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Addressing reliability challenges in generation capacity planning under high penetration of renewable energy resources and storage solutions: A review

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A B S T R A C T

This study offers a comprehensive survey of generation capacity planning from a reliability perspective, considering the influence of renewable resources and energy storage systems. The uncertainties surrounding intermittent resources raise concerns about power system reliability. This has led to the proposal of new assessment and optimization frameworks in generation expansion planning, as evidenced by numerous reports and original research works. In addition to the challenge concerning power system reliability, phenomena such as Dunkelflaute require thorough consideration when planning problems. Furthermore, energy storage systems have emerged as a promising solution to address these challenges. Consequently, numerous researchers have worked on methods for handling uncertainty in generation outputs, selecting appropriate reliability indices, and evaluating reliability techniques. This review paper offers a survey of research works exploring the relevant aspects of generation capacity planning under the high penetration of renewable energy resources. This survey also highlights new research opportunities for scholars seeking to assess the associated reliability challenges of integrating renewables into modern power systems.

1. Introduction

The challenges of supplying increasing energy demand with the integration of cleaner energy sources have been primary concerns in power generation systems in recent years. It is widely acknowledged that the power generation sector plays a pivotal role in reducing carbon emissions responsible for global warming to curtail the increasing temperatures of the Earth [1]. Renewable energy sources, such as solar and wind, have gained significant importance in this process, and in the future, these clean energy sources will continue to grow in prominence. Accordingly, it is prescient that global annual additions to renewable electricity generation capacity have surged by nearly 50 %, reaching approximately 510 GW by the end of 2023 [2]. Further, the share of renewables in electricity generation is expected to increase from 28 % in recent years to 68 % in 2030 and 91 % in 2050 [3]. Switching to renewable energy systems is crucial to addressing climate goals but also introduces new difficulties. Furthermore, emerging changes in modern life have led to a substantial need for reliable energy sources. Amongst the available types of energy, electricity has become deeply ingrained in various aspects of modern life, where society views it as an indisputable right. Consequently, its reliability has recently attracted much attention [4].

Over the past few decades, due to global warming, renewable energy sources have emerged as a viable alternative to traditional electric power sources [5]. In particular, to achieve the objectives of the Paris Agreement—which seeks to counter increases in average global temperature to well below 2 °C, and ideally below 1.5 °C above pre-industrial levels—there is a need to shift towards intermittent energy sources like wind and solar power [6]. Renewable energy is becoming a popular alternative to fossil fuels, driven by concerns about climate change and resource depletion [5]. The Net Zero Emissions (NZE) by 2050 plan anticipates the penetration of Variable Renewable Energy (VRE) resources, such as solar farms, wind farms, and Distributed Photovoltaic (DPV) systems, to increase. Conversely, electricity consumption is expected to rise due to increased electrification of various end-users and changes in how electricity is generated [7]. However, integrating these resources into the power grid can be challenging due to their intermittent behavior, which may disrupt the normal functioning of the grid [8]. One of the most challenging problems related to the integration of VRE resources is the Dunkelflaute phenomenon, characterized by a sudden and dramatic decrease in their

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List of abbreviations

BESS	Battery Energy Storage Systems
DSM	Demand-Side Management
DPV	Distributed Photovoltaic
ELCC	Effective Load Carrying Capability
ERCOT	Electric Reliability Council of Texas
ESS	Energy Storage System
EENS	Expected Energy Not Supplied
EENU	Expected Energy Not Unserved
EIR	Expected Interruption Rate
EPNS	Expected Power Not Supplied
ESEC	Expected Solar Energy Curtailment
EUE	Expected Unserved Energy
EWES	Expected Wind Energy Spilled
GEP	Generation Expansion Planning
HRES	Hybrid Renewable Energy System
LSBS	Large-Scale Battery Storage
LDES	Long Duration Energy Storage
LOEE	Loss of Energy Expectation
LOLD	Loss of Load Duration
LOLE	Loss of Load Expectation
LOLF	Loss of Load Frequency
LOLH	Loss of Load Hour
LOLP	Loss of Load Probability
LPSP	Loss of Power Supply Probability
MILP	Mixed-Integer Linear Program
MINLP	Mixed-Integer Nonlinear Programming
NECP	National Energy and Climate Plans
NZE	Net Zero Emissions
PLC	Probability of Load Curtailment
SWIS	South West Interconnected System
VRE	Variable Renewable Energy

availability [9]. Despite this, integrating renewable energy sources into the grid is still considered a viable option, even though it may cause some distortion in the power grid [8]. Renewable energy resources are highly variable and uncertain, posing a significant challenge to system reliability. One solution to address this issue is to utilize Energy Storage Systems (ESSs) [10,11]. The significance of a reliable power supply is well-discussed [12–18], where it is an established technical fact that power system reliability is crucial to any national development and social welfare investment program in countries. Accordingly, policymakers must consider it while working on strategic development plans.

However, achieving a power supply system that is 100 % reliable is not feasible due to variables such as inherent component failures, unpredictable energy sources, and uncertainties related to load profiles. One focus of this research is on the impact of VRE resources on generation system adequacy, determining the role that storage systems can play in improving reliability. When a power system is integrated with intermittent energy sources, system blackouts can be expected to occur under certain conditions, as discussed in Ref. [19]. In this scenario, investing in electric power generation and transmission facilities is the key to alleviating the risk of energy deficiency.

These challenges should be effectively addressed in capacity planning, classically coined as Generation Expansion Planning (GEP). These involve optimization problems determining the type and capacity of new energy sources required to be in service or retired at specific sites and times. Energy storage systems should be well-modeled and considered in GEP to ensure power system reliability toward decarbonization and guarantee the integration of higher penetration of VRE sources.

This survey's main contribution is to examine the critical role of energy storage in transitioning away traditional energy resources. As intermittent renewable resources increasingly transform the energy supply landscape, their inherent characteristics and limitations introduce significant complexities in electricity system planning and operations, particularly affecting system reliability. This survey reviews recently published articles, highlighting how energy storage contributes to network reliability and generation capacity planning. Furthermore, it identifies gaps and challenges that need further study to avoid potential issues in a fully or predominantly renewable energy network.

The remainder of this survey is structured as follows. Section 2 reviews the methodological strategy employed in the study. Section 3 provides a high-level insight into the concept of reliability relevant to power system planning. Section 4 reviews energy storage systems and some of their contributions to power system reliability challenges. The impact of VRE resources and ESSs is discussed in Section 5, and Section 6 gives a view of generation capacity planning focusing on integrating of VRE resources and ESSs. Section 7 concludes the review.

2. Review methodology strategy

The methodology adopted in this review is outlined in Fig. 1, illustrating the comprehensive process undertaken. The review commences by clearly delineating its objective to illuminate and analyze existing research concerning the influence of VRE resources and energy storage on the reliability of power networks. The initial step involves conducting an extensive literature review to pinpoint articles that articulate the reliability of power systems incorporating renewable energies and storage solutions. This encompasses traditional reliability indices and those tailored to address the distinct challenges VRE penetration brings. Subsequently, the review explores how VRE resources, such as wind and solar power, impact the reliability of power systems. A central facet of this review survey is examining the effects of weather on the reliability of decarbonized power systems, with particular emphasis on the Dunkelflaute phenomenon. This phenomenon refers to periods characterized by minimal or no wind or solar power generation, which pose significant challenges to system reliability. Furthermore, the review examines how integrating storage technologies can support the reliability of power systems with high VRE levels. This entails evaluating the impact of ESSs on power system reliability and their efficacy in mitigating the intermittency and variability of renewable energy sources. The final step concentrates on the planning aspects of modern power systems, notably generation expansion planning. Each of the noted steps is interconnected, culminating in a comprehensive framework for evaluating the reliability impacts of VRE resources and storage on power systems. The overarching objective of this process is to furnish a holistic comprehension of the current state of research, pinpointing gaps and proposing avenues for future studies. The detailed steps of this are visually depicted in Fig. 1, offering a clear roadmap pf the review process.

It should be noted that despite fulfilling a pivotal role in the global transition of electricity, other technologies, such as electric vehicles and demand response programs, have not been directly discussed in this study but are addressed under a broader category of their type.

Fig. 2 depicts an overall view of the literature and relevant fields and concepts relating to the capacity planning of power systems throughout the energy transition shift. This figure presents synergies that contribute to GEP, reliability, ESSs, and VRE resources, forming a comprehensive idea of how the research area has been shaped to address moves toward reliable decarbonization in power systems.

Fig. 3 illustrates published research on versatile topics related to this review paper. The data is based on extraction from the Scopus website database, explicitly focusing on integrating VRE resources and ESSs. Approximately 2500 research papers published from 2019 to 2024 were

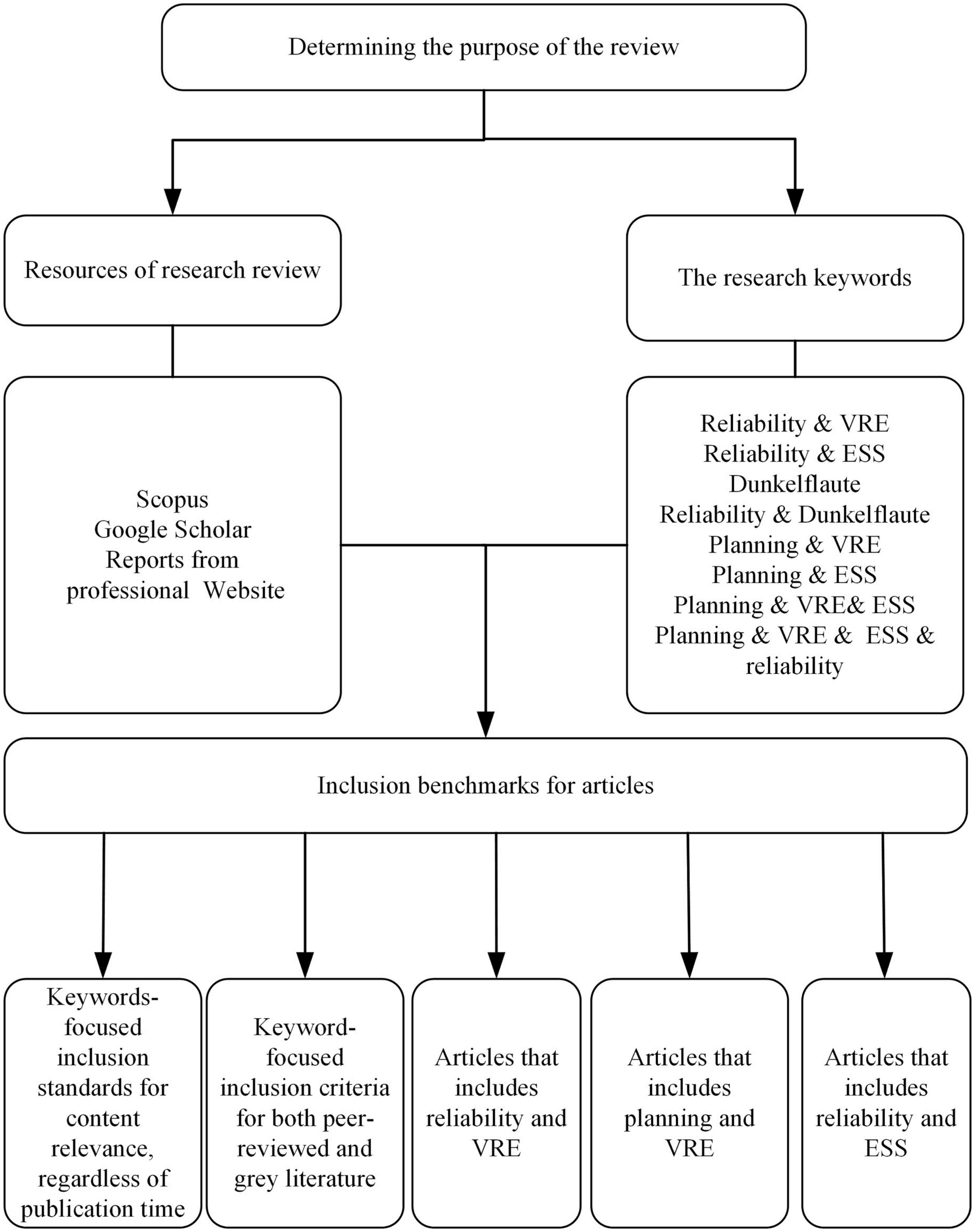

Fig. 1. The methodology of review.

assessed with due diligence, considering those published by reputable and relevant journals. The papers were categorized into six groups characterized by specific research trends. In this way, the research trends were selected to reflect the focus of this survey. The illustrated data supports this general idea that studies in the areas of interest mainly focus on capacity planning problems in the presence of VRE resources. It can be interpreted from the figure that articles addressing all aspects, such as GEP, VRE resources, ESSs, and reliability, are not considerable when compared to other categories. Notably, except for one study [20], there is currently a lack of research investigating the Dunkelflaute phenomenon's impact on capacity planning and reliability in the context of future net-zero emissions.

Although it is crucial to study the implications of VRE resources and their contributions to power system reliability, this is not reflected in the current research. Accordingly, Fig. 4 The curve graph, also obtained from the Scopus website database, visually represents the scarcity of research papers published in this field. It underscores the need for studies covering reliability-oriented capacity planning in the presence of

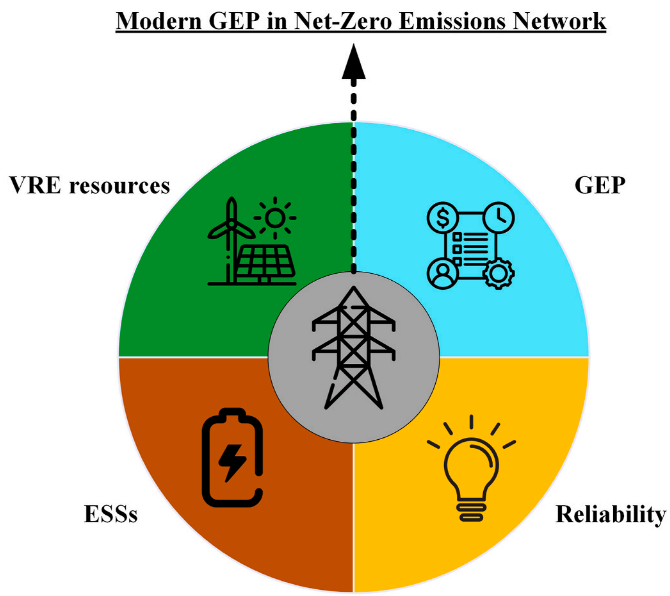

Fig. 2. Contribution of main research areas in energy transition shift from electric power perspective.

VRE and ESS resources from 2012 to 2024.

This review survey adopts a structured framework to systematically address the key aspects of power system reliability, focusing on VRE integration and energy storage at the generation system reliability level, as shown in Fig. 5. The framework is organized into four interconnected steps, providing a clear and logical approach to analyzing the methodologies and challenges discussed in the review methodology's strategy.

3. Power system reliability

The power system's ability to provide electrical energy to customers with minimal interruptions is referred to as reliability, which encompasses both the security and adequacy of the power system. The availability of sufficient transmission, generation, and distribution infrastructure to meet consumer demand while accounting for planned and unplanned system component failures is known as power system adequacy. The resilience of a power system to disruptions, like the loss of generating units or transmission facilities, is known as power system security [22]. As shown in Fig. 6, a power system consists of three hierarchical levels. The facilities that generate power are called "Hierarchical level-1" or "HL-I." Further, "Hierarchical level-2," or "HL-II," designates establishments that handle both the generation and transmission of electricity. Lastly, the power system's whole infrastructure—including its transmission, distribution, and generation of the power system—is referred to as "Hierarchical level-3" or "HL-III." Specific indicators for each level can be applied to more than one level or separately [23]. In this survey, we focus on the first level of reliability evaluation, HL-I.

Accordingly, reliability indices can be analyzed at the component level, examining the outage rate of each component, or at the system level, evaluating overall system conditions. Moreover, dependability indices that consider the entire system or end users can also be assessed [22]. Table 1 displays several reliability indices from the generating section (HL-I). Some traditional indices applied in power systems with thermal generation include Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE), Loss of Load Duration (LOLD), and Expected Energy Not Supplied (EENS). Additionally, with the integration of VRE into modern power networks, new indices have been introduced, such as Expected Solar Energy Curtailment (ESEC), Expected Energy Not Unserved (EENU), and Expected Wind Energy Spilled (EWES).

3.1. Reliability of power system in the presence of renewable and storage resources

Several papers have concentrated on enhancing the reliability of electrical networks through the integration of VRE resources into power systems [33,34]. The significance of incorporating diverse sources, such as electric vehicle technologies, wind turbine generators, ESSs, and DPV systems into the primary electrical power system is discussed in Ref. [35]. Energy storage systems play a pivotal role in mitigating the

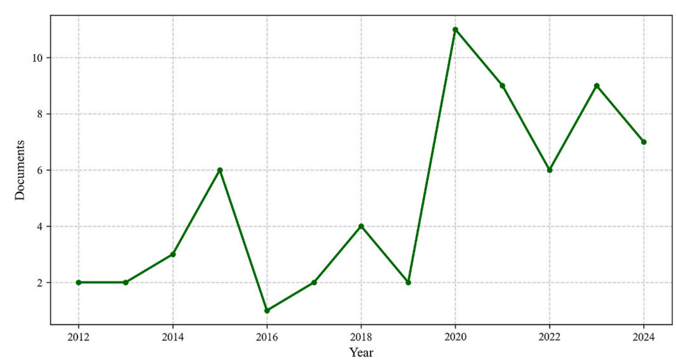

Fig. 4. Distribution of research papers that have worked on capacity planning considering reliability, VRE, and ESS [21].

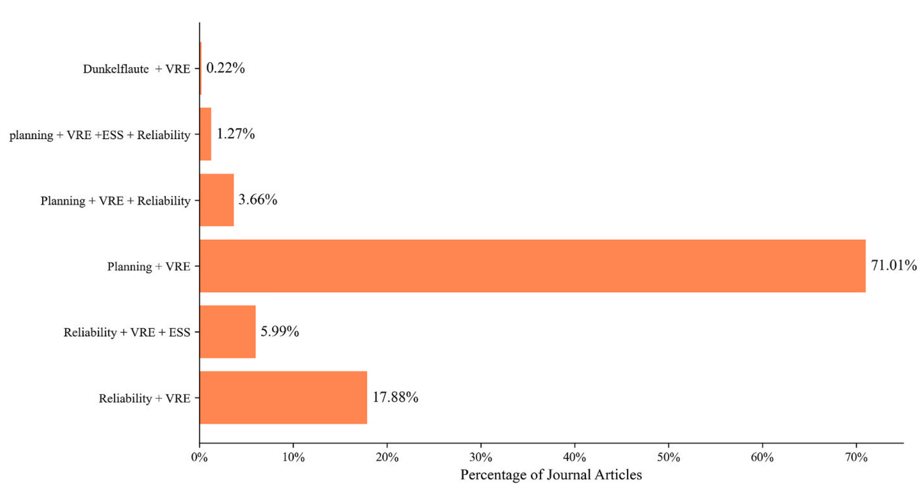

Fig. 3. Quantifying journal article distribution across capacity planning in modern power system.

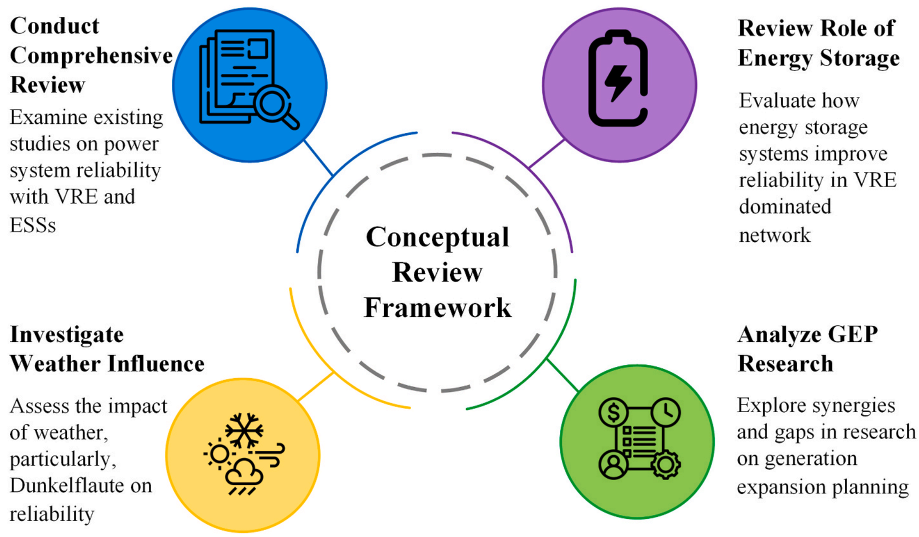

Fig. 5. A structured framework for analyzing power system reliability, focusing on VRE integration and energy storage. It consists of four steps: reviewing existing studies, assessing weather impacts, evaluating energy storage, and analyzing GEP research.

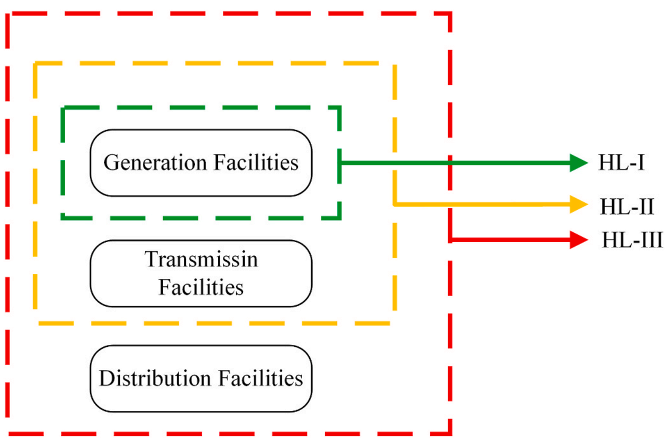

Fig. 6. Evaluating power system reliability at Hierarchical levels [24].

negative impacts prompted by the variability of renewables. This is based on the capability of ESSs to store surplus energy generated during peak periods for later consumption during low-generation output periods. Additionally, including electric vehicles in a power system serves as distributed energy storage, potentially contributing to grid stability and easing strain during peak demand scenarios. Accordingly, these can be categorized under the broader definition of ESSs. The rise of investment in renewable sources has led to a notable increase in uncertain factors and the level of uncertainty (also known as unreliability) within power systems in many renewable energy sources. The uncertainty stems from various sources, such as the behavior of wind power, solar power, charging and discharging patterns of electric vehicles, and the allocation of Battery Energy Storage Systems (BESS). These factors contribute to the complexity and unpredictability of the overall system [36–38]. By analyzing multiple papers, we can categorize these articles based on their focus on the reliability of integrating variable renewable energy. They consider various criteria, including the network's state (either islanded or interconnected) and the level of renewable energy supply (fully or partially provided to the network). Table 2 details how these papers investigate reliability in networks with a high penetration of renewable energy.

One major challenge during the transition from conventional power generation to a net-zero network is the uncertainty of weather conditions. Accordingly, the production of variable renewable energies relies heavily on factors like sunlight availability, wind speed, and temperature. The subsequent analysis details papers specifically addressing scenarios when both solar and wind generators are unavailable.

3.2. Dunkelflaute

The transition towards clean energy sources presents many challenges for the power system industry. Wind and solar power generation and electricity consumption can exhibit significant variations throughout the day, not just short-term fluctuations concerning power system planners and operators but also extended periods of adverse weather conditions or seasonal changes affecting wind and solar output. These prolonged periods, known as "Dunkelflaute" events, or renewable drought as it is known in Australia, are becoming a significant concern from a reliability and economic perspective. These weather phenomena may persist for many hours or several days. Thus, it is evident that during such meteorological conditions, no energy from renewable sources can be expected [9].

The most challenging issues in grids primarily reliant on weather-dependent sources are load-generation balance, securing the electric transmission system (congestion management), and ensuring reliability. For example, low solar and wind availability periods may result in extreme challenges in meeting demand over peak periods, resulting in catastrophic consequences. These doldrum periods have recently attracted attention and have been addressed by papers and technical reports. Some of these are surveyed below, based on the regions where the phenomenon occurred.

3.2.1. The case of Western Australia

Western Australia's primary electric grid, the South West Interconnected System (SWIS), supplies electric power to most of the state's population, with more than 1.1 million customers. The SWIS is a geographically and electrically isolated grid with no interconnections to other transmission systems. The grid was planned and developed around centralized, large-scale, dispatchable generation, with recent significant investments in VRE resources. An unexpected Dunkelflaute activity over Western Australia in June 2023 led to an imbalance in renewable energy generation and overall consumption, whereby the operator had to deploy demand-side management and diesel generators due to the issue's urgency [7].

Table 1
Reliability indices related to load and energy.

Indices	Description	Formulation	Unit
LOLP	The probability of the system being unable to meet demand due to insufficient generation capacity [24].	$\frac{\sum_{k=1}^{N} P_k}{N}$	%
LOLE	The expected duration of load loss over a specified period is often expressed in hours per year [24].	$\sum_{k=1}^{N} P_k t_k$	$\frac{hours\ or\ days}{year}$
LOLH	Total duration of load loss within a given timeframe [24].	$\sum_{k=1}^{N} P_k t_k$	$hours/\ year$
EENS	The amount of electricity that was unavailable to customers was due to flaws in the system [24].	$\sum_{k=1}^{N} E_k P_k$	$MWh/year$
EIR	The proportion of energy interrupted to all energy delivered in a certain time frame [24].	$1 - LOEE_{p.u.}$	$p.\ u$
EUE	Energy is not supplied to consumers due to system failures or disruptions.	$\sum_{k=1}^{N} E_k P_k$	$MWh/year$
PLC	Probability of load curtailments [25]	$\sum_{k=1}^{N} P_k$	%
LOEE	quantifies the shortfall in the generation system's ability to meet load demand (Loss of Energy Expectation) [26]	$\sum_{k=1}^{N} E_k t_k$	$MWh/year$
LOLF	indicates the average frequency of load curtailment events [26]	$\sum_{k=1}^{N} \lambda_k$	$occurance/year$
LOLD	The ratio of *LOLE* to *LOLF* (Loss of Load Duration) [26]	$\frac{LOLE}{LOLF}$	$MWh/occurance$
EPNS	assesses the anticipated load curtailment during failure scenarios [27]	$\frac{\sum_{k=1}^{N} p_k t_k}{N}$	MW
LOHE	Loss of Health Expectation [28]	$8760 - \frac{1}{N}\sum_{k=1}^{N} T_k$	$hours/\ year$
ESEC	Expected Solar Energy Curtailment [29]	$\sum_{k=1}^{N} E_k P_k$	MWh/yr
LPSP	Loss of Power Supply Probability [30]	$\frac{LOEE}{\sum_{k=1}^{N} L_k t_k}$	%
EENU	Represents energy wasted in wind farms [31]	$\sum_{k=1}^{N} E_k P_k$	MWh/yr
EWES	The amount of wind energy spilled from systems with high penetration of wind energy is denoted as WES_k, representing the wind energy spilled in year k [32]	$\frac{\sum_{k=1}^{N} WES_k}{N}$	MWh/yr

P_k: The individual probabilities, t_k: Duration of each state E_k: Energy curtailed by a capacity outage, λ_k: The failure transition rate, p_k: Power curtailed by a capacity outage, L_k : *the load at the time k* , T_k: a healthy state duration.

3.2.2. The case of Germany

Germany is seeking to reach net zero emissions by 2045, whereby to meet this ambitious target, 80 % of all electricity supply will need to come from VRE resources by 2030 (and 100 % by 2035), with coal to be completely phased out [1–3]. Accordingly, the need for backup technologies, assessment methods, and optimal reliability-centered capacity planning is a trending research interest. Although total drops in both wind and solar generation are rare, the German power system experiences sharp falls in wind output every year, which increases the need for utilities to compensate with higher production from fossil fuels that raise emissions. The authors in Ref. [49] have conducted a comprehensive survey to explore the contribution of VRE resources to storage requirements in a renewable-dominant power system. Further, the impact of the low readiness level of energy storage infrastructure towards the net zero target in 2045 from a reliability perspective is investigated in Refs. [50,51].

3.2.3. The case of the Electric Reliability Council of Texas

On April 8, 2024, a total solar eclipse crossed from Texas to Maine in the United States, temporarily blocking sunlight from utility-scale solar

Table 2
Review of papers studying reliability in variable renewable energy.

Ref	Islanded Network/ Interconnected Network	Partially/ Fully VRE connected	Output/conclusion
[39]	Isolated microgrid (MG)	Fully VRE connected	This paper introduces a Chance-constrained programming (CCP)-based scheduling model that maximizes ESS usage to offer spinning reserve services for isolated microgrids.
[40]	Interconnected Network	Partially VRE connected	The optimum number of batteries, inverter capacity, wind turbines, and DPVs are thus determined.
[41]	Islanded Network	Partially VRE connected	The framework developed for evaluating reliability quantifies the impact of energy storage on bulk power system reliability. It underscores the importance of comprehending how widespread energy storage and renewable energy deployment affect power system reliability.
[42]	Islanded Network	Partially VRE connected	The findings indicate that coordinating wind power and hydro units provides sufficient benefits when adequate hydro units are allocated to follow the wind variation based on wind penetration, reservoir size, and water inflow.
[43]	Interconnected Network	Partially VRE connected	The proposed models can help with ESS reliability assessments and planning decisions that increase a power system's economic efficiency.
[44]	Islanded Network	Partially VRE connected	The results highlight the benefits of the proposed operational strategies and provide valuable insights into the impact of EES capacity, power limits, and Wind Turbine Generator (WTG) capacity on both reliability and economic performance.
[45]	Islanded Network	Partially VRE connected	The article describes how integrating energy storage and renewable energy generation at the best site has increased the system's reliability.
[46]	Interconnected Network	Partially VRE connected	The paper outlines a novel method for determining optimal ESS sizes in demand peak shaving,
[47]	Islanded Network	Partially VRE connected	This work has discussed the implications of wind power's low inertia characteristics and stochasticity for system reliability. It has also looked at how energy storage could increase the reliability of the integrated system.
[29]	Interconnected Network	Partially VRE connected	The optimization algorithm strategically deploys batteries for maximum coverage, while coordinated algorithms work to decrease solar curtailment and boost PV capacity credit.
[48]	Interconnected Network	Partially VRE connected	This paper provides a novel generation rescheduling algorithm that adjusts the conventional generation output based on the uncertainty of renewable production to reduce the impact of uncertainty on power networks.

power installations. Texas was notably affected due to its high solar capacity penetration. The Electric Reliability Council of Texas (ERCOT), the state's primary grid balancing authority, lost 8.9 GW of solar capacity during the eclipse. This event highlighted the ongoing challenges ERCOT faces with its heavily VRE-dependent grid. The operator declared an Emergency Level 2 on September 6, 2023, because reserve generation capacity had dropped to less than 1,750 MW due to wind dropping off on a very hot summer afternoon [52]. Some extreme operations events and the effects of Dunkelflaute have been simulated and modeled in several networks, and the problem associated with ERCOT is addressed in Ref. [53].

3.2.4. The case of Spain

Spain is a pioneer in the energy transition due to its energy and climate change policies. The current Spanish framework for energy and climate is based on its 2050 objectives of national climate neutrality, 100 % renewable energy in the electricity mix, and 97 % renewable energy in the total energy mix [1–3]. The installed generation capacity proposed by Spain's National Energy and Climate Plans (NECP) appears to be sufficient to meet the load demand but not well enough modeled to account for unexpected conditions such as Dunkelflaute [54]. A conceptual methodology for jointly evaluating the adequacy and operational flexibility of the Spanish power system in 2030 for a fully renewable-integrated grid is addressed in Ref. [55].

3.2.5. The case of Poland

Poland's 2021–2030 NECP, updated in 2019, set a target of 21–23 % of renewable energy in gross final energy consumption by 2030, a goal that has already been met. By 2030, the country could generate almost 70 % of its electricity from renewables, as shown by multiple modeling studies [1–3]. In this regard, assessing the effects of Dunkelflaute is crucial for the country's ambitious plan. Authors in Ref. [49] carried out a numerical analysis of the hypothetical power system in Poland, using Monte Carlo Simulation to combine hourly capacity factors of renewable energy sources in Poland, which enabled the selection of the optimal generation capacity mix.

3.2.6. Evaluation and assessment

Dunkelflaute occurrences are not isolated incidents; in recent years, multiple Dunkelflaute events have happened globally. These events have significant consequences for the grids and electricity markets. There is no indication that Dunkelflaute events will decrease in the future. On the contrary, the adverse effects of Dunkelflaute events are likely to become even more severe as the penetration level of renewable energy in the power grid increases [9]. Extreme weather and inter-annual variability are two ways to calculate the storage capacity needed in a system powered entirely by renewable energy sources. For instance, in Ref. [56], the authors present WISRnet (Wind and Solar Network), a two-step, unsupervised deep learning framework. This framework automatically detects spatial patterns in wind speed and sunlight and effectively identifies Dunkelflaute periods. Artificial neural networks are another method that has been used to analyze and categorize Dunkelflaute (dark doldrum) events [57]. During a Dunkelflaute event, a network with dominant VRE resources and whose electricity production depends on the weather can face many challenges. The main problem that this event can cause is a mismatch between load and generation [58]. Issues related to power mismatches in the presence of VRE resources are well addressed in Refs. [59,60], whereby the inherent intermittency of VRE generations increases predicted inaccuracies, resulting in unplanned mismatches between generation and load. This, in turn, can lead to load curtailment, generation redispatch, or activation of balancing power reserves [61]. In contrast to traditional dispatchable generators, VRE energy outputs cannot be increased to match demand. Further, the use of renewable energy sources may be limited in matching declining demand, which would result in energy waste and higher energy costs from decreased use [61]. This is particularly the case in an isolated electric grid, where if the amount of electricity generated does not balance with demand, this can compromise the reliability and stability of the grid, potentially leading to power outages. During periods without the availability of both wind and solar generation, especially in isolated grids where traditional power plants are retired, maintaining the reliability level of the system becomes challenging. One solution for managing days with Dunkelflaute events in a network with a high presence of VRE resources is the implementation of energy storage systems. Authors in Ref. [62], employed weather time series data and associated load profiles to investigate fully renewable-based power systems in Europe. They considered wind turbines and DPV systems as primary resources. Due to the natural fluctuations of these resources, a high degree of spatial and temporal flexibility within the electric grid is necessary. Accordingly, various storage technologies have been examined to mitigate these fluctuations across different time scales. The role of power storage in energy systems characterized by high shares of variable renewables has been studied in Ref. [63]. The research involves developing a model to identify cost-effective configurations of generation sources, Demand-Side Management (DSM), power storage capacities, and optimal utilization strategies.

In contrast, the study in Ref. [64] aims to identify the most cost-effective approach for transitioning Europe's power sector to 100 % renewable energy by 2050. In this manner, the primary goal is to achieve the power supply's sustainability, reliability, and security while minimizing costs. In Ref. [65], the goal is to systematically explore a wide array of similarly costly but diverse technology mixes, such as storage solutions, for European power systems. Authors in Ref. [49] determine the maximum energy deficit by examining three decades' renewable and load time series data to characterize Dunkelflaute. They also compute the necessary energy storage capacity using a simplified cost optimization model with the same data input. This optimization model seeks to identify the most cost-effective approach to achieving a 100 % renewable electricity system, using Germany as an illustrative example. The model assesses investments in VRE resources and ESSs.

4. Energy storage system

Utilities and power system operators can use battery storage technology to store energy for later use. A BESS is an electrochemical device that stores energy from a power plant or the grid and releases it later to supply electricity or other grid services as needed. For grid-scale applications, some battery chemistries are either already commercially available or are being researched, including lithium-ion, lead-acid, redox flow, and molten salt (including sodium-based chemistries) [66]. As discussed in the previous section, in June 2023, an unexpected Dunkelflaute event occurred within Western Australia. It caused a significant mismatch in renewable power generation and electrical consumption [67], which could have been managed using energy storage systems. Moreover, according to ERCOT, winter peak demand has been increasing faster than summer peak demand, contrary to the typical planning scenario for the ERCOT system. Winter peak demand has also exhibited more significant variability than the more steadily increasing and predictable summer peak demand. Consequently, planners need to address these challenges accordingly [68].

Batteries can be implemented in large or small quantities for various purposes in various locations. For instance, grid-scale or Large-Scale Battery Storage (LSBS), comprised of many batteries deployed together, can function as a large-scale power generator linked to the electrical transmission system. Smaller batteries can be used individually as a form of virtual power plant. They can also serve as backup power sources in houses. Over the next several years, it is anticipated that the usage of batteries for renewable energy will rise due to the technology's adaptability and declining costs [69]. For example, on April 30, 2024, in the California grid, batteries replaced natural gas in managing the daily ramping up and down of solar generation. Batteries charge with inexpensive solar energy during the day, thus replacing

Table 3
Crucial roles of ESSs in modern power systems.

REF	application of ESS	reason
[76–78]	Time shifting	Excess wind energy can be stored in a battery in a low-demand period. This stored energy can be released when necessary to compensate for any shortfalls in the total generation capacity or wind power availability.
[74,77,79,80]	Output smoothing	A wind farm's inconsistent power output causes system frequency and voltage fluctuations. BESS plays a crucial role in stabilizing the system under such circumstances.
[78,81,82]	Transmission congestion mitigation	Wind farms are often located in remote regions, leading to energy loss during long transmissions. This can overwhelm transmission lines, causing congestion due to capacity limitations. BESS can store surplus energy, easing network congestion and reducing associated costs.
[76–78]	Delay transmission upgrade	During transmission network congestion, BESS stores energy and releases it during peak periods. This strategy diminishes the necessity for investing in extra transmission infrastructure.
[76,79,83]	Energy arbitrage	BESS facilitates economical energy storage during periods of low electricity prices. It efficiently discharges stored energy when prices surge, taking advantage of hourly price variations.
[74,76–78,84,85]	Frequency and voltage control	Fluctuations in frequency can upset the balance between power supply and demand, underscoring the importance of maintaining frequency within specified parameters. Additionally, adequate provision of reactive power plays a crucial role in preserving voltage stability.
[77,81,86]	Uninterrupted power supply	BESS can act as a backup, fulfilling electricity demands during sudden disruptions in power plant operations.

peak management by natural gas generators. Consequently, reliance on gas during morning and evening peaks becomes reduced, allowing for a decrease in the amount of gas held online during uneconomic midday conditions in preparation for evening solar down ramps. This change either decreases the price of electricity or improves the duckling demand curve [70].

Power systems must embrace the emerging technology of Long Duration Energy Storage (LDES) to achieve a reliable and decarbonized grid. These new technologies can help ensure a stable energy supply, balance variable generation resources with unpredictable customer demand, and fortify the electric grid against weather events. The mismatch between electricity consumption and generation for NZE purposes will drive the need for the LDES [71]. This problem becomes more challenging when considering that most electricity generation in the network is provided through coal, natural gas, and oil resources, which will all need to be replaced by 2050 in the move towards NZE. More than 50 % of the electricity in the SWIS is currently provided by coal and gas [72]. Moreover, for isolated networks like SWIS, ensuring stability and reliability using these technologies is essential.

ESS can rectify short-term mismatches between load and generation within 2 h or less. Furthermore, significant increases in the share of storage systems have resulted in providing auxiliary services in more extended periods, such as load following, operational spinning reserve, arbitrage, and peak shaving [73]. The application of the LDES technology can be extended beyond ancillary services, enhancing the reliability of electric grids by offering sustained discharge capabilities during peak demand periods [71]. BESS is widespread among different energy storage systems because it can respond quickly, be adjusted in size, and is not limited by location. By incorporating the BESS, integrating renewable energy sources into a power grid can improve the system's flexibility and reliability [74,75]. Table 3 highlights key applications of ESSs in power systems.

5. Impact of renewable and storage resources on the reliability assessment

Generation and transmission systems with high levels of VRE resource integration are significantly impacted by weather conditions, which affect reliability indices [87]. Accordingly, traditional reliability evaluation methods are no longer sufficient to accurately assess the increased complexity and uncertainty associated with this transformation [88]. Both power system planners and operators now require new computational tools to manage the modern power system and address the evolving power system market specification [89]. Several studies have examined how reliable small renewable energy systems are, using different methods to determine this. For example, some researchers have focused on making renewable energy systems cost-effective and reliable. Accordingly, they have created a Hybrid Renewable Energy System (HRES) design that considers reliability and financial constraints to achieve optimal results [40,90,91]. One study [92] presents a technique for analyzing the reliability of large-scale, grid-connected DPV systems using an exponential distribution based on the fault tree analysis method. It considers the presence of a battery system and charge controller.

Tables 4 and 5 present a compilation of papers that assess network reliability in the context of renewable energies. These tables outline the specific indices analyzed in each study. Table 4 examines isolated case studies where the network operates independently without connecting to other networks. In contrast, Table 5 explores scenarios where there is a connection with other networks.

In [41], the effect of an ESS operating with an innovative strategy and integrating VRE resources on the reliability of the local distribution system has been examined. Furthermore [93], demonstrated how energy storage capacity with different penetration levels substantially impacts system reliability, evaluating the sufficiency of generating system capacity when the ESS is used.

To assess the adequacy of a power system, another study [42] coordinated hydropower with a utility wind farm and an ESS. The study suggested that future research might evaluate optimum reservoir sizes to increase reliability. Sensitivity analysis was implemented in Ref. [43] to identify ideal ESS capacity, numerous ESS installations at different wind

Table 4
Reliability indices in islanded network.

Ref	Partially RES integrated	Fully RES integrated	Wind	Solar Farm	DPV	Storage	Reliability indices
[39]		*	*		*	*	The spinning reserve probability constraints
[41]	*		*			*	LOLP, EENS
[93]	*		*		*	*	LOLE, EENS
[42]	*		*			*	LOLE, LOEE
[44]	*		*	*		*	LOLP & EENS
[45]	*		*			*	EENS
[47]	*		*			*	LOLE, LOLF, LOLP, & LOEE
[94]	*			*		*	LOEE & LOHE

Table 5
Reliability indices in interconnected network.

Ref	Partially RES integrated	Fully RES integrated	Wind	Solar Farm	DPV	Storage	Reliability indices
[40]	*		*		*	*	The equivalent loss factor
[46]	*		*	*		*	EENS
[29]	*			*		*	–
[48]	*		*	*	*		–
[95]	*		*				LOLP, EPNS & LOLF
[25]	*		*				PLC & EENS
[26]	*		*				LOLF, LOEE, LOLD & LOLE
[27,96]	*		*				LOLP, EPNS & LOLF
[97]	*		*				EENS
[98]	*			*			LOLE
[99]	*		*	*			EIR & EENS
[100]	*		*	*			EENS

farms were used to lower uncertainty in integrating VRE resources. In addition [101], has suggested the best location for ESSs on buses to lower operating expenses, considering ESS limitations, such as energy capacity and power rating, and how they affect system reliability. Fossil fuel supplies are depleted because of rising energy demand and an expanding global population. Presently, 85 % of the world's energy needs are satisfied by traditional energy sources. ESS can also be used in conventional power plants to alleviate excessive electricity use through peak shaving [23]. Table 6 provides an overview of relevant research that examines the impact of ESS on system reliability.

6. Reliability-oriented generation capacity planning integrating renewable and storage resources

Capacity planning is a comprehensive term involving strategic decisions about the optimal configuration of power generation facilities. This includes determining the types of power plants to be built, where they should be located, when they should be constructed, and when existing plants should be retired, aiming to meet electricity demand over a specific planning period effectively. The primary goal of capacity planning, sometimes called GEP, is to balance electricity supply and demand throughout the planning horizon. This balance is crucial for maintaining the reliability of the electricity supply, which is essential for supporting various industrial, commercial, and residential activities. Over the years, traditional approaches to GEP have evolved to incorporate more sophisticated models and solution algorithms. Some prominent research concerning GEP in the presence of VRE and ESS sources is addressed below.

6.1. Generation expansion planning with energy transition requirement

Recently, there has been a growing recognition of the importance of integrating VRE resources into the GEP framework [12]. Furthermore, the capacity value of renewables is shaped by factors like penetration level, location, technology, and the method used to estimate capacity credit. However, industry-standard deterministic approaches may overestimate their reliability during high-risk periods by overlooking the stochastic nature of outage rates. As renewable penetration increases, acknowledging and incorporating this stochastic element becomes essential for precise capacity value assessment, which can inform resource planning for systems with greater renewable integration [106]. Additionally, the integration of ESSs has become increasingly important. This reflects a broader societal shift towards prioritizing environmental sustainability and reducing greenhouse gas emissions. Incorporating VRE resources and ESSs into GEP helps planners manage the intermittent nature of renewable energy sources. This integration enhances the overall reliability and resilience of the electricity grid. This integration also aligns with the broader goals of transitioning towards a greener and more sustainable energy system [12]. Furthermore, it is crucial to consider the plausible energy mix in the expansion of renewable energies. In Ref. [107], a model for Germany's power system transitioning to 100 % renewable energies has introduced various scenarios to examine moderate to extreme conditions. This analysis aims to determine a reasonable energy mix, and the associated required investment costs. Another study has outlined Indonesia's power system transition to 100 % VRE resources by 2050. The study's findings reveal that the contribution of nuclear power plants is estimated at 16 %. In comparison, utility-scale solar power plants are estimated to constitute 70 % of energy output, with the transition requiring an investment of USD$95 billion. Eliminating nuclear power systems increases solar farm and battery storage capacity [108]. Several research papers and surveys have examined capacity planning through the lens of network adequacy, employing various relevant indices and methods, which are well referenced in Ref. [109].

As power consumption surges and significant power failures become more frequent, establishing a reliable infrastructure within power systems becomes more indispensable. Furthermore, as renewable energies are increasingly integrated into the network, assessing plant availability poses a considerable challenge. Ensuring uninterrupted fulfillment of customers' electricity needs remains a top priority. Developing new optimization models for power system expansion planning that rely on probabilistic reliability indices involves incorporating various factors that have been proposed in Refs. [110,111]. In Ref. [112], a planning model tackles multi-objective generation expansion, aiming to cut costs, reduce environmental impact, and improve reliability. Meanwhile, in Ref. [113], the authors introduce a reliability assessment measure (like Expected Energy Not Served) into an optimization model. They compare the outcomes between traditional expansion planning models and this reliability-focused approach, examining how non-linearity impacts the search for practical solutions within a reasonable timeframe. On the one hand [114], has introduced a Mixed-Integer Linear Program (MILP) expansion planning model for distribution systems that prioritizes reliability and penalizes power loss within the model. On the other hand [115], presents a multi-objective optimization model for expansion planning. This model aims to minimize costs, power losses, and CO_2 emissions. Further, it incorporates Markov processes and three reliability evaluation indices to assess power system reliability.

The main objective of power system planning is to meet predicted electricity consumption cost-effectively and environmentally sustainable. Various factors must be considered in this process. If too many generation facilities are constructed, the average generation cost increases, leading to higher customer tariffs. Conversely, insufficient capacity results in unmet demand. Therefore, by considering the operational attributes of a system, the optimal reliability level for its generation can be determined. Technical criterion is typically employed as a minimum standard for evaluating the performance of a generation system. This index can be represented as an economic criterion, integrated directly into the minimum-cost model to consider reliability factors. As a result, system reliability can be incorporated into the objective function(s) or constraints in the planning process [12]. Ensuring a balance between the size of the power system and its diverse components poses a significant challenge in planning and operating a

Table 6
A summary of articles that focus on the assessment of the reliability of ESS.

RES	Indices	Contributions	Ref
Hybrid	LOLP, EENS, LOLE	Assessing how dependable a micro-grid is and finding ways to make it work better by using a mix of fuel cells, batteries, wind, and solar power sources.	[30]
Wind	LOLE, EENS	Combining ESS with RES to assess the sufficiency and cost-effectiveness of a distribution system.	[44]
Wind	EENS	Increases the power system's reliability by integrating ESS and wind energy in the most efficient places.	[45]
Hybrid	LOLP, LOHE	A well-being method for calculating the reliability indices of isolated electric grids is presented, which incorporates the ESS with solar, wind, and other energy sources.	[28]
Wind	LOLP, EENS	Evaluating how reliable a local distribution system becomes when ESSs are used and how these systems are managed intelligently while integrating renewable energy sources.	[41]
Hybrid	LOLE, EENS	This study evaluates the generating system's capacity adequacy when ESS is present. It delineates various energy storage capacity levels, each of which plays a notable role in enhancing reliability.	[93]
Wind	LOLE, LOEE	Hydropower combined with energy storage and synchronized with wind energy to create a more sustainable power system.	[42]
Wind	LOLE, EENS, EIR	Placing multiple Energy Storage Systems (multi-ESS) in different wind farms reduces the unpredictability of integrating RE. Additionally, sensitivity analysis is used to find the best ESS capacity to improve system reliability.	[43, 101]
Wind	EENS	Investigates the impact of ESS on enhancing the reliability of the power system when dealing with network contingencies.	[101]
Wind	EENS	Employing a probabilistic approach, ESS reduces the peak power demand, thereby increasing the security of the distribution network's electricity supply.	[46]
Wind	EENS	An analytical method was applied to evaluate how ESS affects the reliability of the power system, mainly when used with wind turbine generators.	[31]
WIND	–	This paper examines the effects of low inertia and intermittent wind on wind power and proposes an enhanced reliability model. Additionally, it introduces a simple analytical method, discrete convolution, for evaluating system reliability in the presence of wind power.	[47]
–	–	The study proposes a method to optimize the operational strategy and the growth plan of a multi-stage active distribution network by incorporating ESS. It also evaluates the impact of centralized and distributed ESS on the network's reliability. The load is not served, and outage hours are considered reliability indices.	[102]
–	LOLE	Suggesting a framework for concurrently handling generation expansion planning and ESSs scheduling, leveraging extensive ESSs to minimize generation expansion planning expenses and mitigate pollution.	[103]
Wind	–	This paper introduces a stochastic mathematical model integrating operational and tactical choices to increase reliability. The system's reliability is assessed by calculating the percentage of committed energy not supplied.	[104]
Hybrid	LOLP	Schedule ESS is utilized to reduce fuel and aging costs for optimal economics and reliability.	[105]
Solar	–	This paper explains how renewable energy affects transmission system reliability and proposes a novel generation rescheduling algorithm to enhance power system reliability by accounting for renewable energy variations within the system network model. The overload probability is calculated for reliability purposes.	[48]

system. This highlights the importance of reliability evaluation, where utility and independent system operators must comprehend the system's status and components. They need to consider the trade-off between reliability levels and investment costs [116]. Accordingly, the main goal is to provide satisfactory electricity services while minimizing procurement expenses [117].

Numerous existing GEP models have primarily focused on conventional power plants, where adjusting fuel inputs is sufficient to manage load fluctuations. However, incorporating VRE resources into power generation capacity planning introduces new challenges. This arises because renewable energy sources are influenced by unpredictable factors like wind speeds and solar radiation, which are often beyond human control. Consequently, integrating VRE resources into power grids can escalate system uncertainty issues. To counter this variability and uphold stringent security criteria, the system may necessitate additional quick-response reserves to address unforeseen contingencies arising from the uncertainty of intermittent injections from renewable sources [12]. One of the effective strategies for mitigating the challenges presented by the variability of renewable energy sources involves integrating storage units into the power system. Energy storage technologies enable the capture and storage of surplus energy produced during high renewable energy output periods. This stored energy can then be utilized during low-generation or peak-demand times. By integrating storage units, the power system enhances flexibility and reliability, enabling it to manage fluctuations more effectively in renewable energy generation and upholds overall system reliability [118–120]. Authors in Ref. [121] have conducted a comprehensive study to minimize storage requirements in Australian grids, particularly when the entire energy generation comes from renewable sources. The study explores the impact of inflexible generation sources, like solar and wind, and flexible generation sources, such as hydroelectric power, on the capacity requirements for energy storage. To achieve these objectives, the study utilizes high-resolution real-world generation data obtained from existing power generators in Australia. By analyzing this data, the researchers aim to find an optimal balance between investing in increased storage capacity and intentionally overbuilding renewable generation capacity. Accordingly, the goal is to determine the most cost-effective approach for ensuring a reliable and sustainable power supply while maximizing the use of renewable resources.

The Effective Load Carrying Capability (ELCC) is a method to determine the optimal contribution of VRE resources and ESSs. ELCC measures how much extra load a power system can reliably support by adding intermittent and energy-limited resources. ELCC is determined by simulating various load and resource conditions over time to evaluate reliability. It compares the reliability contributions of these resources to an ideal, always-available generator. ELCC also accounts for the benefits of combining resources, such as solar power with battery storage. By using ELCC in capacity planning, system reliability, and economic efficiency are maintained, even as more renewable energy sources and storage solutions are added to the grid [122].

6.2. Reliability assessment: indices

The stochastic nature of renewable energies poses a challenge to maintaining the desired level of reliability in GEP within power systems aimed at achieving NZE. Different reliability criteria are considered in many power utilities such as LOLE, EENS, and EUE. For example, for power utilities in the USA, LOLE has been examined, whereby it should be 0.1 day/year [123], and EUE should be less than 0.002 % of annual consumption in Western Australia [7]. These factors are also included in numerous GEP models. However, simplified test systems or linearly estimated values are used instead because of their nonlinear nature. A multistage Mixed-Integer Nonlinear Programming (MINLP) model is introduced for solving the GEP problem [103]. Similarly, LOLE is also taken into account in a MINLP model for microgrids [124]. Additionally [125], employs MINLP for validation, utilizing a scaled-down version of a generation system with a capacity of 1600 MW in Thailand. Further [126], incorporates LOLE as a constraint in MILP, where an approach for approximating the linear method is introduced. One study [112] proposes a Multi-objective Generation Expansion Planning (MMGEP) model for evaluating LOLE. Furthermore [127], presents a microgrid investment planning model that integrates a sequential Monte Carlo simulation method to assess reliability indices.

In several recent GEP models, EENS has also received significant attention. The EENS index, as computed in Refs. [128,129], can be utilized to calculate costs associated with unmet demand. A novel generation and transmission expansion planning approach has been proposed, wherein EENS is considered one of the objective functions with the aim of minimization [130]. An alternative approach to integrating LOLE into GEP is to use a reserve margin as a reliability index, which can then be adjusted as needed [131,132]. Initially, the LOLE is calculated and compared to a predetermined threshold. If the outcome is unsatisfactory, the GEP can be recalculated with the reserve margin constraint adjusted accordingly. This process is then iterated until the LOLE index reaches an acceptable level.

The nature of renewable energies, as well as power consumption, is probabilistic. Therefore, the probabilistic method, as opposed to the deterministic method, may be more suitable for evaluating reliability indexes, particularly for power systems heavily reliant on renewable energy sources. For instance, LOEE and LOLE have been incorporated as reliability constraints in an optimization approach aimed at designing and managing hybrid systems effectively, encompassing photovoltaic panels, wind turbines, and fuel cells [133]. In addition to choosing the system reliability index, whether LOLE or reserve margin, determining the value of the criterion is equally crucial. An excessively high-reliability level can prompt overinvestment, leading to inflated power generation costs, which may be reflected in electricity tariffs. Conversely, underinvestment can result in the opposite scenario [24], where, despite potentially lower electricity costs, the system's reliability level may fall below acceptable standards.

Another method of optimizing reliability criteria involves integrating a customer interruption cost. This cost, representing expenses incurred by customers due to electricity supply failures, can be calculated using the Interrupted Energy Assessment Rate and EENS [134]. This approach combines interruption costs with electricity generation costs to derive the total costs as a reliability function [135]. Furthermore, the total system cost can be evaluated across different reliability criteria to determine the optimal cost through comparison. Several publications have implemented this approach. For instance, Billiton [135] applied this method to specify the optimum reserve margin for a test system, while a research group implemented this method on the wholesale electric market of the ERCOT in 2014 and 2018 [136,137].

Several deterministic and probabilistic techniques have been developed to evaluate power system reliability, particularly in generating capacity adequacy. Power systems worldwide face challenges due to the emergence of new-generation technologies and a more dynamic demand side. Thus, probabilistic methods, such as convolution functions, probability density functions, frequency and duration analysis, Monte Carlo simulations, Markov processes, and artificial neural network techniques, have been emphasized to address these challenges. These techniques aim to ensure that power systems can effectively integrate VRE resources while maintaining system reliability at acceptable levels [24,

Table 7
Summary of articles that focus on reliability assessment in GEP.

Ref	Reliability criteria	Contribution(s)	study case
[141]	estimated load not supplied (ELNS)	This paper uses a novel mixed-integer linear formulation to solve the GEP-TEP problem by considering unit retirements, reliability, fuel constraints, emission, uncertainty, and annual cost.	Test system
[142]	reliability of the system (ENS-Energy Not Served)	This research aimed to analyze the GEP problem while considering a high penetration level of RES. Additionally, a hydro plant was utilized for storage. The research investigated the effects of RES on the environment and economy.	Tamil Nadu (TN), India,
[143]	EENS	The study proposes a hybrid framework to address a multi-objective Power Generation Expansion Planning (PGEP), which includes small hydro, wind, and solar power. Decision-making considers four criteria: economic, environmental, reliability, and vulnerability.	Thailand
[112]	LOLP, EENS	This paper aims to formulate the GEP problem with renewable energy and hydro units as a multi-objective optimization problem. The solution is represented using the Pareto-based multi-objective optimization method, Corrected Normal Boundary Intersection (CNBI).	Test system
[144]	LOLP, EENS	The study aims to conduct the GEP analysis, focusing on the effects of the increasing adoption of wind power technology. The objectives include assessing the influence of increasing wind technology on the system's future generation mix and determining the investment spectrum associated with different policy propositions regarding wind induction levels. Additionally, the study seeks to identify strategies for controlling emissions from thermal plants amidst these changes.	India
[145]	LOLP, EENS	In this work, the GEP modeling study is conducted for a candidate region to examine the impact of increasing penetration of solar power technology.	India
[146]	LOLP, EENS	This study aims to investigate the enduring effects of progressively integrating solar plants into a system through two distinct investment approaches: either as substitutes for oil plants or as alternative investment candidates. Furthermore, it delves into the repercussions of incorporating solar	India

(continued on next page)

Table 7 (*continued*)

Ref	Reliability criteria	Contribution(s)	study case
		technologies with storage capabilities.	
[147]	LOLE	This paper introduces a coordinated GEP-TEP framework for the deregulated electricity market, focusing on integrating wind farms. It comprises two levels: slave and master. At the slave level, optimization maximizes profits for GENCOs and TRANSCOs using PSO and Monte Carlo simulation to address wind farm uncertainty. The master level, overseen by ISO, ensures safe system operation through constraints like reserve margins. Simulation results affirm their efficacy in maximizing profits amid uncertainty.	Test System
[148]	For a specific year, the total energy generated by operational units must be adequate to satisfy the energy demand for that period.	This study aimed to explore the role of renewable energy in long-term electricity generation through GEP. It sought to assess its contribution to overall generation and its impact on electricity and the economy. The objective was to secure a dependable power supply to meet future energy demands, considering reserve capacity. The study employed a mathematical GEP model to plan, examining economic and technical aspects of various power sources, including costs, performance, and reliability.	Turkey
[149]	LOLE	This paper outlines a methodology to facilitate the development of long-term investment strategies for novel generation capacity. This approach entails using a dynamic model to simulate the extended evolution of the electricity market, encompassing variables like demand, market pricing dynamics, and capacity factors for each technology. Furthermore, the solution methodology addresses discrete mixed-integer optimization problems employing Genetic Algorithms.	Turkey
[150]	Capacity reliability	The capacity adequacy of multi-type generators is evaluated, and a mechanism for unit capacity compensation, alongside the Marginal Costing principle, is delineated. This mechanism comprises a capacity pricing model, a compensation model, and a capacity quota model, and a cost settlement model.	a region of China
[151]	Capacity reserve constraint for power supply reliability	This paper investigates the optimal grid integration of high VRE and hydrogen storage penetration levels by developing a high-time-resolution model. Simulation results suggest that cost reductions and CO_2 regulation policies incentivize the installation of hydrogen storage with an optimal capacity of mixed renewable power plants.	Japan
[152]	LOLP & LOLH	This paper presents a Monte Carlo-based probabilistic reliability model to estimate wind or solar generators' effective load-carrying capability (ELCC). It aims to determine the contribution of solar and wind sources. Additionally, by integrating storage, the model evaluates how storage capacity positively impacts the adequacy of networks with renewables.	the Western United States
[153]	LOLE	This paper proposes a simplified MILP model to solve the GEP problem, incorporating VRE, ESS, and full-year hourly power balance constraints.	Thailand
[103]	LOLE	This paper employs the Particle Swarm Optimization (PSO) algorithm to tackle the multistage GEP problem, incorporating the integration of large-scale ESSs. These ESS capacities are strategically allocated to address peak load periods, thereby mitigating planning costs and environmental pollution.	Test System

138–140]. Table 7 illustrates which reliability criteria have been investigated in solving GEP for different case studies.

6.3. *Generation expansion planning and challenges*

GEP for power systems with high renewable energy penetration faces various challenges, including the variability and intermittency of renewable sources, computational complexities, economic constraints, and regulatory gaps. Addressing these issues requires advanced models and innovative strategies to ensure system reliability, flexibility, and efficiency. Table 8 outlines key challenges, including resource adequacy, energy storage limitations, market design issues, and power quality concerns. It summarizes how recent studies address these challenges using advanced optimization methods, probabilistic approaches, and robust planning frameworks.

7. Conclusion

This paper comprehensively has reviewed the requirements, challenges, and advancements in generation capacity planning for VRE-dominated power systems, focusing on ensuring reliability. The study provides extensive literature on the optimum integration of renewable energy resources into modern power grids and highlights approaches to addressing the associated reliability challenges. The study emphasizes addressing rare but critical phenomena, such as Dunkelflaute, through specialized planning methods and regulatory interventions. The crucial role of ESS in mitigating the intermittency of VRE and enhancing grid reliability is explored in detail. This review synthesizes current

Table 8
Overview of key challenges in GEP for renewable-dominated systems and the strategies proposed in recent studies to address them.

Ref	Challenges	Contributions
[154]	Intermittency and Variability of Renewables	This study presents a stochastic hierarchical planning framework to address the uncertainties introduced by VRE resources. It emphasizes the importance of advanced planning models to maintain system reliability.
[155]		This paper introduces a stochastic bi-level optimization model for expansion planning of electricity transmission, energy storage, and gas networks, considering uncertainties in renewable generation and infrastructure reliability. By integrating security constraints, the model ensures robust investment decisions that improve system flexibility and resilience under high renewable energy penetration.
[15]		This paper presents a methodology for generation expansion planning that addresses wind generation variability and uncertainties. It optimizes expansion by enhancing reliability, reducing costs, and integrating wind energy efficiently into power grids.
[89]	Reliability assessment Under Evolving	This paper comprehensively analyzes the evolution of reliability indices in power systems, focusing on the challenges and adaptations required for high renewable energy integration. Traditional indices like LOLP and EENS may require modifications to address the dynamic, distributed nature of renewable-based systems. A key research challenge lies in developing indices that reflect the reliability contributions of storage systems and demand-side management.
[156]		This paper presents a novel reliability evaluation framework for composite power systems with VRE, tackling uncertainty and variability. It integrates non-sequential Monte Carlo simulations with an enhanced Estimation of Distribution Algorithm to accurately model VRE variability and optimize reliability assessments.
[157]	Energy Storage Limitations	This study examines how energy storage systems mitigate renewables' intermittency. It addresses challenges like high capital costs and the need for advanced planning models. Effective storage integration requires evaluating cost-benefit trade-offs, particularly for emerging technologies like flow batteries and hydrogen storage.
[158]	Economic and Policy Constraints	This study explores how energy storage systems mitigate renewables' intermittency, addressing challenges like high capital costs and the need for robust planning models. Large-scale integration of renewables and storage often faces barriers such as high initial investments and uncertain policy environments. To overcome these, policy mechanisms like capacity markets and renewable energy certificates must support reliable generation while encouraging innovation and flexibility.
	Impact of Climate Change	Inter-annual variability in wind and solar generation challenges system planning and resource adequacy by causing fluctuations in renewable availability, particularly during peak demand. Traditional methods with static capacity assumptions may overestimate reliability and lead to underinvestment in backup resources. Given the seasonal and regional nature of inter-annual variability, adopting probabilistic approaches is crucial for ensuring reliability in renewable-dominated systems.
[159]	Computational Complexity and Data Requirements	This study proposes methods to reduce computational complexity in capacity expansion planning, tackling challenges from large-scale renewable integration. High-penetration renewable systems demand advanced optimization models and significant computational resources.
[160]		This study presents a robust optimization approach for dynamic transmission and generation expansion planning, addressing computational challenges and scalability in large-scale renewable integration. Limited granular data on resource availability, load profiles, and storage performance often result in suboptimal or overly conservative planning decisions.
[161]	Market and Regulatory Challenges	VRE resources, such as wind and solar, challenge electricity markets with variability, uncertainty, and reduced capacity contributions, rendering traditional metrics like the Planning Reserve Margin (PRM) inadequate. VRE's near-zero operating costs suppress prices, causing revenue insufficiency for essential generators. This paper advocates probabilistic metrics, including LOLE and ELCC. It highlights the importance of integrating flexibility into planning to address VRE variability and ensure long-term reliability and market stability.
[162]	Integration of Emerging Technologies	This study presents optimization models for integrating emerging technologies into power systems while maintaining reliability under high renewable penetration. Advanced technologies, such as vehicle-to-grid systems, AI-based forecasting, and hybrid renewable systems, offer new opportunities but add complexity to generation planning. A key challenge is ensuring these technologies are compatible and interoperable with existing systems.
[163]	Power quality	This paper aims to design and evaluate a microgrid generation capacity with high penetration of renewable energy sources, such as wind and solar, supported by energy storage systems. It presents a generalized method to determine capacity requirements and proposes control strategies to address power quality challenges, optimize resource utilization, and improve system reliability.

knowledge, identifies gaps, and offers actionable insights for researchers and policymakers to advance GEP in transitioning to net-zero energy systems. In closing, the following points may be concluded based on this survey:

1 Flexible generation capacity planning frameworks that incorporate key factors such as uncertainty, investment cost, and reliability are recommended. For greater accuracy and effectiveness, specific uncertainties associated with wind and photovoltaic systems should be modeled using probability distribution functions. Effective integration of ESS into the GEP requires high-temporal-resolution modeling to capture its dynamic behavior, including charging and discharging cycles, and effectively address associated technical constraints.
2 A balanced approach to VRE deployment is essential, incorporating ESS and other flexibility measures to address the risks of excessive

VRE penetration and ensure system reliability in the face of high-impact, low-probability events.
3 Refining reliability indices for VRE integration is critical but complex for capacity planning researchers. It requires metrics that effectively capture system dynamics and address VRE-specific challenges.
4 Addressing rare but critical phenomena, such as Dunkelflaute, requires bespoke planning methods, regulatory interventions, and the strategic deployment of backup technologies to maintain reliability in a renewable-dominated grid.
5 Transparent and accessible data is crucial for advancing research and investment in future grid infrastructure. Establishing comprehensive databases with key grid parameters, including generation types, historical reliability data, operational costs, and climatological information, is essential for supporting informed decision-making.

Credit author statement

Taraneh Ghanbarzadeh: Conceptualization, Methodology, Formal Analysis, Investigation, and Writing—Original Draft. **Daryoush Habibi:** Review, Editing, and Supervision. **Asma Aziz:** Writing, Review, Editing, Supervision, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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