clear long-term energy policies prioritizing the integrationof renewables and providing stability for investors and utility companies.
		Offer Incentives for VRE investment.	Funding programs for renewable energy, such as feed-in tariffs, tax breaks, and subsidies, should be promoted to motivate private sector investments in VRE.
		Access toGrids and tariffs	Flexible laws on grid access by VRE producers should be put in place and implemented to support tariff structures on energy sales and transmission projects.
		Implementation of the grid code	Countries' grid codes should be revisited to incorporate the variability of VRE, emphasizing grid stability, frequency variation, and grid flexibility.
2	Infrastructural development	Reinforcing grid infrastructure	Transmission and distribution structures should be upgraded to accommodate the variable nature of VRE, building smart grids, storage systems, and high-voltage lines.
		Installation of Energy Storage Systems (ESS)	Scaling up investment in storage technologies, e.g., batteries and pumped hydro, which mitigates variation in VRE and stabilizes grid functioning.
		Innovative grid management technologies	Practical application of continuous surveillance, smart grid technology, and automated management systems to improve network adaptiveness to VRE intermittency and incorporate distributed generation.
3	Capacity building and transfer of technical know-how	Skills development and training avenues	Training sessions and workshops should be organized for technicians, engineers, and policymakers to equip them with technical knowledge in RE investment and management.
		Sharing knowledge through platforms	The exchange of ideas about the success stories of other countries or organizations well advanced in VRE integration will bolster local capacities and prowess.

		Collaborating with international organizations	Working together with international financial and technical organizations such as the World Bank, UNDP, IEA, IMF, and WEC will enhance know-how and resource mobilization.
4	Investing in research and innovation	Promote localize research	Research and development of renewable energy technologies and grid solutions best suited for regional geographic, climatic, and economic situations should be motivated.
		Building financing models	Lofty financial schemes such as microfinancing, multi-sourcing, and green bonds will help decentralize RE projects, especially in rural or isolated grid zones.
		Pilot projects	Commissioning pilot projects permits the testing of diverse VRE-incorporated technologies and methods, issuing important data for scaling up strides.
5	Power system flexibility and systems integration	Hybrid power system	Installation of hybrid grids that constitute VRE and traditional generation/or other renewables, for the efficient matching of demand and supply.
		Demand-side management	Running demand-side management programs such as time-of-use (ToU) tariffs, to displace power demand to correspond to renewable energy availability and cut down dependency on fossil fuels.
		Cross-border energy market	Collaboration among regions and international energy sales helps mitigate variability in RE availability via grid interconnections with nearby nations.
6	Public sensitization and stakeholder involvement	Public awareness campaigns	Organizing VRE sensitization campaigns increases awareness of carbon-free energy sources and fosters sustainable development (SG7).
		Community involvement	Engaging local communities in RE planning and decision-making guarantees their needs are met and promotes universal acceptance of VRE projects.
		Involving the private sector	Joining task forces with private companies will stimulate research, innovation, and the deployment of renewable technologies to meet local and country needs.
7	Monitoring, evaluation, and constant upgrading	Develop performance metrics	Establishing parameters to trace the path covered by VRE integration projects, with emphasis on reducing CO2 emissions, grid reliability, and cost-effective energy strategies.
		Adaptive management	Establish assessment loops for evaluating renewable energy policies, technologies, and infrastructure, and fine-tune strategies for mitigation.
		Data-driven decision	Design and invest in real-time monitoring data analytics systems to obtain reliable information for decision-making, optimization of VRE efficiency, and grid robustness.

V. Conclusions

Challenges of integrating Variable Renewable Energy (VRE)—especially **solar and wind**—into electrical power grids. The focus is mainly on:

- **Supply-side variability** (changes in solar/wind generation),
- **Demand-side variability** (changes in electricity use by consumers).

It examines how **countries like China, Germany, Australia, Spain, the UK, and the USA** handle these challenges using **technology, economic tools, and policy actions**.

Main Challenges Identified

1. **Unpredictability of Solar and Wind Energy**
   Solar and wind power depend on nature, so their output changes constantly (e.g., clouds or low wind). This makes it tough for grid operators to keep the system stable and reliable.
2. **Fluctuations in Power Demand**
   Electricity demand also changes due to weather, time of day, and economic activity, making it harder to match supply and demand.

Methodology Used in the Study

The study carefully selected **recent peer-reviewed articles (2020–2024)** and high-quality technical reports. Only the **most relevant and recent studies** were included.

Key Findings and Solutions

✅ **Technological Solutions:**

- **Long-Duration Energy Storage (LDES):** Stores extra power from solar/wind when it's available, and releases it when needed (like during cloudy or windless hours).
- **Virtual Power Plants (VPPs):** Combines small energy sources (like rooftop solar and batteries) to act as one big, flexible power source.
- **Smart Grids:** These advanced grids allow real-time monitoring and quick responses to changes in electricity supply and demand.
- **Cross-Border Interconnections:** Linking grids between countries or regions helps share renewable energy and balance supply and demand better.
- **Power-to-X (Sector Coupling):** Converts renewable electricity to other energy forms (like hydrogen or heat), connecting the power grid with transport, heating, and industries.

💰 **Economic and Policy Measures:**

- **Financial Incentives:** Subsidies and tax breaks support the growth of renewable energy.

- **Dynamic Pricing and Markets:** Encourages users to shift their energy use to times when renewable energy is more available (e.g., using washing machines during sunny hours).
- **Capacity Markets:** Make sure enough power is always available, even when renewable sources are low.

🔁 **Grid Flexibility:**

A flexible grid can better adapt to changes, which is essential for managing renewables effectively.

Proposed 7-Point Policy Framework

The study offers a **7-part plan** to help countries and stakeholders (governments, producers, operators, and consumers) work together to solve variability problems:

1. Long-Duration Energy Storage
2. Virtual Power Plants
3. Smart Grids
4. Cross-Border Interconnections
5. Power-to-X (sector coupling)
6. Financial support and incentives
7. Policies that support grid flexibility and modernization

Highlights of the Conclusion

This review gives a clear overview of:

- The **current challenges** in integrating solar and wind into power systems,
- The **latest technologies and strategies** that countries are using,
- And a **conceptual policy framework** to guide future action.

It is especially useful for:

- **Researchers** exploring renewable energy integration,
- **Industry professionals** working on grid systems,
- And **policy makers** aiming to build cleaner, more stable energy systems worldwide.

Prospects

Adding solar and wind power (known as variable renewable energy or VRE) to power grids brings both **challenges** and **opportunities**. One big challenge is that these sources depend on the weather and don't produce power all the time, which can make it hard to keep the grid stable. However, using more renewable energy also brings chances to modernize the grid, improve sustainability, and ensure long-term energy security.

To build the **"grids of the future,"** countries around the world need to adopt new technologies and smart policies. These changes are key to solving the problems that come with using more solar and wind energy.

One important step is to make the **electrical grid more flexible**. New solutions like **smart grids**, **demand-response systems**, and **advanced grid management** will help match electricity supply with demand, even when solar and wind energy change quickly. Using **artificial intelligence (AI)** to predict energy production can also help grid operators plan better and keep the system running smoothly.

Energy storage—especially batteries—will play a huge role. As battery technology improves, it will be easier to store extra renewable energy and use it later when the sun isn't shining or the wind isn't blowing. New types of storage, like **flow batteries** and **solid-state batteries,** will be especially useful for **long-term storage**.

Governments also need to set up **market systems** that support flexibility and storage. These systems, like **flexibility markets**, will pay businesses and people who help balance the grid, especially when solar or wind power suddenly changes [68].

Using more renewable energy helps **cut carbon emissions**, reduce dependence on fossil fuels, and move us toward **clean energy goals** like those in the **Paris Agreement**. Countries around the world are using VRE to lead this green energy transition.

Microgrids and **Virtual Power Plants (VPPs)** are becoming more common, too. These systems combine smaller energy sources—like rooftop solar panels, batteries, and smart appliances—so they can work together. They can either run on their own or connect with the main grid, helping to better handle VRE power.

Because of the variable nature of solar and wind, **grid flexibility** is now more important than ever. Governments should invest in **modern infrastructure**, including **stronger transmission systems**, to help handle the ups and downs of renewable energy. This includes updating old power lines and making sure the grid can carry power from many different places [68].

Capacity mechanisms are also helpful. They make sure there is always enough backup electricity when renewables aren't generating much. **Market integration policies** make it easier to move renewable power between different regions, helping to balance power over larger areas.

Policies like **Renewable Portfolio Standards** and **Feed-in Tariffs (FITs)** support VRE growth. FITs, for example, guarantee a price for renewable energy, encouraging more people and companies to invest. Countries like the **USA, Germany, and China** have used these policies to grow their renewable sectors.

In the future, combining new technologies—like **better batteries**, **AI forecasting**, and **international power-sharing**—with smart policies such as **carbon pricing** and **grid upgrades** will make it easier and more affordable to use renewable energy. This will lead to **cleaner, stronger, and more reliable power systems** [69].

Future Study

This research paper does not claim to cover every detail of the topic, so there's a need for future studies. More research should focus on how **artificial intelligence (AI)** can be used in power grids. For example, AI could be used to improve **digital twins**—virtual models of the grid—to help manage energy automatically, predict changes in renewable energy like solar and wind, and detect equipment problems before they happen. Strong **cybersecurity systems** will also be needed to protect these digital twins from possible cyberattacks in smart grids.

In addition, **training programs** should be created so that all users and stakeholders know how to work with AI tools and understand the data from digital twins throughout their use, as explained in the policy suggestions shown in Table 5.

Future research should also look into **AI-based forecasting models** that can give accurate weather predictions for very small areas and different time frames (short or long). These are important for tracking how much sun or wind energy can be produced.

Another area of study could be the creation of **super grids** that link different countries or continents. This would allow areas with more sunlight or wind at different times to share power and support each other, for example, using solar energy during the day and wind power at night. Research could focus on how to make these networks efficient, reduce wasted energy, and keep the grid stable across large areas.

Lastly, a detailed study is needed to understand the **political, legal, and technical challenges** that could slow down the global trade of renewable energy. These factors also affect how flexible and reliable power grids can be in the future.

Reference

[1]. Lund, Henrik, "Smart Energy and Smart Energy Systems." Energy, vol. 137, 2017, pp. 556–565. https://doi.org/10.1016/j.energy.2017.05.123.

[2]. International Energy Agency. World Energy Outlook 2020. IEA, 2020.

[3]. Cochran, Jaquelin, Flexibility in 21st Century Power Systems. National Renewable Energy Laboratory (NREL), 2014.

[4]. Milligan, Michael, Integration of Variable Generation, Cost-Causation, and Integration Costs. NREL/TP-5500-51860, National Renewable Energy Laboratory (NREL), 2011.

[5]. Denholm, Paul, Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart. National Renewable Energy Laboratory (NREL), 2015.

[6]. REN21. Renewables 2021 Global Status Report. REN21 Secretariat, 2021, https://www.ren21.net/reports/global-status-report/.

[7]. Juma, D.; Munda, J.; Kabiri, C. Power-System Flexibility: A Necessary Complement to Variable Renewable Energy Optimal Capacity Configuration. Energies 2023, 16, 7432. [CrossRef]

[8]. Xu, T.; Gao, W.; Qian, F.; Li, Y. The implementation limitation of variable renewable energies and its impacts on the public power grid. Energy 2022, 239, 121992. [CrossRef]

[9]. Zaheb, H.; Ahmadi, M.; Rahmany, N.A.; Danish, M.S.S.; Fedayi, H.; Yona, A. Optimal Grid Flexibility Assessment for Integration of Variable Renewable-Based Electricity Generation. Sustainability 2023, 15, 15032. [CrossRef]

[10]. Joshi, M.; Inskeep, S. Institutional Framework of Variable Renewable Energy forecasting in India; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2023.

[11]. Shafiullah, M.; Ahmed, S.D.; Al-Sulaiman, F.A. Grid Integration Challenges and Solution Strategies for Solar PV Systems: A Review. IEEE Access 2022, 10, 52233–52257. [CrossRef]

[12]. Fang, Y.; Han, J.; Du, E.; Jiang, H.; Fang, Y.; Zhang, N.; Kang, C. Electric energy system planning considering chronological renewable generation variability and uncertainty. Appl. Energy 2024, 373, 123961. [CrossRef]

[13]. Magaña-González, R.C.; Rodríguez-Hernández, O.; Canul-Reyes, D.A. Analysis of seasonal variability and complementarity of wind and solar resources in Mexico. Sustain. Energy Technol. Assess. 2023, 60, 103456. [CrossRef]

[14]. IEA. Renewables 2023; Revised Version; IEA: Paris, France, 2024.

[15]. Njema, G.G.; Ouma, R.B.O.; Kibet, J.K. A Review on the Recent Advances in Battery Development and Energy Storage Technologies. J. Renew. Energy 2024, 2024, 2329261. [CrossRef]

[16]. Graham, E.; Fulghum, N. Wind and Solar Overtake EU Fossil Fuels in the First Half of 2024; EMBER: Wales, UK, 2024.

[17]. Wiatros-Motyka, M.; Fulghum, N.; Jones, D. Global Electricity Review; EMBER: Wales, UK, 2024

[18]. International Energy Agency. Electricity Grids and Secure Energy Transitions: Enhancing the Foundations of Resilient, Sustainable and Affordable Power Systems; OECD: Paris, France, 2023; ISBN 978-92-64-70296-7.

[19]. Medina, C.; Ana, C.R.M.; González, G. Transmission Grids to Foster High Penetration of Large-Scale Variable Renewable Energy Sources—A Review of Challenges, Problems, and Solutions. Int. J. Renew. Energy Res. 2022, 12, 146–169. [CrossRef]

[20]. IEA. Renewables 2023; Revised Version; IEA: Paris, France, 2024.

[21]. Rathore, K.; Kumar, S. Net Zero Emissions for Our Future Generations through Renewables: A Brief Review. Int. J. Energy Resour.Appl. 2023, 2, 39–56. [CrossRef]

[22]. Global Wind Energy Council. Global Wind Report 2024 Global Wind Energy Council, Rue de Commerce 31 1000 Brussels, Belgium. April 2024. Available online: https://www.gwec.net/?s=global+wind+council+energy+reports (accessed on 14 December 2024).

[23]. Thukral, K.; Wijayatunga, P.; Yoneoka, S. Increasing Penetration of Variable Renewable Energy: Lessons for Asia and the Pacific; Asian Development Bank: Manila, Philippines, 2017.

[24]. Min, C.-G. Analyzing the Impact of Variability and Uncertainty on Power System Flexibility. Appl. Sci. 2019, 9, 561. [CrossRef]

[25]. Gao, M.; Knobelspiesse, K.; Franz, B.A.; Zhai, P.-W.; Cairns, B.; Xu, X.; Martins, J.V. The impact and estimation of uncertainty correlation for multi-angle polarimetric remote sensing of aerosols and ocean color. Atmos. Meas. Tech. 2023, 16, 2067–2087. [CrossRef]

[26]. Tyloo, M.; Hindes, J.; Jacquod, P. Finite-time correlations boost large voltage angle fluctuations in electric power grids. J. Phys. Complex. 2023, 4, 015006. [CrossRef]

[27]. Singh, A.R.; Kumar, R.S.; Bajaj, M.; Khadse, C.B.; Zaitsev, I. Machine learning-based energy management and power forecasting in grid-connected microgrids with multiple distributed energy sources. Sci. Rep. 2024, 14, 19207. [CrossRef]

[28]. Fernandez, M.I.; Go, Y.I.; Wong, D.M.L.; Früh, W.-G. Review of challenges and key enablers in energy systems towards net zero target: Renewables, storage, buildings, & grid technologies. Heliyon 2024, 10, e40691. [CrossRef] [PubMed]

[29]. Joshi, M.; Inskeep, S. Institutional Framework of Variable Renewable Energy forecasting in India; National Renewable Energy Laboratory (NREL): Golden, CO, USA, 2023.

[30]. Worku, M.Y. Recent Advances in Energy Storage Systems for Renewable Source Grid Integration: A Comprehensive Review.Sustainability 2022, 14, 5985. [CrossRef]

[31]. Skov, I.R.; Schneider, N.; Schweiger, G.; Schöggl, J.-P.; Posch, A. Power-to-X in Denmark: An Analysis of Strengths, Weaknesses, Opportunities and Threats. Energies 2021, 14, 913. [CrossRef]

[32]. Karakitsios, I.; Lagos, D.; Dimeas, A.; Hatziargyriou, N. How Can EVs Support High RES Penetration in Islands? Energies 2023, 16, 558. [CrossRef]

[33]. Dimnik, J.; Topic´ Božicˇ, J.; Cˇ ikic´, A.; Muhicˇ, S. Impacts of High PV Penetration on Slovenia's Electricity Grid: Energy Modeling and Life Cycle Assessment. Energies 2024, 17, 3170. [CrossRef]

[34]. Iung, A.M.; Cyrino Oliveira, F.L.; Marcato, A.L.M. A Review on Modeling Variable Renewable Energy: Complementarity and Spatial–Temporal Dependence. Energies 2023, 16, 1013. [CrossRef]

[35]. Min, C.-G. Analyzing the Impact of Variability and Uncertainty on Power System Flexibility. Appl. Sci. 2019, 9, 561. [CrossRef]

[36]. Huclin, S.; Ramos, A.; Chaves, J.P.; Matanza, J.; González-Eguino, M. A methodological approach for assessing flexibility and capacity value in renewable-dominated power systems: A Spanish case study in 2030. Energy 2023, 285, 129491. [CrossRef]

[37]. Bonilla-Campos, I.; Sorbet, F.J.; Astrain, D. Radical change in the Spanish grid: Renewable energy generation profile and electric energy excess. Sustain. Energy Grids Netw. 2022, 32, 100941. [CrossRef]

[38]. Teixeira, R.; Cerveira, A.; Pires, E.J.S.; Baptista, J. Advancing Renewable Energy Forecasting: A Comprehensive Review of Renewable Energy Forecasting Methods. Energies 2024, 17, 3480. [CrossRef]

[39]. Akinsooto, O.; Ogundipe, O.B.; Ikemba, S. Regulatory policies for enhancing grid stability through the integration of renewable energy and battery energy storage systems (BESS). Int. J. Frontline Res. Rev. 2024, 2, 022–044. [CrossRef]

[40]. DFEM; AEMO. South Australia Green Paper on South Australia's Energy Transition; DFEM: Adelaide, Australia, 2023.

[41]. Potapenko, T.; Döhler, J.S.; Francisco, F.; Lavidas, G.; Temiz, I. Renewable Energy Potential for Micro-Grid at Hvide Sande.Sustainability 2023, 15, 2234. [CrossRef]

[42]. Teixeira, R.; Cerveira, A.; Pires, E.J.S.; Baptista, J. Advancing Renewable Energy Forecasting: A Comprehensive Review of Renewable Energy Forecasting Methods. Energies 2024, 17, 3480. [CrossRef]

[43]. NESO; National Grid ESO. National Grid ESO Electricity Capacity Report; National Energy System Operator: Warwick, UK, 2021.

[44]. NESO; National Grid ESO. 2021–23 Mid-Scheme Report: Executive Summary; Executive Summary; National Energy System Operator: Warwick, UK, 2022.

[45]. IRENA. World Energy Transitions Outlook: 1.5 ◦C Pathway; IRENA: Abu Dhabi, United Arab Emirates, 2021.

[46]. IEA. NORWAY 2022: Energy Policy Review; IEA: Paris, France, 2022.

[47]. Holdman, G.; Gudleifsson, E. Insights Into The Icelandic Energy Market; ACEP: Fairbanks, AK, USA, 2023.

[48]. IEA. World Energy Outlook (2020); IEA: Paris, France, 2020.

[49]. NETL. 2020 Summer Resource Adequacy in the ERCOT Region; ERCOT: Austin, TX, USA, 2020.

[50]. Cao, K.H.; Qi, H.S.; Tsai, C.H.; Woo, C.K.; Zarnikau, J. Energy trading efficiency in ERCOT's day-ahead and real-time electricity markets. J. Energy Mark. 2022, 15, 59–81. [CrossRef]

[51]. Han, K.B.; Jung, J.; Kang, B.O. Real-Time Load Variability Control Using Energy Storage System for Demand-Side Management in South Korea. Energies 2021, 14, 6292. [CrossRef]

[52]. Gonçalves, A.C.R.; Costoya, X.; Nieto, R.; Liberato, M.L.R. Extreme weather events on energy systems: A comprehensive review on impacts, mitigation, and adaptation measures. Sustain. Energy Res. 2024, 11, 4. [CrossRef]

[53]. Amir, M.; Deshmukh, R.G.; Khalid, H.M.; Said, Z.; Raza, A.; Muyeen, S.M.; Nizami, A.-S.; Elavarasan, R.M.; Saidur, R.; Sopian,K. Energy storage technologies: An integrated survey of developments, global economic/environmental effects, optimal scheduling model, and sustainable adaptation policies. J. Energy Storage 2023, 72, 108694. [CrossRef]

[54]. Ahmed, F.; Al Kez, D.; McLoone, S.; Best, R.J.; Cameron, C.; Foley, A. Dynamic grid stability in low carbon power systems with minimum inertia. Renew. Energy 2023, 210, 486–506. [CrossRef]

[55]. Naval, N.; Yusta, J.M. Assessment of cross-border electricity interconnection projects using an MCDA method. Int. J. Crit.Infrastruct. Prot. 2024, 46, 100703. [CrossRef]

[56]. Muyizere, D.; Letting, L.K.; Munyazikwiye, B.B. Decreasing the Negative Impact of Time Delays on Electricity Due to Performance Improvement in the Rwanda National Grid. Electronics 2022, 11, 3114. [CrossRef]

[57]. IEA. Managing Seasonal and Interannual Variability of Renewables; IEA: Hiroshima, Japan, 2023.

[58]. Göransson, L.; Granfeldt, C.; Strömberg, A.-B. Management of Wind Power Variations in Electricity System Investment Models: A Parallel Computing Strategy. Oper. Res. Forum 2021, 2, 25. [CrossRef]

[59]. Reguieg, Z.; Bouyakoub, I.; Mehedi, F. Optimizing power quality in interconnected renewable energy systems: Series active power filter integration for harmonic reduction and enhanced performance. Electr. Eng. 2024. [CrossRef]

[60]. Krasopoulos, C.T.; Papaioannou, T.G.; Stamoulis, G.D.; Ntavarinos, N.; Patouni, M.D.; Simoglou, C.K.; Papakonstantinou,A. Win–Win Coordination between RES and DR Aggregators for Mitigating Energy Imbalances under Flexibility Uncertainty.*Energies***2023**,*17*,21.[CrossRef]

[61]. Hirschhorn, P. Rising to the Challenges of Integrating Solar and Wind at Scale; BCG Institute: Sydney, Australia, 2021.

[62]. AhmadiAhangar, R.; Plaum, F.; Haring, T.; Drovtar, I.; Korotko, T.; Rosin, A. Impacts of grid-scale battery systems on power system operation, case of Baltic region. IET Smart Grid 2024, 7, 101–119. [CrossRef]

[63]. Halekotte, L.; Vanselow, A.; Feudel, U. Transient chaos enforces uncertainty in the British power grid. J. Phys. Complex. 2021,2, 035015. [CrossRef]

[64]. Turner-Bandele, N.; Pandey, A.; Pileggi, L. A Risk-Managed Steady-State Analysis to Assess the Impact of Power Grid Uncertainties. arXiv 2022, arXiv:2111.10290.

[65]. Energinet, Fingrid, Statnett, and Svenska kraftnät, "Nordic Grid Development Perspective 2023", Nordic TSOs, Nordic Nations, Bi-Annual. 2023. Available online: https://www.svk.se/siteassets/om-oss/rapporter/2023/svk_ngpd2023.pdf (accessed on 14 December 2024).

[66]. Zaman, A. 100% Variable Renewable Energy Grid: Survey of Possibilities. Master's Thesis, University of Michigan, Ann Arbor, MI, USA, 2018.

[67]. De Carne, G.; Buticchi, G.; Zou, Z.; Liserre, M. Reverse Power Flow Control in a ST-Fed Distribution Grid. IEEE Trans. Smart Grid 2018, 9, 3811–3819. [CrossRef]

[68]. Hirschhorn, P. Rising to the Challenges of Integrating Solar and Wind at Scale; BCG Institute: Sidney, Australia, 2021.

[69]. Kabir, M.R.; Halder, D.; Ray, S. Digital Twins for IoT-Driven Energy Systems: A Survey. IEEE Access 2024, 12, 177123–177143. [CrossRef]

[70]. Iweh, C.D.; Gyamfi, S.; Tanyi, E.; Effah-Donyina, E. Distributed Generation and Renewable Energy Integration into the Grid: Prerequisites, Push Factors, Practical Options, Issues and Merits. Energies 2021, 14, 5375. [CrossRef]

[71]. Mansouri, N.; Nasri, S.; Lashab, A.; Guerrero, J.M.; Cherif, A. Innovative Grid-Connected Photovoltaic Systems Control Based on Complex-Vector-Filter. Energies 2022, 15, 6772. [CrossRef]

[72]. Peng, Q.; Buticchi, G.; Tan, N.M.L.; Guenter, S.; Yang, J.; Wheeler, P. Modeling Techniques and Stability Analysis Tools for Grid-Connected Converters. IEEE Open J. Power Electron. 2022, 3, 450–467. [CrossRef]

[73]. Basit, M.A.; Dilshad, S.; Badar, R.; Sami Ur Rehman, S.M. Limitations, challenges, and solution approaches in grid-connected renewable energy systems. Int. J. Energy Res. 2020, 44, 4132–4162. [CrossRef]

[74]. Li, C.; Jin, C.; Sharma, R. Coordination of PV Smart Inverters Using Deep Reinforcement Learning for Grid Voltage Regulation. In Proceedings of the 2019 18th IEEE International Conference on Machine Learning and Applications (ICMLA), Boca Raton, FL, USA, 16–19 December 2019; pp. 1930–1937.

[75]. Chernyakhovskiy, I.; Koebrich, S.; Gevorgian, V.; Cochran, J. "Grid-Friendly Renewable Energy", NREL, U.S DOE. 2019. Available online: https://www.nrel.gov/docs/fy19osti/73866.pdf (accessed on 14 December 2024).

[76]. Soomro, A.H.; Larik, A.S.; Mahar, M.A.; Sahito, A.A.; Soomro, A.M.; Kaloi, G.S. Dynamic Voltage Restorer—A comprehensive review. Energy Rep. 2021, 7, 6786–6805. [CrossRef]

[77]. Jha, K.; Shaik, A.G. A comprehensive review of power quality mitigation in the scenario of solar PV integration into the utility grid-Prime-Adv. Electr. Eng. Electron. Energy 2023, 3, 100103. [CrossRef]

[78]. Sampaio, F.C.; Tofoli, F.L.; Melo, L.S.; Barroso, G.C.; Sampaio, R.F.; Leão, R.P.S. Smart Protection System for Microgrids with Grid-Connected and Islanded Capabilities Based on an Adaptive Algorithm. Energies 2023, 16, 2273. [CrossRef]

[79]. Kaushik, E.; Prakash, V.; Mahela, O.P.; Khan, B.; El-Shahat, A.; Abdelaziz, A.Y. Comprehensive Overview of Power System Flexibility during the Scenario of High Penetration of Renewable Energy in Utility Grid. Energies 2022, 15, 516. [CrossRef

[80]. Heptonstall, P.J.; Gross, R.J.K. A systematic review of the costs and impacts of integrating variable renewables into power grids.Nat. Energy 2020, 6, 72–83. [CrossRef]

[81]. Shafiullah, G.M.; Arif, M.T.; Oo, A.M.T. Mitigation strategies to minimize potential technical challenges of renewable energy integration. Sustain. Energy Technol. Assess. 2018, 25, 24–42. [CrossRef]

[82]. Otuo-Acheampong, D.; Rashed, G.I.; Mensah, A.A.; Haider, H. Three-phase fault analysis of power system transient stability based on TCSC controller using FPA for its location. J. Phys. Conf. Ser.. 2023, 2467, 012014. [CrossRef]

[83]. Sadiq, R.; Wang, Z.; Chung, C.Y.; Zhou, C.; Wang, C. A review of STATCOM control for stability enhancement of power systems with wind/PV penetration: Existing research and future scope. Int. Trans. Electr. Energy Syst. 2021, 31, e13079. [CrossRef]

[84]. Hossain, E.; Tur, M.R.; Padmanaban, S.; Ay, S.; Khan, I. Analysis and Mitigation of Power Quality Issues in Distributed Generation Systems Using Custom Power Devices. IEEE Access 2018, 6, 16816–16833. [CrossRef]