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SURVEY

Enhancing Electric Grid Flexibility for the Integration of Variable Renewable Energy: Challenges, Innovations, and Future Directions

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ABSTRACT The rapid deployment of variable renewable energy sources, particularly solar photovoltaic and wind power, is fundamentally transforming the operating model of electricity systems. While tasks and technologies are critical to achieving the fundamental carbon goals, inherent volatility and unpredictability, and grid sustainability, reliability, and economic efficiency. The integration of highly variable renewable energy is primarily driven by grid flexibility, the ability of the electricity system to balance supply and demand fluctuations across time and space scales. This paper highlights the critical role that flexibility plays in contemporary electricity systems, examining the technological, financial, and regulatory barriers to renewable energy deployment. In addition to exploring the importance of digitalization and market reforms, the study also examines innovative solutions such as sector interconnection, demand response, improved forecasting, hybrid renewable energy storage solutions, and long-duration energy storage. The analysis emphasizes that, in addition to technological advancements, cross-sector integration, policy coherence, and coordinated investment plans are all key factors in achieving maximum flexibility. This paper offers an inclusive background to improve grid flexibility and enable a strong, economical and sustainable renewable energy system, combining challenges, innovations and strategic pathways. This study adopts a structured survey methodology, systematically reviewing recent literature and organizing flexibility solutions into generation-side, demand-side, storage-based, network-oriented, digital, and policy-driven categories. Unlike prior reviews that focus on isolated technical aspects, this survey integrates techno-economic, regulatory, and socio-political dimensions within a unified framework to provide a holistic perspective on grid flexibility for high VRE penetration.

INDEX TERMS Flexibility, variable renewable energy, wind, photovoltaic (PV).

I. INTRODUCTION

A. BACKGROUND

One of the basic components of climate change mitigation initiatives is the global energy transition, which aims to reduce greenhouse gas emissions and improve long-term energy security [1]. At the end of the day, technical evolution and variable renewable energy (VRE), in particular solar photovoltaic (PV) and wind energy, are at the basis of this development [2], [3]. Between 2010 and 2023, the levelized cost of electricity (LCOE) of large-scale solar power stations and onshore wind power plants decreased by 89%

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and 70%, respectively, production them cheaper than fossil fuel power generation in many areas [4], [5]. VRE production depends mainly on weather conditions and the daily cycle, resulting in variability and intermittency over different time periods [6], [7]. Power systems initially based on centralized, dispatchable generation become operationally challenging due to this time lag between generation and demand, making increasing system flexibility a critical operational requirement [8]. The ability of a power system to continuously and economically balance supply and demand at all relevant times, in the face of unpredictability and uncertainty, while maintaining system stability and power quality, is known as system flexibility [9], [10]. Flexibility reduces renewable curtailment, improves the use of generation, storage and transmission resources, and enables adaptation to rapid fluctuations in generation under the widespread deployment of VRE [11], [12]. The combination of supply-side solutions, storage technologies, demand-side response (DSR) initiatives and increased interconnection between regions can ensure flexibility [13], [14]. Furthermore, grid operators are now able to better anticipate and respond to fluctuations thanks to advances in weather forecasting and machine learning (ML)-based load modelling [15], [16]. Flexibility is no longer an added bonus, but rather a fundamental component of the system as the share of diversified renewable energy sources (RES) increases, ensuring a secure, efficient and carbon-free electricity supply [17], [18].

The integration of VRE poses technological, financial, and regulatory challenges [19]. Given the unpredictability of VRE and limited transmission capacity, ancillary services such as frequency management, rotating RES, and reactive power backup are technically more essential [20], [21]. Contempt developments in forecasting technology, residuals can prime to substantial nonconformities from expected production, necessitating the need to deploy additional storage resources [22]. Transmission system bottlenecks can exacerbate curtailments and reduce system efficiency, particularly when they occur between resource-rich generation areas and high-demand load centers [23]. In many jurisdictions, current electricity market structures undervalue flexibility services from an economic perspective, limiting incentives to invest in enabling infrastructure [24], [25]. As grid regulation and operating standards in some regions continue to be biased toward traditional generation models, regulatory barriers make integration even more difficult [26]. Coordinated changes in market structure, legislative frameworks and technology implementation are needed to address these issues [27].Numerous technological and commercial developments have improved grid flexibility [28]. Digitalization of the power grid infrastructure through computerized control systems, phase measurement units, and unconventional metering structure provides near-real-time situational awareness and improved sensitivity [29]. Variability in power generation can be reduced with hybrid systems that combine solar, wind, and storage [30], [31]. Sectoral interconnection, transportation, combining electricity, cooling, heating and industrial events empowers flexible demand adaptation and broader decarbonization [32], [33]. Market strategies that have successfully encouraged the adoption of flexibility include production-based incentives, expanded ancillary services markets, and dynamic pricing schemes [11].

According to forecasts by the International Energy Agency (IEA), under net-zero emissions pathways, organic RE could interpretation for 60% to 80% of electricity generation in main economies by 2050 [34]. At such levels, a lack of flexibility could lead to further declines in RE, higher operating costs, reliability issues, and even system instability [35], [36]. Therefore, flexibility is a prerequisite for achieving deep decarbonization without sacrificing reliability or financial efficiency [37]. Achieving sufficient flexibility requires coordinated developments in market processes, legal frameworks, and technical expertise, supported by well-informed investments in enabling infrastructure [38]. By aligning technological innovation, policy design, and market reform, power systems can evolve into resilient and adaptive networks capable of accommodating high shares of low-carbon RE [39], [40].

Figure 1 shows the framework that delineates the essential elements of grid flexibility for the integration of VRE, emphasizing the inherent intermittency and unpredictability of resources such as wind and solar. To tackle these challenges, various strategies are accessible, including the implementation of energy storage, enhancement of transmission capacity, demand response programs (DRP), market mechanisms, and flexible generation resources. Nevertheless, adoption frequently encounters technical obstacles, elevated expenses, environmental compromises, and policy or regulatory limitations. The framework prioritizes strategies such as digitalization, sector coupling, advanced forecasting, and long-duration storage technologies to surmount these challenges. In sum, achieving a truly flexible power system will depend on coordinated action that bridges research, regulation, and real-time operations.

Although considerable advancements have been achieved in connecting VRE sources to power grids, current networks still face persistent challenges in optimizing efficiency, balancing supply and demand, integrating storage, and maintaining overall system stability. The integration of solar and wind resources into traditional infrastructures is particularly challenging due to their intermittent, seasonal, and unpredictable nature. This review concludes by evaluating the prospects for developing power systems that are dependable and resilient, as well as environmentally sustainable. While several review studies have examined individual flexibility options such as energy storage, demand response, or power electronics, most existing works remain limited to single-domain technical perspectives. In contrast, this study adopts a system-level survey approach that integrates technical solutions with economic feasibility, regulatory frameworks, governance structures, and cross-regional deployment experiences. Moreover, the

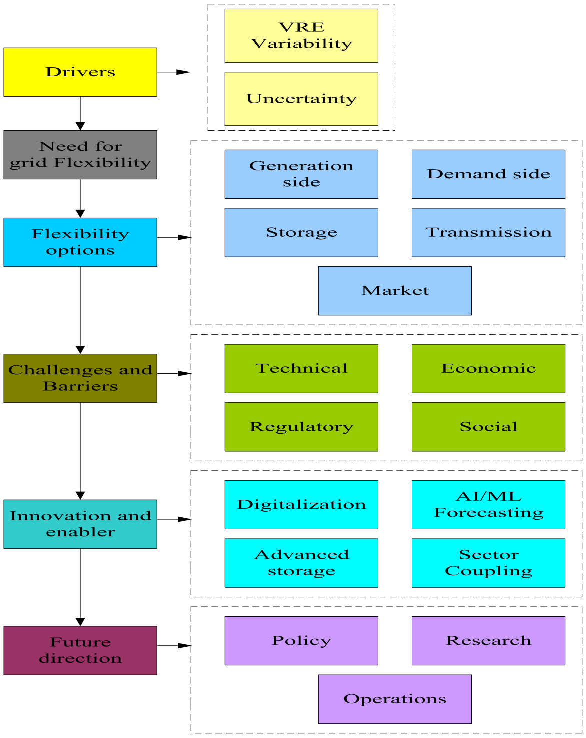

FIGURE 1. Framework for improving grid flexibility through the integration of VRE.

present review emphasizes comparative synthesis across operational timescales and geographical contexts, thereby offering insights that extend beyond technology-centric analyses found in prior literature.

In this study, network stability refers to the ability of the power system to maintain acceptable frequency, voltage, and dynamic operating conditions following disturbances such as load variations, renewable intermittency, or component failures. Reliability, on the other hand, denotes the system's capability to continuously supply electricity to consumers with acceptable quality, encompassing resource adequacy, continuity of service, resilience to outages, and recovery capability.

This study's contribution diverges from prior reviews in several significant aspects:

- Integrating technical and socio-political dimensions: This analysis underscores not only engineering challenges but also institutional obstacles, public acceptance, and psychological factors that frequently influence the practical success of flexibility solutions.
- The work adopts a comprehensive, multi-faceted approach, integrating technical, economic, policy, environmental, and social factors within a unified framework, thereby providing a more expansive perspective than analyses that focus solely on a single dimension.
- Critical evaluation of emerging solutions: Innovative approaches, including digital twins, AI- and ML-driven forecasting, advanced storage technologies, and novel market models, are analyzed in conjunction with traditional methods, focusing on both advantages and drawbacks.
- A proactive agenda: In addition to summarizing existing practices, the study delineates a framework for future research and policy, pinpointing knowledge deficiencies, priority areas for innovation, and strategies to enhance the integration of VRE.
- The paper is structured as a comprehensive survey that systematically classifies grid flexibility mechanisms based on their functional role, operational timescale, and overall system impact.
- The review methodology integrates a comparative analysis of flexibility technologies, a cross-regional evaluation of policy and regulatory approaches, and a synthesis of market design frameworks.
- Unlike earlier reviews that focus on isolated technical solutions, this survey explicitly links technological options with economic feasibility, governance structures, and real-world deployment experiences, providing a holistic and system-level perspective.

The remainder of this paper is organized as follows. Section II introduces the conceptual foundations of power system flexibility and performance criteria. Section III reviews flexibility resources and classification frameworks. Section IV presents taxonomy of flexibility mechanisms and their operational characteristics. Section V discusses advancements and innovations in enabling technologies. Section VI examines market, regulatory, and policy aspects, followed by regional and case-based analyses in Section VII. Finally, Section VIII concludes the paper and outlines future research directions.

II. CHARACTERISTICS OF VRE

A. VARIABILITY AND INTERMITTENCY OF RES

Variability and intermittently are issues that come up when RES like wind and solar power are integrated into electrical power systems. Using a variety of techniques, including energy storage devices, cross-border connections, demand-side management (DSM), network flexibility, supply and demand balancing measures, etc., several countries and areas around the world have been successful in successfully containing the chaos brought on by VRE grid coupling [41]. These developments have, for the time being, guaranteed the networks' stability and dependability. When integrating VRE, smart grids that use grid-forming inverters, massive battery storage, and real-time predictive modeling are essential tactics for preserving grid balance [42]. Numerous nations are made impressive strides toward resolving the problems that VRE sources have brought to the grid [43]. Table 1 provides an overview of leading countries that have effectively addressed variability challenges [44]. Solar radiation fluctuates across multiple time scales. Seasonal changes arise from the Earth's position relative to the sun, daily variations occur due to shifts in the solar angle with respect to the Earth's surface, and very short-term changes occurring within minutes or even seconds are driven by local weather conditions such as cloud cover or dust storms [45].

These rapid fluctuations pose significant challenges for utility operations. Since electricity markets involve advance contracting and backup generators must be dispatched or curtailed depending on the output of intermittent and stochastic RES, some generators are required to remain online even while producing little or no electricity so they can provide instantaneous compensation for sudden drops in renewable production [46]. Variability, uncertainty, and location specificities involve specific costs and technical phenomena summarized in Table 2 [45].

B. WIND POWER AND SOLAR FORECASTING CHALLENGES

1) VRE TEMPORAL DISTRIBUTION AND SPATIAL

The main purpose of this section is to present the most relevant approaches and recent developments in forecasting and scenario modeling for VRE. These methods must account for the inherent uncertainty of weather-dependent resources as well as their spatial and temporal interdependencies [47]. The reliability of such studies is strongly influenced by the modeling process, which often relies on simplifying assumptions such as variable independence or the use of normal distributions that may not fully capture real-world dynamics. In systems with high levels of RE penetration, however, it is essential to recognize and model the stochastic dependencies among VRE sources [11]. Accurately reflecting this interdependence improves decision-making across multiple domains, including system expansion planning, day-to-day operations, commercial strategies, and risk management [48].

Measuring this interdependence is a crucial step in this process, and improvements in these processes must be linked to the goals that are being pursued. The main goal for medium- and long-term operation or expansion planning is to ensure the energetic balance, while the goal for short-term operation decisions is to ensure load curve attendance [49]. The literature offers a variety of approaches, methods, and processes to address the uncertainty problem, ranging from deterministic forecasts to a scenario generation approach, taking into account only one source or a hybrid system supplied by multiple sources [50]. Further details on these approaches are presented in the subsequent sections. Before that, however, it is important to introduce a general definition of energy complementarily and explain its relevance in the VRE literature. As outlined in [51], the concept of complementarily is well defined and encompasses three distinct forms of correlation: temporal, spatial, and spatiotemporal. These forms are described below.

- Temporal: It was also observed that VREs deployed in the same area may or may not share a natural resource. This complementarities' primary feature has to do with the temporal domain. The annual pattern of wind and solar generation, which compares their performance in the spring-summer and autumn-winter periods, is a notable example of temporal complementarily.
- Spatial: Geographically dispersed RES, whether or not they use the same natural resource, may exhibit this type of correlation, whereby a generation deficit in one area could be made up by a generation from another VRE. If there is sufficient transmission capacity to move energy between regions, this would benefit the power system and ensure demand attendance [47].
- Improving the modeling of VREs complementarily is the key to better developing the activities of planning and operating the power system, assuring secure levels of demand attendance and system reliability [9].

Astronomical factors are the primary drivers of the temporal and spatial variability of solar radiation. In [60], the clearness index (CI in %) was defined as the ratio between the observed terrestrial global irradiance (GI) to the extraterrestrial GI [61], thereby filtering out the astronomical portion of the signal from sunset to sunrise. The non-astronomical space-time variability of solar irradiance and consequently solar PV output arises primarily from cloud presence and movement, which can be analyzed using the CI and GI. Factors such as season, atmospheric turbidity, and air mass exert a moderate influence on CI [62]. The probability distribution of CI is mainly shaped by the average clarity during the daily or monthly period under study. At high temporal resolutions, CI often displays a bimodal distribution due to the effect of individual clouds, whereas at lower resolutions (hours or longer) it tends to follow an asymmetric unimodal distribution as a result of aggregated cloud effects [63].

III. FLEXIBILITY NEEDS IN POWER SYSTEMS

To compensate for the unpredictability and fluctuation of RES, flexible generating sources are crucial [64]. Flexible generation plays a crucial role in maintaining grid voltage and frequency stability. These resources can promptly address demand spikes, particularly during intervals of low renewable generation [65], [66]. Gas turbines and combined-cycle plants are especially adept at balancing RE owing to their fast ramping capabilities [67], [68]. Hydropower, especially reservoir-based systems, also provides significant flexibility thanks to fast startup times and adjustable output. Biomass and biogas represent renewable options that can be utilized in adaptable power plants to supply flexible energy. In addition to conventional generators, energy storage systems such as batteries and pumped hydro function as flexible assets by storing surplus energy and releasing it when required [69]. These resources mitigate the fluctuations of RE, guaranteeing a dependable electricity supply and facilitating increased renewable integration into the grid. When powered by low-carbon fuels or coupled with storage, flexible generation also contributes to greenhouse gas reduction. Furthermore, it enhances power market efficiency by supporting system stability and balance [70]. A grid's required capacity for flexible energy sources needs to be carefully considered.

TABLE 1. Variability in global power systems.

Region	Grid Project	Approach/Success Elements	Significant Hallmarks	Refs
USA (Texas)	Electric Reliability Council of Texas (ERCOT).	Improved forecasting models, market-oriented balancing, and extensive power sharing with neighboring systems.	More than 30% of electricity from renewable by 2020.	[52]
USA (California)	California Independent System Operator (CAISO).	Demand response (DR) initiatives, energy storage, VRE forecasting models, and grid modernization.	High levels of wind and solar power integration.	[53]
Iceland	Hydropower–Geothermal Integration.	Reliable and dispatchable renewable sources to offset demand variations.	Hydroelectric and geothermal plants supply nearly all electricity.	[44]
China	National Energy Plans (12th & 13th Five-Year Plans).	Ultra-high voltage transmission and large-scale renewable integration.	Rapid expansion of wind and solar capacity.	[54]
Norway	Hydroelectric Power Integration.	Interconnections with neighboring countries for flexibility.	Hydropower provides ~98% of electricity.	[55]
UK	National Grid Electricity System Operator (ESO).	Smart grid measures: stability tools, battery storage, demand flexibility, advanced forecasting.	Offshore wind integration and interconnections with Europe.	[53]
Australia	Transition to RE.	Virtual power plants, grid-forming inverters, battery storage, and stringent regulatory tools.	Wind and solar plants contribute 60% of VRE.	[56]
Spain	Spanish Power Grid (Red Eléctrica).	Interconnections with neighboring nations, dynamic grid management, and peak storage capacity.	Large-scale renewable integration (>40% by 2020).	[57]
Germany	Energiewende	DR, smart grids, decentralized generation, and energy storage.	High penetration of wind and solar in the national grid.	[58]
Denmark	Island of Energy Initiative.	High wind capacity, strong interconnections with Sweden and Germany.	100% of the island's demand met by RE (wind and solar).	[59]

TABLE 2. Markets and engineering-based comparison of integration costs in a framework.

Characteristic		Location specificity	Uncertainty	Variability		
Definition		Production from solar and wind varies geographically.	Actual production deviates from the forecast for the next day.	Production from solar and wind varies throughout time.		
Market View point	Impact of price	Locational price structure changes	Controlling power and preventing price hikes	Changes in the hourly price structure.		
	Economic significance	The quality of electricity is not constant throughout space.	The short-term solution is expensive.	Over time, electricity is not a uniform good.		
	Relevant market	Nodal spot markets.	Power markets that is intraday and balanced.	The spot market for the day ahead.		
A View point on Power System	Effect on the operation of thermal plants.	Market splitting for re-dispatch.	More standby reserves and rotating.	The use of plants declines.	Increased adaptability in plant operations.	
	Effect on the power system	More restrictive grid restrictions and higher transmission losses.	The RL forecast error rises	Change in the residual load duration curve is nonsequential.	Sequential: RL fluctuates more between hours.	Intra-hourly: RL fluctuates more during each hour.
	Response	Grid expenditures; curtailment and re-dispatch.	Provide flexibility for contingencies.	Change the generation mix to accommodate the mid- to peak load.	Allow for flexibility in scheduling.	

Policies that promote investment in flexible generation technology must be put in place by governments. Continuous technological advancement is necessary to maintain the effectiveness and environmental performance of flexible generation sources [71]. Forecasting tools and advanced grid management systems are necessary for effective integration. Some flexible generation sources, like natural gas plants, still produce greenhouse gas emissions. The cost of developing new flexible generation facilities can be significant. Managing the balance between loose and renewable sources

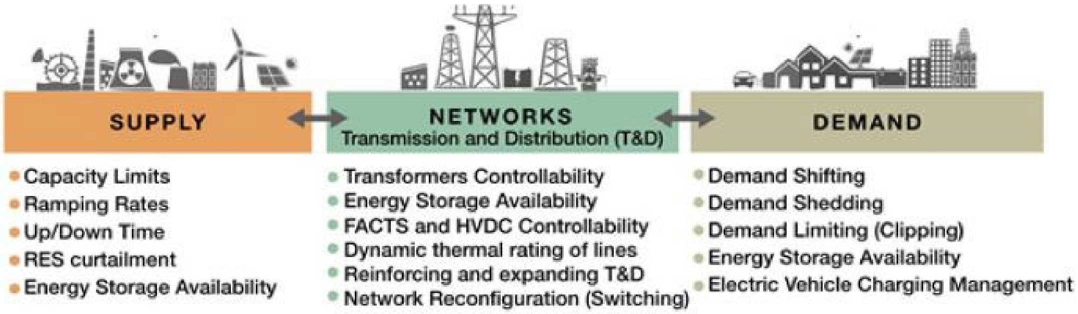

FIGURE 2. Power system flexibility [74].

requires advanced grid management techniques [72]. Regulatory frameworks may only sometimes keep pace with technological advancements and market needs. Flexible generation is going to benefit more from advances in battery and energy storage technology. Newer, greener forms of flexible generation may be made possible by the advancement of hydrogen and renewable gas technology [73].

A. IMPORTANCE OF FLEXIBILITY IN GENERATION, TRANSMISSION, DISTRIBUTION, AND DEMAND

The flexibility of a power system encompasses its ability to adapt to various renewable resource generation, changing consumption patterns, and potential disruptions or emergencies. Some of the components that comprise flexibility include the ability of the transmission and distribution networks to handle fluctuating loads and generation, demand-side flexibility (DSF, the ability to modify consumer power usage), and power plants' ability to quickly ramp up or down [75]. Flexibility is a critical requirement for maintaining stability and reliability in modern power systems, especially in light of the intermittent behavior of RES. Traditional electricity grids were originally designed to accommodate consistent and predictable power flows from centralized generators, but they now face the challenge of adapting to decentralized and variable energy inputs [76]. Evaluating system flexibility has therefore become critical for maintaining efficient and dependable electricity supply amid rising renewable integration and evolving demand patterns. Such assessments help identify system shortcomings and guide strategic decisions in investment and policymaking. The evaluation of flexibility in power systems is frequently conducted through quantitative metrics. Common metrics encompass the ramp rate, which quantifies the speed at which generation units can adjust their output; the reserve margin, indicating the surplus capacity available beyond projected peak demand; and system inertia, which denotes the grid's intrinsic resistance to frequency fluctuations. In addition to these measures, standardized indices like the generation flexibility index and the grid flexibility index are utilized to assess a system's flexibility to variability and uncertainty [77]. Moreover, complex modelling and simulation techniques are employed to forecast system performance under scenarios such as sudden demand fluctuations or differing degrees of RE incorporation [78]. Operational analyses, based on historical data, also play a crucial role by examining how previous grid events were handled, thereby offering insights into real-world adaptability and performance. Figure 2, which was re-created from [74], illustrates the power system's versatility.

The complex, multi-nation power system of Europe is steadfastly dedicated to RE and cross-border electricity trading. As of 2023, RE sources have grown dramatically across Europe, with solar and wind power accounting for a substantial portion of the energy mix [79], [80]. For instance, wind power accounted for only 15% of the EU's electricity in 2022 [81]. The European grid benefits from high levels of interconnection; over 8% of installed generating capacity is used for cross-border power trading. In Europe, where investments have been made in this area, pumped hydro energy storage (PHES) accounts for over 90% of the energy storage capacity [82]. By the end of 2022, battery storage capacity increased to almost 3 GWh. DR initiatives are increasingly being adopted to shift or reduce electricity consumption during periods of peak demand. Despite the evident advantages of these measures, the European power system continues to face challenges, notably in attaining regulatory harmonization among member states and rectifying regional disparities in RE accessibility [83]. Conversely, the United States, particularly California, has established itself as a leader by implementing ambitious climate objectives and striving for a complete transition to 100% clean energy by 2045. By 2022, California's RE capacity had significantly increased, with solar generation comprising roughly 24% of the state's electricity supply [51]. In that year, over 2.5 GW of battery storage capacity was installed, significantly addressing the variability linked to solar power. In California, DRP have shown the capability to reduce peak electricity demand by up to 5%, serving as a crucial mechanism for managing consumption spikes, especially during evening hours [84]. However, the well-known "Duck Curve" challenges remains, as PV generation declines sharply after sunset, necessitating rapid ramping of other generation resources to maintain system stability. To address these flexibility needs, California has introduced supportive measures such as the Self-Generation Incentive Program, which promotes the deployment of storage systems and other flexible technologies [85].

B. IMPACTS OF VRE ON GRID STABILITY AND RELIABILITY

There are several potential as well as a number of problems associated with integrating VRE source (wind and solar) technologies into grid-connected electrical networks [11]. The first issue is that solar and wind energy generation is sporadic and irregular, which affects grid reliability and stability [86]. The transition toward a higher share of RE not only strengthens energy security but also creates opportunities for modernization and long-term sustainability. Governments must adopt robust technological solutions and effective regulatory frameworks to address the challenges of integrating VRE into traditional power networks. Reference [87]. Several emerging technologies and policy approaches offer promising pathways for advancing VRE integration [88]. Central to these efforts is the enhancement of grid flexibility, which remains a critical factor in enabling the successful incorporation of VRE into future power systems. Real-time supply and demand balancing will be made easier by innovations like smart grid technology, DRP, and advanced grid management systems, which will also reduce the inherent fluctuation of VRE [89]. Additionally, grid operators' ability to predict RE production and optimize grid operations globally will be greatly enhanced by the use of AI in forecasting and predictive analytics [90].

It is anticipated that energy storage, especially battery technology, would develop considerably and play a key role in mitigating the volatility linked to VRE [91]. The development of long-duration energy storage technologies, such as solid-state and flow batteries, will make it easier to store excess RE for use in periods of low generation or high demand [92]. It is essential to establish market mechanisms that promote adaptability, energy storage, and the incorporation of VRE sources. Particularly in periods of notable uncertainty in VRE generation, creative market frameworks, such as flexibility markets, can provide financial incentives for resources that aid in supply and demand balancing [75]. Significant opportunities for reducing greenhouse gas emissions, reducing dependency on fossil fuels, and producing carbon-free energy are presented by the widespread integration of VRE [93]. By spearheading the energy sector's decarbonization, nations are positioned to employ VRE to meet the Paris Agreement's global climate goals. One of the main strategies for handling the fluctuating problems with RE penetration in today's systems is flexibility. Therefore, in order to improve the standards and flexibility of power system grids in the future, government measures such grid modernization and infrastructure upgrades should be encouraged [94], [95]. These will entail making monetary expenditures in transmission systems that can more effectively accommodate the distributed character of VRE sources and relieve grid power flow congestion [96].

IV. FLEXIBILITY RESOURCES

To provide a structured understanding of flexibility resources, this section adopts a taxonomy that classifies flexibility options into four main categories: (i) generation-side flexibility, including dispatchable and fast-ramping generation units; (ii) demand-side flexibility, encompassing demand response and load-shifting mechanisms; (iii) storage-based flexibility, covering short-, medium-, and long-duration energy storage technologies; and (iv) network-based flexibility, including transmission expansion, interconnections, and digital grid solutions. These categories operate across different temporal scales, ranging from milliseconds to seasonal balancing, and collectively enable power systems to accommodate high shares of variable renewable energy.

VRG is progressively displacing conventional power plants in modern electricity systems. However, no single resource can provide the level of flexibility required to reliably support such systems; instead, a combination of solutions is necessary [95], [97]. To be considered flexible, a power system must continuously balance supply and demand, adapt to fluctuations in renewable output, and rapidly reconfigure in response to unexpected disturbances [98]. The following resources are identified as key contributors to system flexibility, as illustrated in Figure 3.

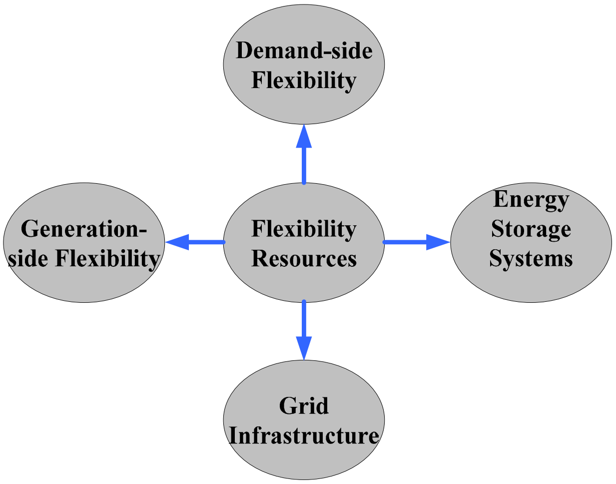

FIGURE 3. Power system flexibility sources.

A. GENERATION-SIDE FLEXIBILITY

Flexible generators are a crucial element of modern power systems, enabling rapid and reliable responses to fluctuations in supply and demand. Their ability to quickly increase or decrease output makes them particularly effective in balancing the VRE. Gas-fired power plants and certain RE sources with variable output, such hydropower, are examples of flexible generation resources [99]. Based on their technological and economic characteristics, generation plants are separated into three groups:

1) BASE LOAD POWER PLANTS

The rated power level is used to operate these power plants. They are utilized to provide the base load and constantly run plants (such as nuclear and hydropower plants) because of their properties. These plants can take anything from an hour to a day to start up.

2) INTERMEDIATE (LOAD FOLLOWING/MID-MERIT) POWER PLANTS

Electricity production in these plants is modified in response to variations in demand. Based on efficiency, cost, capacity, and other considerations, they are situated between base load and peak power plants.

3) PEAK LOAD POWER PLANTS

These facilities, like solar power plants, are utilized when demand is strong. After a cold start, these power plants can quickly reach full capacity in a matter of minutes. Because they provide reserve generation, these plants are essential to the system's dependability [97].

B. DEMAND SIDE FLEXIBILITY (DSF)

1) IMPLEMENTING INITIATIVES FOR DR

Flexible power systems are capable of adjusting to the variability of RE generation, shifting consumption patterns, and unexpected disruptions or emergencies. Flexibility in contemporary power systems can be attained through various options, including demand-side strategies, grid adaptability, and the ability of power plants to rapidly change their output. The inherent variability of RES necessitates an increasing reliance on flexibility to maintain stability and reliability. Traditional grids, initially designed for centralized and stable generation, must now adapt to support decentralized and fluctuating energy flows [76]. On the DSF prioritizes adjusting consumption patterns in reaction to price signals or grid limitations instead of altering supply. Initiatives like DR and DSM incentivize consumers to adjust or decrease their electricity consumption during peak demand or times of limited RE availability. The increasing availability of smart meters and digital energy management tools have made these strategies more accessible and scalable, facilitating substantial flexibility without necessitating additional generation capacity [100]. Energy storage technologies constitute a vital component of flexibility. Battery systems and PHES facilitate the retention of excess electricity generated during peak renewable production for subsequent use when demand increases or generation falls. Decreasing lithium-ion battery costs, along with progress in alternative storage technologies, are solidifying the importance of storage as a crucial component of adaptable grid operation [101].

2) THE IMPLEMENTATION OF DR INITIATIVES

The effective adoption of DSF and DRP is closely tied to the development of smart grid technologies. Unlike conventional power systems, smart grids incorporate digital communication, automation, sensing, and advanced data analytics, allowing for smarter monitoring and control. These advancements convert the grid from a traditional one-way electricity delivery model into a responsive, adaptive, and interactive network [102].

3) ADVANCED METERING INFRASTRUCTURE (AMI)

Advanced metering infrastructure underpins DSF and DR initiatives. In contrast to conventional meters that solely document cumulative consumption, AMI utilises smart meters that can acquire high-resolution, real-time electricity usage data [103]. This allows consumers and utilities to monitor energy usage on an hourly or even sub-hourly basis. A significant benefit of AMI is its bidirectional communication capability, enabling utilities to transmit pricing signals, DR notifications, and load management directives directly to consumers, while concurrently obtaining comprehensive usage data and feedback [104]. AMI additionally facilitates dynamic pricing models, including time-of-use (TOU), critical peak pricing (CPP), and real-time pricing (RTP). By enhancing the visibility and controllability of electricity usage, AMI enables consumers to modify demand in accordance with grid conditions, thus promoting extensive DSF [105].

a: SMART DEVICES AND AUTOMATION

Automation is a key enabler of consumer participation in DR initiatives. Because many end-users may be unwilling or unable to manually adjust their electricity consumption, smart devices and automated controls streamline the process [106]. For instance, intelligent refrigerators can postpone defrost cycles during periods of high demand, heating, ventilation, and air conditioning (HVAC) systems can pre-cool or pre-heat structures prior to peak times, and home energy management systems (HEMS) can coordinate appliance operations to coincide with off-peak, reduced-cost intervals. In industrial applications, automation improves DR by reallocating energy-intensive operations while preserving overall production efficiency. By removing the burden of manual intervention, automation ensures that DR becomes seamless, reliable, and consumer-friendly, thereby improving participation rates and overall system flexibility [107].

b: CONTROL AND COMMUNICATION SYSTEMS

Large-scale implementation of DR depends on reliable and fast communication infrastructure. Smart grids utilize information and communication technology (ICT) systems such as fiber-optic networks, cellular connections, and wireless mesh platforms to establish links between utilities, consumers, and grid devices [108]. These systems enable real-time monitoring and data exchange, allowing operators to transmit DR signals immediately during peak demand periods. Communication networks facilitate direct load control (DLC), enabling utilities to temporarily regulate appliances like HVAC systems or water heaters. Furthermore, control systems with feedback mechanisms allow operators to validate customer responses and confirm their alignment with anticipated results. Communication and control technologies collectively form the basis for coordinated, dependable, and synchronized demand adjustments throughout the grid [109].

c: ENHANCING GRID RELIABILITY AND SECURITY

Smart grid technologies are crucial for improving the reliability and security of DR initiatives. Real-time monitoring facilitated by sensors and control systems enables operators to swiftly detect and isolate faults, thereby reducing outage duration and enhancing overall system flexibility [110]. Automated controls enhance stability by regulating voltage and frequency amid demand variations, thereby ensuring a consistent and dependable power supply [79]. The digitalization of grid operations concurrently presents novel cyber security challenges. To address these risks, measures such as encryption, intrusion detection, and secure communication protocols are necessary to protect both system operations and consumer data [111]. Together, these capabilities establish a resilient and secure environment for DR, boosting user trust while improving grid performance [112].

C. SYSTEMS FOR STORING ENERGY

Lithium-ion batteries are extensively utilized storage technologies, esteemed for their high energy density and efficiency, rendering them appropriate for residential and large-scale grid applications [113]. Nevertheless, batteries constitute merely one category within the extensive array of energy storage solutions. PHES is the most developed and widely implemented technology worldwide, representing over 90% of Europe's total storage capacity [114]. Pumped hydroelectric storage operates by elevating water into a reservoir during periods of excess electricity and subsequently releasing it during peak demand, thus transforming gravitational potential energy into electrical power. Compressed air energy storage (CAES) provides a substantial capacity solution, wherein pressurized air is retained in subterranean caverns and subsequently released to activate turbines; nonetheless, its implementation is constrained by particular geological prerequisites [115]. Moreover, hydrogen-based storage is emerging as a multifaceted long-duration solution. Surplus renewable electricity can be converted into hydrogen via electrolysis, stored for extended periods, and subsequently reconverted into electricity using combustion turbines or fuel cells, offering a scalable pathway for balancing VRE. Leading nations in incorporating hydrogen storage into their energy systems are Germany and Japan [116]. Figure 4 displays the electricity storage in a flexible energy system that was replicated from [117].

The ability of energy storage systems (ESSs) to respond quickly to shifts in the supply and demand for power maintains grid stability. By storing extra RE, storage devices ensure a higher rate of utilization of generated RE. Thanks to ESSs, Peaker plants which are usually based on fossil fuels and used during periods of high demand can be used less frequently [118]. ESSs act as a buffer against supply interruptions and power outages, enhancing grid reliability. While many storage technologies require significant initial investment particularly emerging ones—their costs are steadily declining as innovation and large-scale deployment progress. Certain storage technologies are still in the early stages of development and face limitations related to efficiency, lifespan, and energy density [119]. Moreover, the manufacturing of batteries and other storage devices often depends on scarce resources such as lithium and can involve environmentally harmful processes. Wider deployment is also restricted by inadequate market structures and insufficient regulatory support. Ongoing research is therefore directed toward enhancing efficiency, lowering costs, and developing sustainable materials for ESS. With the rapid growth of RE deployment and continuous cost reductions, the ESS market is expected to expand substantially in the coming years. The market for ESS is anticipated to expand dramatically due to rising deployment of RE sources and falling pricing. The global ESS market is expected to develop at a compound annual growth rate of roughly 20–25% over the next ten years, according to a number of industry reports [120]. Governments are increasingly implementing policies to promote the integration of ESS as their critical role becomes more widely recognized. Looking ahead, the power grid is expected to evolve into an intelligent, digitally enabled system that is deeply integrated with ESS, ensuring more efficient distribution and utilization of energy. [121].

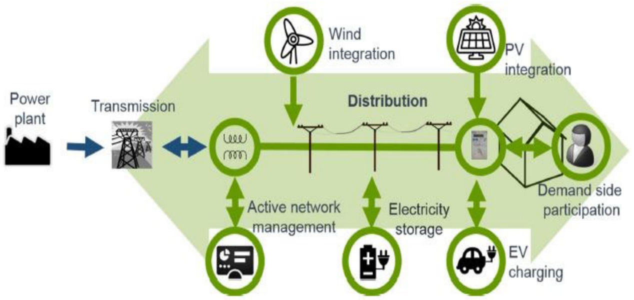

FIGURE 4. **Electricity storage in flexible energy systems [117].**

1) GRID SUBSTRUCTURE

The transmission network constitutes the foundation of any power system, tasked with conveying substantial quantities of electricity from generation facilities to distribution systems and, ultimately, to end-users [122]. As the proportion of VRE increases, enhancing gearbox systems becomes essential for preserving stability and efficiency. Numerous RE resources, including offshore wind farms and solar plants situated in arid regions, are distanced from principal demand centers, resulting in a geographic incongruity between generation and consumption. Reliable, high-capacity, and flexible transmission infrastructure is essential to surmount this challenge [123]. High-voltage direct current (HVDC) technology represents a highly promising solution, facilitating efficient long-distance power transmission with reduced losses relative to traditional alternating current (AC) systems [124]. HVDC facilitates asynchronous interconnection of regional grids, enhancing controllability and enabling cross-border electricity trading [41].

In addition, sophisticated real-time monitoring instruments like wide area monitoring systems (WAMS) and Phasor Measurement Units (PMUs) improve situational awareness by assessing voltage, frequency, and phase angle variations within milliseconds [125]. These capabilities enable operators to swiftly detect and address potential instabilities. Enhanced transmission facilitates interregional balancing, permitting surplus renewable generation in one area to be supplied to regions with elevated demand [126]. Transmission upgrades strengthen the centralized grid, while the concurrent expansion of distributed energy resources (DERs) and microgrids introduces localized flexibility [127]. A microgrid is a localized energy system that incorporates various resources such as solar PV, wind turbines, diesel generators, and energy storage, along with controllable loads [128]. Microgrids function in both grid-connected and islanded modes, improving reliability and energy security, especially in remote or disaster-prone regions [129]. DERs, including rooftop solar panels, small wind turbines, residential and commercial battery systems, and electric vehicles (EVs) equipped with vehicle-to-grid (V2G) technology [130], enhance the decentralization of power generation and storage [94]. These innovations enable consumers to act as "presumes" who generate, store, and sell electricity, thus diminishing reliance on centralized plants, minimizing transmission losses, and enhancing overall system flexibility [131]. When incorporated via smart grid platforms and sophisticated control algorithms, DERs and microgrids can provide essential grid services, including peak shaving, frequency regulation, and voltage support. By equilibrating local supply and demand, they alleviate strain on transmission networks and facilitate increased integration of RE sources [11].

V. ADVANCEMENTS AND INNOVATIONS IN ENERGY TECHNOLOGIES

A. ADVANCED GRID MANAGEMENT TOOLS

Innovative technologies are becoming indispensable for strengthening the adaptability, efficiency, and reliability of modern power networks. With RE sources contributing an increasing share of electricity, sophisticated grid management solutions are required to safeguard stability and optimize overall system performance. Among the most important tools are energy management systems (EMS), Supervisory Control and Data Acquisition (SCADA) systems, and artificial intelligence (AI) applications, especially those employing ML techniques for forecasting and operational optimization [132].

1) SUPERVISORY CONTROL AND DATA ACQUISITION SYSTEMS

SCADA systems are fundamental to contemporary grid operations, offering ongoing monitoring and control functionalities. These systems consist of central control centres, communication networks, programmable logic controllers (PLCs), and remote terminal units (RTUs) [133]. SCADA gathers real-time data from substations and transmission assets, including voltage, current, frequency, transformer loading, breaker positions, and fault conditions. This information is communicated to operators, who can assess system status, analyze performance, and issue commands directly to field equipment. In grids abundant in renewable resources, SCADA is crucial for overseeing the variability of distributed energy sources like wind and solar power [134]. Operators can promptly respond to generation fluctuations by activating reserves or deploying flexible generation units. Contemporary SCADA systems incorporate cyber security measures to safeguard against malicious threats, thereby ensuring secure and dependable communication. Moreover, sophisticated functionalities like predictive analytics facilitate proactive maintenance by detecting equipment susceptible to failure and averting cascading outages. Thus, SCADA supports situational awareness, prompt fault detection, and synchronized system control, all of which are vital for grid resilience [135].

2) ENERGY MANAGEMENT SYSTEMS (EMS)

EMS functions as the cognitive framework for contemporary power system operations. In contrast to SCADA, which emphasizes real-time monitoring and control, EMS utilizes this data to facilitate long-term planning, optimization, and strategic decision-making. The primary functions encompass load forecasting, unit commitment, economic dispatch, and contingency analysis [136], all of which facilitate the efficient allocation of generation resources, uphold grid stability, and minimize operational expenses. EMS are especially beneficial in environments with significant proportions of VRE, as they orchestrate flexible resources including DR, battery storage, and cross-border interconnections [137]. Furthermore, EMS guarantees adherence to grid codes by regulating frequency, voltage, and reactive power. To effectively manage forecasting uncertainty in demand and renewable generation, advanced EMS platforms increasingly utilize sophisticated optimization techniques, including stochastic and robust methods [138].

Optimization-based energy management strategies typically aim to minimize operational costs, emissions, or power losses while maximizing system reliability and flexibility. Common constraints include power balance equations, network capacity limits, storage operational constraints, and regulatory requirements. To solve these problems, a range of optimization techniques is employed, including linear and mixed-integer programming for deterministic formulations, as well as metaheuristic and stochastic methods for handling uncertainty and nonlinearity. These approaches seek near-global optimal solutions while balancing computational efficiency and solution robustness.

In addition to conventional SCADA and EMS, microphasor measurement units (μPMUs) have emerged as a critical enabling technology for distribution networks. μPMUs provide high-resolution, time-synchronized measurements of voltage and current phasors, enabling enhanced situational awareness, state estimation, and early detection of disturbances at the distribution level. When integrated with EMS, SCADA, and AI-driven analytics, μPMUs significantly improve monitoring accuracy and operational flexibility in networks with high penetration of distributed energy resources.

3) ML AND AI FOR RENEWABLE FORECASTING AND GRID OPTIMIZATION

AI and machine learning algorithms are applied in power systems for forecasting renewable generation and demand, fault detection, adaptive control, and real-time optimization. Supervised learning methods such as neural networks and support vector machines are commonly used for prediction tasks, while reinforcement learning is increasingly adopted for real-time control and energy management. Although AI-based approaches offer high adaptability and improved predictive accuracy, they are often constrained by data availability, computational requirements, and limited interpretability, which may affect their deployment in safety-critical grid operations.

The application of AI and ML in power system operations has markedly increased due to escalating uncertainty from renewable energy variability and heightened system complexity. Traditional deterministic or rule-based models frequently fail to accurately represent the nonlinear interdependencies among weather, demand, and renewable output [139]. By contrast, ML techniques including neural networks, deep learning, and support vector machines are highly effective at extracting patterns from large, multidimensional datasets. One of the most prominent applications of AI is RE forecasting. Utilizing meteorological data, satellite imagery, sensor data, and historical generation records, AI-driven models can deliver accurate forecasts of wind speeds, solar radiation, and associated generation levels. These projections enhance scheduling decisions, diminish curtailment, and decrease reserve requirements.AI is also central to real-time grid optimization: reinforcement learning, for example, can create adaptive dispatch policies that balance costs, system stability, and emissions under uncertain conditions [90]. In addition, predictive maintenance powered by AI helps identify anomalies in equipment such as inverters, transformers, and transmission infrastructure, minimizing unplanned outages. AI-driven tools improve DR by predicting user behavior, automating load modifications, and optimizing engagement in flexibility programs. Collectively, these technologies convert traditional power systems into adaptive, self-learning networks capable of effectively managing uncertainty, mitigating operational risk, and facilitating increased renewable integration [140].

B. ROLE OF POWER ELECTRONICS AND INVERTER TECHNOLOGIES IN SUPPORTING THE GRID

The increasing incorporation of RES, including PV systems, wind turbines, and battery storage, has transformed the operational dynamics of contemporary power grids. In contrast to conventional synchronous generators, these technologies utilize power electronic converters and inverters for grid connection. This transition has fundamentally altered the methods of electricity production, management, and distribution. Power electronics serve as the interface that transforms VRE outputs into stable, grid-compatible AC power, while ensuring precise and efficient regulation of critical parameters including voltage, frequency, and overall power quality [141].

1) FUNCTIONAL ROLE OF POWER ELECTRONICS

Contemporary power electronic systems provide significantly more than fundamental energy conversion. They offer swift and accurate regulation of both active and reactive power, aid in voltage and frequency stabilization, and tackle power quality issues including harmonics, flicker, and imbalances. Advanced technologies such as voltage source converters (VSCs) and modular multilevel converters (MMCs) are being increasingly utilized due to their high efficiency, modular architecture, scalability, and ability to facilitate bidirectional power flow. In grids with significant RE integration, these devices constitute the foundation of flexibility, allowing distributed and variable resources to operate harmoniously with extensive power networks [142].

2) INVERTER-BASED RESOURCES (IBRS) AND THEIR ROLE IN GRID STABILITY

IBRs encompass RE technologies and storage systems that interface with the grid via inverters. In contrast to conventional synchronous generators, IBRs do not possess intrinsic rotational inertia, a characteristic that has traditionally been crucial for sustaining frequency stability during system disturbances [143]. The rising proportion of IBRs, coupled with the lack of inertia, heightens the risk of significant and rapid frequency fluctuations, which may jeopardize system stability. Next-generation inverters with grid-forming capabilities are being developed to address these challenges. These devices can emulate inertia, deliver synthetic frequency response, and function in both grid-connected and islanded configurations. By autonomously managing voltage and frequency, grid-forming inverters significantly improve the resilience and flexibility of modern power systems [144].

3) ANCILLARY SERVICES FOR GRID SUPPORT

Power electronics and IBRs are increasingly providing ancillary services that were previously dominated by conventional synchronous generators. These services encompass frequency regulation, spinning reserves, reactive power management, and black-start capability. Modern inverters can actively enhance grid stability through advanced control methodologies, including droop control, virtual synchronous machine (VSM) concepts, and model predictive control (MPC). Moreover, inverter-connected storage technologies can deliver rapid frequency response, mitigating the variability and intermittency linked to wind and solar energy generation [145].

4) SCIENTIFIC PROGRESS AND EMERGING CHALLENGES

Recent research advancements focus on improving the stability, interoperability, and scalability of inverter-based systems. Principal areas of investigation encompass the juxtaposition of grid-following and grid-forming control strategies, the advancement of adaptive droop mechanisms, and the synchronized operation of hybrid energy resources. Notwithstanding these advancements, numerous challenges remain. Maintaining system stability amidst significant IBR integration, reducing harmonic distortions and interactions, and developing robust control frameworks to endure cyber-physical threats are critical issues. The future development of power systems is anticipated to be significantly enhanced by smart inverters featuring AI-driven controls, which will allow them to learn, adapt, and self-optimize in real time to satisfy fluctuating grid demands [146].

C. EMERGING ADVANCES IN HYBRID ENERGY SYSTEMS AND ENERGY STORAGE

Power networks are increasingly implementing energy storage solutions to address discrepancies between generation and demand. These systems retain surplus electricity generated during periods of peak renewable production and release it when supply diminishes or demand escalates. Battery energy storage systems (BESS) are crucial for mitigating variability and ensuring grid stability among the available options [147]. Utility-scale storage installations improve reliability by mitigating short-term fluctuations and bolstering overall grid stability. Nevertheless, large-scale deployment demands significant investment in advanced storage technologies, complemented by clear regulatory policies and innovative financing models to ensure long-term sustainability and cost-effectiveness [44]. Energy storage systems are known to be very successful at balancing the supply and demand for energy, especially in power systems that incorporate a large number of VRES [148]. Energy storage devices come in a variety of forms, including mechanical, electrical, electromagnetic, thermal, hydrological, and electrochemical systems. Moreover, integrating power-to-X technologies, such as power-to-gas (hydrogen) and power-to-heat solutions, can improve the performance of energy storage systems [149]. The ability of energy storage devices to be disseminated is crucial component that supports climate flexibility.

A distributed energy storage system is a crucial component of power systems that rely heavily on RES because of its notable spatiotemporal flexibility and fast response times. Advanced forecasting and predictive analytics: Using ML models, AI algorithms, and excellent weather data collection systems, one of the most reliable ways to manage VRE integration is to have precise forecast and prediction models for solar and wind energy [150]. Table 3 presents different categories of energy storage technologies, each operating on distinct principles electrical, mechanical, chemical, or thermal and offering unique technical characteristics and performance capabilities. Current system analysis studies show short, mid, and long-term energy storage requirements [4], [5]. Currently, it can be highly advantageous to use the hybrid energy storage system (HESS) method, which combines storage technologies with additional operating features. In a HESS typically one storage (ES1) is dedicated to cover "high power" demand, transients and fast load fluctuations and therefore is characterized by a fast response time, high efficiency and high cycle lifetime. The other storage (ES2) will be the "high energy" storage with a low self-discharge rate and lower energy specific installation costs as shown in Table 3 and Figure 5 [151].

To enable a meaningful comparison of the technologies discussed, this survey adopts representative performance metrics and indicators, including response time, scalability, cost-effectiveness, contribution to stability and reliability, flexibility provision capability, and implementation complexity. These indicators provide a consistent basis for assessing the relative strengths and limitations of different flexibility-enabling technologies across diverse power system contexts.

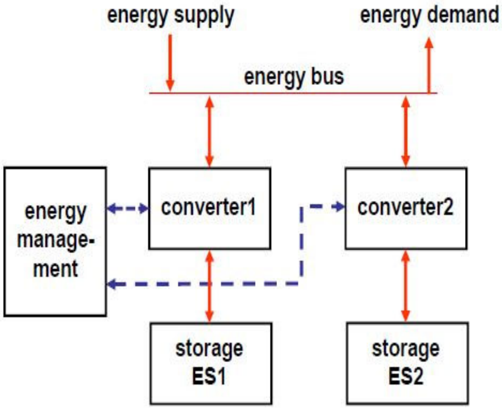

FIGURE 5. **HESS fundamental framework.**

In many HESS applications, batteries especially lithium-ion batteries are essential. They can be used as either "high power" or "high energy" storage. In comparison to batteries, supercaps and flywheels have even greater power densities, efficiency, and cycle lives. Redox-flow batteries are a promising technology because of their good cycle lifespan, recycling capabilities, and instantaneous decoupling of power and stored energy. Both methane (CH4) and renewable hydrogen (H2) are extremely promising choices for long-term energy storage. The concepts of power-to-heat and heat storage will

TABLE 3. Evaluations of various energy storage technologies.

	Supercap	SMES	Flywheel	Lead-acid	Lithium ion	NaS	Redox-flow	Hydrogen	Pumped Hydro	CAES
Life time in years	15	20	15	$5 - 15$	$5 - 20$	$15 - 20$	$10 - 15$	20	80	$ca25$
System efficiency in %	$77 - 83$	$80 - 90$	$80 - 95$	$70 - 75$	$80 - 85$	$68 - 75$	$70 - 80$	$34 - 40$	$75 - 82$	$60 - 70$
Self-discharge rate	Up to 25% in first 48h	$10 - 15\%$ /day	$5 - 10\%$ /day	$0.1 - 0.4\%$ /day	5% /day	10% /day	$0.1 - 0.4\%$ /day	$0.003 - 0.03\%$ /day	$0.005 - 0.02\%$/day	$0.5 - 1\%$ /day
cycle Life time	$> 1Mill$	$> 1Mill$	$> 1Mill$	$500 - 2000$	2000-7000	500-10000	> 10000	> 5000		
Installation costs in €/kwh	$15 - 200$	High	300	$150 - 200$	$150 - 200$	$150 - 200$	$1000 - 1500$	$1500 - 2000$	$500 - 1000$	$700 - 1000$
Long-term ($> 2d$)				X		X	XX	XXX	XXX	XX
Mid-term (>1min,< $2d$)			X	XXX	XXX	XX	XX	X	XX	XX
Short term ($< 1min$)	XXX	XXX	XXX		X		X			
Reaction time	$< 10ms$	1-10ms	$> 10ms$	3-5ms	3-5ms	3-5ms	$> 1s$	$10min$	$> 3min$	$3 - 10min$
Energy density in Wh/I	$2 - 10$	$0.5 - 10$	$80 - 200$	$50 - 100$	$200 - 350$	$150 - 250$	$20 - 70$	750/250 bar 2400 /Liquid	$0.27 - 0.5$	$3 - 6$

also become more significant in the context of future HESS applications. The storage of heat generated from power-to-gas conversion processes (such as electrolyze or fuel cell) and excessive RE will increase the overall utilization rate of renewable energies. Additionally, power-to-heat will allow HESS to perform peak shaving, which will significantly reduce the stress on the public grid and other storage components [151].

Main advantages of a HESS are:

- Decrease in overall investment costs when compared to a single storage system.
- Improvement in overall system efficiency.
- Enhancement of storage and system longevity [151].

Table 3 highlights why Hybrid Energy Storage Systems (HESS) is increasingly preferred in power systems with high VRE penetration. No single storage technology can simultaneously deliver high power density, long energy duration, low cost, and extended lifetime. HESS architectures address this limitation by combining complementary technologies, such as batteries with super capacitors or hydrogen storage, allowing each component to operate within its optimal performance range. The primary trade-offs involve higher system complexity and control requirements; however, these are offset by improved overall efficiency, reduced degradation of individual components, enhanced system lifetime, and lower total cost of ownership compared to single-technology storage solutions.

From a comparative survey perspective, the reviewed advancements demonstrate a clear shift from conventional rule-based grid operation toward data-driven, adaptive, and inverter-dominated power systems. While traditional SCADA and EMS platforms provide foundational monitoring and control, AI-enabled forecasting, grid-forming inverters, and hybrid storage architectures offer superior responsiveness and resilience under high VRE variability. However, these advanced solutions introduce new challenges related to cyber security, interoperability, and regulatory adaptation. The synthesis indicates that technological progress alone is insufficient; coordinated evolution of market structures and grid codes is essential to fully realize the benefits of next-generation flexibility solutions.

VI. REGULATORY, MARKET, AND POLICY FRAMEWORKS FOR ENERGY SYSTEMS

A. POLICIES FOR ENHANCING FLEXIBILITY IN POWER SYSTEMS

Enhancing the adaptability of power systems to rapidly changing energy conditions requires strong regulatory frameworks and strategic planning. Such measures are essential for addressing the growing demand for sustainable and dependable energy, maintaining grid stability, and efficiently managing the increasing integration of RES [152].

1) SHORT-TERM STRATEGIES

Short-term strategies to improve system flexibility focus on optimizing the utilization of current infrastructure and resources to address variations in energy supply and demand. Expanding DRP is essential, as they incentivize consumers to assist in grid stabilization by decreasing consumption during peak times. Simultaneously, investment in sophisticated grid technologies is crucial for facilitating real-time monitoring and control of power systems. The implementation of energy storage solutions, including battery systems, PHES, and other advanced technologies, is essential for balancing supply and demand and ensuring backup power availability [114].

2) LONG-TERM STRATEGIES

Improving strategic flexibility in future power systems necessitates a holistic approach. The application of AI and ML improves the precision of RE forecasting, thereby facilitating enhanced planning and operational decisions [90]. Enhancing cross-border interconnections facilitates resource sharing and promotes regional grid stability. Simultaneously, decentralized solutions like rooftop solar, community wind initiatives, and localized storage enhance both flexibility and efficiency. Policymakers must create supportive frameworks that promote flexibility to implement these strategies effectively. Such frameworks may encompass capacity markets, time-of-use pricing models, and mechanisms that incentivize investment in flexible technologies. Moreover, the accelerated adoption of RE and storage systems can be encouraged through financial incentives, including subsidies, tax benefits, and targeted support initiatives [17].

B. MARKET ARRANGEMENTS THAT PROMOTE ADAPTABLE OPERATIONS

Developing market structures that properly value flexibility such as capacity and ancillary service markets [153], is essential for advancing RE integration. Complementary policy instruments such as feed-in tariffs, renewable portfolio standards, and flexibility premiums provide strong incentives for greater participation in renewable integration. Equally vital are efficient standards and procedures that enable the integration of distributed and renewable energy sources, along with focused support for research and development via grants, subsidies, and public-private partnerships. Collectively, these initiatives diversify the energy portfolio, enhance system reliability, and promote investment in adaptable, renewable technologies. Enhancing efficiency and resilience through such reforms not only aids in emissions reduction but also has the capacity to decrease consumer energy expenses. Furthermore, innovation-centric regulatory frameworks can create new job opportunities and stimulate economic growth in the RE sector [154]. Effective policies necessitate close collaboration among governments, industry stakeholders, and the private sector to formulate robust regulations that expedite the implementation of advanced technologies. Essential strategies encompass augmenting energy storage capacity, broadening DR initiatives, and utilizing smart grid technologies to improve real-time monitoring and control, thus enhancing responsiveness and efficiency. Incentives must be meticulously crafted to encourage flexibility and the adoption of renewable energy, while preventing unintended market distortions [155]. To ensure reliability and security in progressively decentralized grids, sophisticated forecasting driven by AI and ML will be crucial for accurately predicting both demand and RE. Regulatory frameworks must facilitate enhanced integration of DERs and fortify regional energy markets. Advancing geographic and resource diversity, along with cross-border power exchanges, enhances system stability. Ultimately, carefully tailored reforms must prioritize resilience and security while facilitating the transition to a renewable- and flexibility-oriented power system [156].

C. POLICY GUIDELINES FOR INTEGRATING VARIABLE RE

Regulatory frameworks form the essential technical and institutional basis for integrating high shares of RE into contemporary power systems. Contemporary grid codes mandate that renewable generators and inverter-based technologies deliver essential grid-support services, such as fault ride-through, reactive power management, and frequency response [157]. These standards guarantee that renewable resources can enhance system stability in a manner akin to conventional synchronous generators. Interconnection regulations delineate the technical and procedural criteria for integrating distributed generation and storage assets into distribution networks, thereby enhancing safety and interoperability. As power systems progressively integrate digital platforms like advanced grid management tools and smart metering infrastructure, data governance and cyber security regulations have become essential for preserving operational integrity [158]. Environmental and siting policies are crucial, reconciling swift renewable deployment with ecological preservation and public approval. Internationally, initiatives such as Europe's cross-border balancing markets demonstrate how standardized regulatory frameworks can bolster energy security, improve efficiency, and enable resource sharing among regions [41].

A cross-regional comparison reveals notable differences in flexibility deployment strategies. European systems emphasize cross-border interconnections and market coupling, while regions such as California rely heavily on battery storage and demand response to manage solar-driven variability. In contrast, Asian power systems increasingly focus on hybrid storage and digital grid expansion to support rapid demand growth. These regional distinctions underline that flexibility solutions must be tailored to local resource availability, market design, and regulatory maturity rather than adopting a one-size-fits-all approach.

VII. CASE STUDIES AND GLOBAL PERSPECTIVES

Denmark is presented in this section as a representative case study due to its exceptionally high wind penetration, strong regional interconnections, and mature flexibility mechanisms. To enhance comparative insight, this discussion is complemented by brief references to other leading regions. Germany demonstrates large-scale integration of variable renewable through market-based flexibility and extensive grid reinforcement, California highlights the role of battery storage and demand response in managing solar variability, and Australia showcases the deployment of grid-forming inverters and virtual power plants. Together, these cases illustrate diverse but complementary pathways toward achieving system flexibility.

One of the best cases of successfully integrating strategic flexibility into a national power structure is Denmark. A notable example of national-level strategic flexibility is Denmark's energy system, which features a high share of RES, including wind and solar power [159]. The country has made remarkable progress in renewable integration and is recognized as a global leader, with wind energy now supplying roughly half of its electricity demand. Denmark has invested much to improve ties with neighboring countries, including Sweden, Norway, Germany, and others [160]. These links allow Denmark to import power during shortages and export excess RE when output exceeds domestic use. For example, Denmark uses Norway's massive hydropower resources to store energy, using Norway's hydroelectric plants as a "green battery." Denmark has adopted demand-response initiatives and energy storage technologies in a trailblazing manner [161]. The nation has implemented various energy-storage technologies, including thermal storage and battery systems, to manage surplus energy. Danish consumers and businesses actively engage in DRP to augment system flexibility by modifying their energy consumption in accordance with market signals and grid requirements. Substantial investments from both the government and the energy sector in advanced grid technologies have enhanced power system management. The widespread installation of smart meters in Danish households facilitates real-time monitoring and regulation of electricity usage, thereby enhancing overall flexibility [162]. Danish consumers and businesses actively engage in DRP, modifying their energy consumption according to market signals and grid requirements to enhance system flexibility. Substantial investments from both the government and the energy sector in advanced grid technologies have enhanced power system management. The widespread installation of smart meters in Danish homes facilitates real-time monitoring and management of electricity usage, thereby enhancing overall flexibility [163].

Economically speaking, the transition to a more flexible and renewable system has also spurred job growth in the green energy sector and technological improvement. Statistics show that Denmark's wind power generation capacity has grown dramatically, and plans are underway to develop much more offshore wind capacity in the years to come. The advantages of an interconnected and flexible power system for both the economy and the environment are clear in Denmark, where roughly 40% of electricity is exchanged with neighboring countries [164]. These transnational flows improve grid stability, optimize regional resource allocation, decrease overall energy expenses, and bolster energy security. Denmark's commitment to RE has yielded substantial economic advantages. By 2020, the RE sector employed approximately 33,000 individuals, with employment consistently increasing in tandem with infrastructure development. In 2020, the wind industry generated approximately EUR 7.2 billion in export revenue, underscoring its significance as a key economic contributor. From 2010 to 2020, the nation allocated more than EUR 20 billion to RE projects, encompassing wind, PV, and grid improvements, which have been pivotal in reducing carbon emissions and bolstering national energy security. Moreover, Denmark has sustained consistent and economical electricity prices despite its significant reliance on RES. Flexibility measures and international electricity trading have facilitated competitive rates, with the average household electricity price in 2020 approximately EUR 0.29 per kWh, comparable to or lower than other European nations with analogous RE targets.

VIII. BARRIERS AND CHALLENGES

Table 4 systematically presents the main impediments to enhancing grid flexibility for the integration of VRE. It not only outlines existing mitigation measures but also identifies potential directions for future research. By organizing these challenges into technical, economic, regulatory, and social categories, the table offers a structured perspective that goes beyond conventional analyses, helping readers grasp both the obstacles and potential solutions for VRE integration [165]. The primary technical challenges include forecasting uncertainties, frequency regulation, and ensuring overall grid stability [166]. Contemporary methodologies tackle these challenges via refined forecasting techniques, Progressive ESS, and augmented frequency response strategies [167]. Looking forward, emerging solutions include hybrid storage configurations (such as combining batteries with hydrogen), AI-driven adaptive control strategies, and next-generation inverters capable of autonomously supporting grid stability [168].

Issues with infrastructure, such as transmission congestion and insufficient capacity, still prevent widespread integration of RES [169]. Although reinforcement strategies, dynamic line ratings, and FACTS devices can provide short-term relief, achieving long-term solutions will require the integration of digital twin technologies for real-time grid modeling and optimization, the development of flexible grid architectures, and the large-scale rollout of meshed HVDC networks [170], [171]. The economic challenges are equally significant, as the elevated expense of flexibility technologies frequently restricts their widespread implementation. Contemporary methodologies tackle these challenges via refined forecasting techniques, progressive ESS, and augmented frequency response strategies [172]. Current approaches such as carbon pricing, capacity markets, and targeted market incentives are helping to reduce these financial barriers [173]. Future research should focus on innovative market mechanisms for distributed flexibility services, comprehensive cost-benefit analyses of technology combinations, and

TABLE 4. **Important issues, suggested solutions, and prospective research paths.**

Important Issues	Suggested Solutions	Category	Prospective Research Paths
Expensive flexibility solutions.	Carbon pricing, market incentives for flexibility, and capacity markets.	Economic	Long-term investment models, cost-benefit frameworks for integrating many technologies, and innovative market designs for distributed flexibility.
Social and environmental issues.	Lifecycle assessments, stakeholder engagement, community-based renewable projects.	Environmental and Social.	Lifecycle assessment, stakeholder engagement, and community-based renewable initiatives.
Transmission constraints and infrastructure limitations.	Flexible AC Transmission Systems (FACTS), dynamic line rating, and grid reinforcement.	Infrastructure and Technology.	Digital twin-based grid planning, HVDC meshed networks, and flexible grid topologies.
Integration of DER	Demand-side control, aggregation platforms, and smart inverters.	Decentralized Systems and DER Integration	Peer-to-peer energy trading via blockchain, AI-enabled decentralized management, and standardized interoperability protocols.
Frequency regulation and grid stability management	Battery storage systems, DSR, rapid-response generation, and advanced frequency regulation mechanisms.	Technical	AI-driven adaptive frequency control, advanced inverter technologies, and hybrid storage solutions integrating batteries with hydrogen.
VRE forecasting uncertainty.	Improved probabilistic forecasting, reserve capacity management, and advanced weather and generation prediction models.		Integrated forecasting across several regions, probabilistic grid management, and ultra-short-term forecasting based on ML.
Institutional, market, and policy barriers.	Regional coordinating systems, uniform grid codes, and policy reforms.	Regulatory and Institutional	Flexible tariff arrangements, cross-border harmonization, and adaptive regulatory frameworks.

TABLE 4. ***(Continued.)*** **Important issues, suggested solutions, and prospective research paths.**

long-term investment strategies that mitigate financial risks for new solutions [174], [175]. Institutional and regulatory challenges, including fragmented policies and inconsistent grid codes, continue to slow the deployment of flexibility measures [176]. Achieving significant progress will require cross-border harmonization of grid operations, flexible tariff structures that incentivize both producers and consumers to provide flexibility, and adaptable regulatory frameworks that evolve alongside emerging technologies [177]. Integrating DER presents both opportunities and challenges. Current implementations include DSM, virtual power plants (VPPs), and smart inverters [178]. To fully harness the potential of DERs, future studies should prioritize blockchain-enabled peer-to-peer energy trading, AI-driven decentralized energy management, and the development of interoperability standards to ensure seamless integration across platforms [179].

Finally, social and environmental dimensions play a pivotal role in ensuring the sustainability and broad adoption of flexibility measures. Ongoing initiatives include stakeholder engagement, life-cycle assessments, and community-based RE projects [180]. Future research should prioritize creating equitable frameworks to ensure fair distribution of flexibility benefits, enhancing socio-technical acceptance models, and adopting circular economy strategies to reduce waste from energy storage technologies [181]. All things considered, Table 4 summarizes what is already known while also pointing out areas that require further study in order to hasten the shift to a highly adaptable, renewable-dominated power system [182].

IX. EFFECTS OF RE USE ON THE ENVIRONMENT

Table 5 presents a detailed summary of the environmental impacts of RE, organized into three categories: benefits, drawbacks, and comparisons with traditional fossil fuel-based systems [183]. Beyond outlining the opportunities and challenges, it also highlights key implications and offers practical guidance for policymakers, researchers, and grid operators [180].

RE provides significant environmental benefits, playing a central role in mitigating climate change by reducing greenhouse gas emissions. By replacing fossil fuel–based power generation, renewable also lower emissions of major air pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_2), and particulate matter, which improves public health outcomes [184]. Technologies like wind and solar PV require considerably less water than conventional thermal power plants, making them particularly advantageous in

TABLE 5. Comparing the environmental effects of conventional and RE sources.

Classification	Allocate	Features	Suggestion
Comparing with Conventional Energy Sources	Wind and solar PV utilize less water than coal, gas, and nuclear power facilities, which use large amounts of water for cooling.	Water Use	Increase the use of renewables in areas that are experiencing water stress or drought.
	Although there are always environmental expenses associated with production and construction, renewables offer lower lifespan emissions.	Lifecycle Impacts	Encourage lifecycle emissions accounting and the development of green industrial techniques.
	Whereas fossil fuels demand the constant extraction of limited resources, renewables depend on naturally occurring flows that are replenished.	Resource Dependence	Encourage localized RE generation as part of energy independence efforts.
	RES avoid much of the mercury, SO_2, NO_x, and particulates that fossil fuels release, which are harmful to human health and water quality.	Air and Water Pollution	Increase the emission limitations on fossil fuels and emphasize the advantages of switching to RE sources.
	The biggest sources of CO_2 emissions are fossil fuel facilities, whereas RE sources have almost nil emissions during operation.	Emissions of greenhouse gases.	Install RE sources in place of outdated fossil fuel infrastructure and fortify carbon pricing plans.
The adverse effects of RE on the environment.	Communities may be uprooted, ecosystems may be changed, and methane may be released from submerged vegetation by large dams.	Hydropower Risks	Prioritize environmentally friendly dam management and small-scale hydro; incorporate methane capture.
	If left unchecked, the mining of lithium, cobalt, and rare earth elements for solar panels, batteries, and turbines can harm the environment.	Material Sourcing and Waste Management.	Promote sustainable mining practices and invest in recycling initiatives and circular economy strategies.
	Onshore wind farms and extensive solar installations can affect biodiversity, agricultural activities, and local ecosystems.	Habitat disruption and land-use impacts.	Prioritize rooftop and brownfield installations and integrate biodiversity assessments into project planning.
	Turbine blades and solar panels generate waste, while recycling methods are continuously advancing to address it.	Issues with end-of life care.	Expand research and development in renewable resource recycling and implement regulations mandating recycling practices.
	Hydropower can interfere with fish migration, while wind turbines may pose risks of collisions for birds and bats.	Impacts on Wildlife	Develop wildlife-friendly turbine designs, invest in fish ladders, and implement ecosystem restoration measures.
Environmental Benefits of RE	Dependence on renewable resources like solar, wind, hydro, and geothermal energy reduces the consumption of finite fossil fuels.	Sustainability of resources.	Encourage diversification of the RE portfolio to ensure long-term sustainability.
	Water requirements for wind and solar PV are lower than those of nuclear, gas thermal plants, and coal.	Reduced Use of Water	To lessen competition for freshwater, encourage wind and solar PV in areas that are water-stressed.
	When opposed to drilling and mining, distributed solutions lessen the effects on land use.	Protection of Habitat	Encourage decentralized energy regulations and provide incentives for community-based and rooftop systems.
	RE sources help lower the risk of cardiovascular and respiratory diseases by eliminating harmful pollutants such as SO_2, NO_x, and particulate matter.	Enhancement of Air Quality.	Strengthen air quality policies that connect the expansion of RE with public health benefits.
	Solar, wind, and hydropower generate minimal or no CO_2 during	Lowering Emissions of Greenhouse Gases.	To reach climate targets, accelerate the deployment of RE in high-emission sectors,

TABLE 5. *(Continued.)* Comparing the environmental effects of conventional and RE sources.

TABLE 5. ***(Continued.)*** **Comparing the environmental effects of conventional and RE sources.**

	operation, contributing to the mitigation of global warming.		such as transportation, industry, and power.

water-stressed regions [185]. Distributed generation solutions, including rooftop solar, help ease land-use pressures and protect ecosystems, while their reliance on abundant natural resources supports long-term sustainability [186]. These factors suggest that policymakers should prioritize RE deployment in high-emission, water-scarce areas and encourage distributed generation through targeted incentives [187].Despite these benefits, RE technologies present environmental challenges. Large-scale solar and wind installations can disrupt ecosystems and biodiversity, while hydropower projects may alter aquatic habitats and displace local communities [188]. The extraction of critical minerals such as lithium, cobalt, and rare earth elements for required for renewable technologies can cause ecological degradation and social issues if not managed responsibly [189]. End-of-life management also poses challenges, as solar panels and wind turbine blades generate significant waste, and recycling technologies are still in early stages of development [190]. Addressing these concerns requires greater investment in sustainable mining practices, advanced recycling methods, and environmentally sensitive project designs. Innovations such as wildlife-friendly turbine models and improved hydropower management strategies show promise for reducing ecological impacts [191].

Overall, the environmental advantages of RE substantially outweigh those of fossil fuel-based systems. Fossil fuels remain the largest global source of CO_2 emissions and contribute significantly to air and water pollution [183]. Their use also involves high water consumption for cooling and continuous extraction of finite resources, further exacerbating environmental strain. Renewable sources, by contrast, rely on naturally replenished flows, produce near-zero operational emissions, and largely avoid harmful pollutants [92]. While the production and deployment of renewable technologies have lifecycle impacts, these are minimal compared to the ongoing environmental damage caused by fossil fuels [192]. Consequently, future policies should emphasize cleaner production processes, stricter emissions standards, and accelerated transition from fossil fuels to RE [193].

X. GLOBAL POLICIES AND INTERNATIONAL COOPERATION

Table 6 illustrates the vital importance of multilayered regulatory frameworks and international collaboration in advancing grid flexibility and the integration of RES. The discussion is organized into four key areas: national and regional policy instruments, cross-border electricity market policies, global regulatory frameworks, and avenues for international cooperation [194]. Each category is associated with specific implications and actionable recommendations that guide the acceleration of the RE transition [180]. On the international scale, cooperation improves grid flexibility by mitigating renewable variability across borders, enabling countries to share excess generation or compensate for shortfalls. Collaborative efforts also create economies of scale through joint procurement, coordinated research and development, and harmonized technical standards, which help reduce costs for advanced technologies such as HVDC transmission, electrolyzes, and digital grid solutions [87]. Cross-border coordination in areas like reserve sharing and congestion management further enhances reliability and lowers overall system costs [195]. Beyond technical considerations, international collaboration supports financial mobilization, technology transfer, capacity building, and supply chain security, ensuring that all regions including emerging economies benefit from the energy transition [196]. Finally, such cooperation must incorporate equity and justice principles, aligning climate objectives with social inclusion and sustainable development priorities [197].

International policy frameworks, including mechanisms for climate finance, the Paris Agreement, and Sustainable Development Goal 7, play a crucial role in guiding and funding the shift toward low-carbon energy [198]. Organizations such as IRENA, the IEA, and Mission Innovation support this transition by establishing global roadmaps, developing technical standards, and promoting knowledge sharing [199]. These frameworks help align national and regional strategies with broader climate objectives. Regionally, effective integration depends on policies that govern cross-border electricity networks, enabling cooperation, resource sharing, and enhanced grid flexibility [200]. Instruments such as regional power pools, market coupling, and harmonized balancing systems enable more efficient trading and utilization of RES [11]. Policies pertaining to cross-border electricity systems are crucial for regional integration. Market coupling, synchronized balancing systems, and regional power pools are some of the mechanisms that maximize the use of RES and facilitate effective electricity trading [201]. HVDC interconnection policies support large-scale cross-border transfers of renewable, while standardized grid codes and interoperability. Standards ensure that inverter-based technologies can operate seamlessly across different power systems [202].

Effective national and regional policies are critical for enabling flexibility in power systems. Key measures include programs that promote DR, facilitate the participation of aggregators, and implement carbon pricing or emissions trading to internalize environmental costs. Support schemes for RE further encourage system-friendly and flexible generation [203]. Complementary policies such as modernized grid planning, compensation for energy storage, hydrogen-specific regulations, and targeted industrial strategies help synchronize infrastructure, technology deployment, and supply chains with the growth of renewable [204]. Additionally, frameworks for a just transition ensure that the economic

TABLE 6. International cooperation and policy frameworks for RE integration and grid flexibility.

Arrangement	Assign	Structures	Recommendation
Policies Supporting Cross-Border Electricity Systems.	Harmonized Technological Standards for Cyber security, Data Exchange, and Inverter-Based Resources (IBRs).	Grid Code Interoperability	Promote Standardized International Interoperability.
	Streamline Cross-Border Transmission Planning.	HVDC Transmission Routes and Interconnection Policies. .	Establish Regional Planning and Cost-Sharing Frameworks.
	Integrated Market and Reserve Mechanisms.	Coupling of markets and regional pools.	Quicken the development of integrated flexibility markets and regional power pools.
Relevant Worldwide	PV-wind-storage co-location regulations, clear classification, and multi-service compensation.	Policies for storage and hybridization.	Make sure storage is appreciated for all of its functions.
	Internalizes emissions, making storage and VRE more competitive.	ETS and carbon pricing.	Increase global carbon markets while maintaining strict enforcement and oversight.
	Guidelines for power-to-X solutions, electrification of transportation and heating, and green H_2.	Combined hydrogen and sector coupling.	Create standardized sector-coupling plans and hydrogen certification programs.
	Incentives for domestic production, laws requiring recycling, and sustainability standards.	Diversification of supply chains and industrial policy.	Encourage the circular economy and lessen your dependency on a single source.
	Efficiency is increased by market coupling, congestion control, and cross-border reserve sharing.	Coordinated activities	Create synchronized system operations and markets for regional balance.
	Risks associated with grid, storage, and RE plant investments are decreased by multilateral banks and climate funds.	Activation of finance.	Increase climate finance concessions, particularly for developing nations.
	Concessional financing for grids and clean energy is offered by GCF, GEF, and JETP.	Tools for climate finance	Boost climate finance's alignment with investments that prioritize flexibility.
	NDCs, decarbonization, long-term openness, and collaborative systems.	Paris Agreement	Increase the ambition of the NDC and incorporate grid flexibility measures.
Global Collaboration	Coordinating standards, toolkits, and roadmaps are IRENA, IEA, Mission Innovation, and CEM.	Global organizations and platforms	Encourage closer collaboration on digital tools and grid flexibility.
	Efficiency gains, a rise in the share of RE, and universal energy access.	UN SDG 7	SDG 7 should serve as the standard for national flexibility and RE plans.

and social benefits of RE expansion are equitably distributed, providing reskilling opportunities and protections for workers and communities affected by the decline of fossil fuel industries [205].

XI. FINANCIAL AND ECONOMIC PERFORMANCE ASSESSMENT

A variety of tools and metrics are used to evaluate the economic viability of flexibility investments. Traditional benefit–cost analysis (BCA) compares avoided costs such as reduced outages, lower renewable curtailment, and decreased reliance on fossil fuel backup with the capital and operational expenditures of flexibility measures [206]. Comparable to the LCOE used for generation, the LCOF provides a standardized approach to assessing the cost-effectiveness of different flexibility technologies [207]. These technologies provide benefits that extend beyond immediate revenue, such as delaying costly transmission upgrades, lowering reserve margins, and enhancing overall grid efficiency [208]. These technologies provide benefits that extend beyond immediate revenue, such as delaying costly transmission upgrades, lowering reserve margins, and enhancing overall grid efficiency [209]. Additionally, co-optimizing multiple revenue streams specially in applications like energy storage or smart DR further strengthens their financial feasibility [210]. Despite this economic promise, significant financial barriers remain. High upfront capital requirements, particularly for grid-scale batteries, HVDC infrastructure, and digital solutions, hinder deployment in the absence of strong public support [208]. In addition, under-monetization of flexibility services generates uncertain income streams, discouraging private sector participation [211]. Regulatory and policy

TABLE 7. Cyber security challenges and strategies for protecting smart and flexible power grids.

Classification	Important Factors	Suggestion
Methods for Defending Grids Against Cyber attacks.	Monitoring in real time and identifying anomalies	Tools powered by AI and ML are able to identify fraudulent activity, unusual traffic patterns, and bogus data injection.
	Network division	Attack propagation is decreased when important control networks are isolated from corporate and administrative IT.
	Planning for incident reaction	To prepare for coordinated cyber attacks, cyber emergency response teams and simulations are used.
	Frequent updates and patching	Makes certain that substations and controllers have as few firmware/software vulnerabilities as possible.
	Security guidelines for the supply chain	Firmware integrity monitoring and vendor certification for imported software and hardware.
	An architecture that prioritizes defense	Multi-layered security using stringent IT/OT access controls, firewalls, and IDS/IPS.
	Models for zero-trust security	Constant user and device verification lessens the need for perimeter security.
	Encryption and verification	To prevent spoofing and unwanted access to SCADA/AMI data, secure communication (IEC 62351, TLS) is used.
The growing use of digital technology in grids presents security challenges.	Dependency on data in real time	Continuous data is necessary for WAMS, SCADA, and EMS; delays or manipulation can result in instability or improper dispatch.
	Threats from malware and ransomware	Grid control centers have the potential to cause widespread blackouts, making them high-value targets.
	Internal dangers	Workers or contractors with special access rights may intentionally or inadvertently violate the law.
	Complexity of physical and cyber systems.	Physical grid operations may be disrupted by cyber attacks, which are more likely to occur when IT and OT systems are integrated.
	Hazards in the supply chain	Hardware and software sourced from around the world may have malicious implants or undiscovered flaws.
	Increased surface area for attacks.	AMI, digital substations, IoT sensors, and smart meters increase the number of points of entry for cyber attacks.
	State-sponsored cyber attacks	Power infrastructure may be the target of nation-state actors during geopolitical conflicts (e.g., Ukraine assaults).

uncertainties, including unclear frameworks for storage, add to long-term investment risks. These challenges are especially acute in developing economies, where high interest rates, weak utility credit ratings, and limited access to affordable finance create additional constraints [212]. Investors also face technology-related risks, as long payback horizons reduce attractiveness and rapid innovation may render assets obsolete. To overcome these barriers, blended financing approaches such as public private partnerships, concessional lending, and climate finance instruments are essential to lower investment risks and mobilize private capital [213].

XII. ELECTRIC GRID SECURITY

With the increasing adoption of digital technologies such as smart meters, IoT devices, AMI, and modern control systems, Table 7 highlights the major security challenges that must be addressed to safeguard today's electric grids. Although advanced grid technologies improve efficiency and flexibility, they also expand the grid's exposure to cyber threats, including ransom ware, insider attacks, supply chain vulnerabilities, and state-sponsored intrusions [214]. The reliance of SCADA, EMS, and WAMS systems on real-time data heightens this risk, as any disruption or manipulation can compromise system dispatch and stability [215]. To mitigate these threats, multiple protective strategies are employed, such as network segmentation, layered defense-in-depth frameworks, advanced encryption methods, and zero-trust security models [216].

Table 7 presents a comprehensive overview of preventive measures. Network segmentation separates less secure corporate IT systems from critical operational networks, forming part of a defense-in-depth strategy that includes firewalls, intrusion detection/prevention systems (IDS/IPS), and tiered access control [217]. Communications in SCADA and AMI networks are protected via encryption and authentication protocols like TLS and IEC 62351 [218]. The deployment of AI and ML enhances real-time anomaly detection, while regular patching addresses exploitable vulnerabilities [219]. Additional measures involve securing the supply chain by verifying hardware and software authenticity and implementing zero-trust architectures to continuously authenticate users and devices [220]. Coordinated response planning, including CERT teams and simulated incident exercises, ensures preparedness for large-scale or complex cyber events [221].

XIII. EFFECTS ON RURAL COMMUNITIES

Table 8 illustrates how integrating RE and enhancing grid flexibility can significantly benefit rural communities. A key

TABLE 8. Impacts of RE integration and grid flexibility on rural areas.

Arrangement	Significant Aspects	Recommendation
Enhancing Rural Living Standards through RE.	Advancing Women's Empowerment.	Decreases dependence on manual labor and fuel, allowing more time for education and income-generating activities.
	Community Self-Reliance	Decentralized energy systems strengthen local governance and reduce dependence on centralized utilities.
	Access to Digital Technologies and Educational Opportunities.	Reliable electricity enables schools, internet access, and digital learning, helping to bridge the rural–urban education divide.
	Improvements in Healthcare Services.	Enhances healthcare outcomes by providing electricity for telemedicine, medical diagnostics, and cold storage of vaccines.
Benefits of Grid Flexibility for Rural Development.	Job Creation and Skill Development.	Investments in storage, monitoring, and smart microgrids provide jobs in technical services, construction, and maintenance.
	Utilization of Local Resources	Enables integration of distributed RE sources while maintaining overall grid stability.
	Flexibility to disasters	In emergency situations, adaptable microgrids can operate independently, ensuring the continuity of essential services.
	Consistent Access to Electricity.	Reduces voltage fluctuations and power outages, ensuring stable electricity supply in rural regions with limited infrastructure.

TABLE 9. Public perceptions, Adoption trends, and psychological aspects of flexible grid deployment.

Classification	Important Features	Particulars
Mental and Emotional Effects of Depending on Variable RE.	Empowerment and Community Identity	Adopting clean energy encourages community pride, promotes environmentally responsible behavior, and strengthens social cohesion.
	Intergenerational Perspectives	While younger generations tend to be optimistic about RE, older populations often exhibit greater skepticism.
	Trust in System Reliability and Associated Concerns.	The intermittency of wind and solar generation can raise worries about potential blackouts or grid instability during the shift from fossil fuels to RE.
	Adaptive Mindset and flexibility	Renewable microgrids strengthen local resilience by ensuring continuity of power during outages and promoting community autonomy.
Community Acceptance of RE and Grid Flexibility Technologies.	Engagement and Sense of Ownership	Projects such as community-owned solar, microgrids, or energy cooperatives enhance acceptance by reflecting and supporting local priorities.
	Public Attitudes and Perceptions	Public acceptance is influenced by how fair, transparent, and beneficial the RE projects are perceived to be.
	Concerns Related to Digitalization	Advanced grid technologies and smart meters can generate concerns related to privacy, monitoring, and equitable digital access.
	NIMBY effects	Community opposition can emerge against wind farms, transmission lines, or energy storage sites because of visual, noise, or land-use concerns.

advantage is improved reliability, as flexible grids minimize blackouts and voltage fluctuations that often affect regions with weak infrastructure [11]. Enhanced stability allows households and rural businesses to access continuous electricity, which is essential for economic growth and social welfare [222]. Grid flexibility also facilitates the integration of local RES, including solar PV, small wind installations, and micro-hydro systems, without compromising overall grid stability [223]. This decentralization diversifies the energy mix and empowers communities to utilize their own natural resources. Economically, flexible, renewable-based grids support vital rural activities such as irrigation, agro-processing, cold storage, and small-scale manufacturing [224], fostering job creation and skill development. Additionally, investments in energy storage, microgrids, and digital monitoring technologies create employment opportunities in construction, operation, and maintenance [225]. By reducing dependence on costly and polluting diesel generators, these systems lower operational expenses while enhancing energy security. Resilient microgrids also ensure that critical services such as healthcare, education, and water supply remain operational during central grid disruptions [127].

Beyond economic advantages, renewable integration significantly enhances rural quality of life [226]. Off-grid and mini-grid solutions expand electrification to remote communities that were previously underserved, overcoming both financial and geographic barriers [227]. By replacing kerosene, firewood, and diesel, access to clean and affordable electricity lowers household expenses and improves indoor air quality. Education is strengthened through electrified schools, internet access, and digital learning opportunities, helping to bridge the rural-urban knowledge divide [228]. Health services benefit from reliable power that supports telemedicine, refrigeration, and diagnostic equipment. Social improvements are equally critical: access to modern energy reduces the time women spend collecting firewood and opens up opportunities for education and income generation, contributing to gender empowerment. Environmentally, localized RE reduces deforestation, carbon emissions, and ecological strain [229]. Finally, decentralized renewable systems enhance community autonomy by giving rural populations greater control over their energy future, reducing dependence on distant utilities [230].

XIV. SOCIETAL AND PSYCHOLOGICAL EFFECTS

Social and psychological factors play a crucial role in shaping the success of energy transitions, particularly regarding grid flexibility and RE adoption. Community acceptance hinges on perceptions of fairness, transparency, and the tangible benefits of renewable projects [231]. Equally important is trust in key institutions governments, utilities, and project developers since reliable and accountable actors foster stronger public support. Although RE enjoys general approval, local opposition can arise, often manifesting as the "Not in My Backyard" (NIMBY) phenomenon [232]. Issues such as noise, visual intrusion, and competing land uses may trigger resistance when wind farms, storage systems, or transmission infrastructure are located near residential areas [233]. Table 9 summarizes public perceptions, adoption trends, and the psychological impacts associated with the deployment of flexible grid technologies.

Adopting participatory approaches and fostering community ownership generally increase acceptance by aligning projects with local interests [234]. Conversely, opposition can arise when benefits such as lower energy costs or employment opportunities are perceived as unfairly distributed, particularly affecting vulnerable groups [235]. While digitalization enhances grid efficiency, it also raises privacy and data security concerns, which may intensify social distrust [236]. Psychologically, reliance on VRE presents both challenges and opportunities. For some individuals, the intermittent nature of solar and wind generation triggers anxiety over reliability, including fears of blackouts or unstable supply, especially in regions historically reliant on fossil baseload generation [237]. These concerns often reflect long-standing associations of energy security with conventional power plants. Flexibility solutions, such as energy storage and DRP, can gradually alleviate these fears [238]. Behavioral adaptation is also necessary, as consumers adjust to practices like dynamic pricing or shifting electricity use to match grid availability. While some adapt readily, others experience stress or resistance to these changes. On the positive side, many individuals feel empowered and take pride in using clean energy, which reinforces pro-environmental identities and strengthens social cohesion. Communities with renewable microgrids gain psychological flexibility, knowing they can maintain autonomy during outages or emergencies [127]. However, media coverage of rare failures, such as instability caused by extreme weather, can heighten perceived risks even when overall reliability remains high. Generational differences are evident in responses to RE adoption: younger populations generally exhibit optimism and a willingness to innovate, whereas older generations may remain skeptical due to a preference for the predictability of fossil-based systems [239].

XV. FUTURE DIRECTION

More comprehensive system planning must be the main goal of increasing electric grid flexibility for VRE integration. It is no longer enough to use traditional planning techniques that handle generation, transmission, distribution, and storage independently. Instead, co-optimization frameworks that incorporate extreme events, demand variability, and stochastic weather patterns are essential. Developing such models enhances system flexibility and ensures long-term resource adequacy in power systems with high shares of VRE. Another critical area is the establishment of standardized stress-testing protocols and flexibility metrics. Currently, widely accepted measures for assessing ramping capabilities or fast frequency response in both planning and operational practices are lacking. Operators and regulators will be able to better assess and control system risks by establishing strong flexibility key performance indicators and putting systems through multi-hazard stress tests, such as simultaneous low-wind periods and heat waves. Research into improvements in forecasting and uncertainty management shows significant potential. Probabilistic forecasting methods that account for tail risks can reduce reliance on reserve capacity and enhance the efficiency of dispatch decisions for renewable generation, demand, and unexpected outages. By integrating uncertainty into optimal power flow (OPF) models particularly through chance-constrained or distributional robust approaches grid operators can better mitigate forecast errors while minimizing operational costs.

Grid-forming inverters represent a cutting-edge technology that warrants continuous focus. Deploying these devices at scale can provide essential grid services such as system strength, synthetic inertia, and black-start capability in networks with declining synchronous generation. Future research should prioritize validating grid-forming inverter models, understand multi-vendor interoperability, and design control strategies for weak grids and multi-terminal HVDC systems. Complementary tools like wide-area monitoring systems and adaptive protection schemes will be vital for maintaining stability in grids dominated by inverter-based resources. Additionally, developing high-fidelity models for flexible loads including buildings, industrial processes, and electric vehicles is critical, as DSF will play an increasingly important role in managing the variability of RE. The key to enabling large-scale, dependable DSF will include privacy-preserving techniques, comfort-aware limitations, and uncertainty-aware aggregation. Furthermore, demand-side resources will be able to offer both local and system-wide benefits if local and transitive energy markets are designed in a way that facilitates coordination between transmission system operators (TSOs) and distribution system operators (DSOs).

Future advancements in grid flexibility will continue to rely heavily on energy storage and hybrid power plants. Key research areas include degradation-aware battery management, valuation frameworks for long-duration storage, and co-optimized hybrid systems that integrate solar, wind, storage, and electrolysis technologies. Considerations for fleet-scale optimization, feeder-level constraints, and cyber security challenges are equally significant when integrating EVs as mobile storage via V2G systems. Sector coupling that integrates energy with industrial processes, desalination, heating, and hydrogen production provides supplementary avenues for flexibility. Research should assess the efficacy of these interrelated systems in relation to decarbonization objectives, climatic variability, and volatile commodity prices. Additionally, innovative control and protection strategies will be necessary for offshore meshed grids and multi-terminal HVDC networks to guarantee resilient and adaptable functionality. In addition to technological innovation, future research must consider social, equity, and policy aspects. Microgrids that facilitate essential services and climate adaptation strategies must be evaluated within the context of extreme and compound hazard scenarios. Attaining widespread stakeholder approval requires the integration of social equity, participatory design, and community engagement into flexible solutions. Regulatory frameworks must adapt to accurately assess ancillary services like rapid frequency response, encourage flexible procurement, and incorporate lifecycle and environmental evaluations of storage and other flexibility alternatives.

XVI. CONCLUSION

This paper illustrates that grid flexibility is essential for the integration of variable renewable energy resources, such as wind and solar, into contemporary power systems. The results indicate that the variability and intermittency of these resources pose considerable technical challenges, especially concerning grid stability, frequency regulation, and reserve adequacy. Although flexibility technologies provide evident long-term economic and efficiency advantages, their implementation is hindered by substantial initial costs, unpredictable revenue sources, and enduring financial obstacles. Overcoming these challenges necessitates both technological advancement and robust financial frameworks alongside regulatory transparency. Robust policy and regulatory frameworks at national and international levels are crucial for facilitating investment and standardizing practices. Market reforms that adequately recognize flexibility services, in conjunction with international collaboration on cross-border electricity trade, grid code harmonization, and cyber security protocols, can significantly expedite advancement. Simultaneously, advancements in energy storage, demand-side management, inverter-based resources, and digital grid technologies are progressively adept at fulfilling system requirements and addressing flexibility deficiencies.

Beyond summarizing existing knowledge, this survey contributes a structured classification of flexibility resources, a synthesis of technological and policy-driven solutions, and a comparative assessment across regions and market designs. By integrating technical, economic, regulatory, and socio-political perspectives, the paper provides a holistic reference framework for researchers, system operators, and policymakers seeking to design resilient power systems capable of supporting high shares of variable renewable energy.

The extensive environmental and social advantages of adaptable, renewable energy systems are equally substantial. In addition to decarbonization and diminished air pollution, they advocate for rural electrification, sustainable development, and enduring resilience. Nonetheless, increasing dependence on digital technologies concurrently heightens vulnerability to cyber threats, rendering comprehensive protection strategies essential for future energy systems. Policymakers must develop regulatory frameworks that priorities flexibility services, enhance climate finance to mitigate investment risks, and guarantee that energy transitions are equitable and socially inclusive. Grid operators must emphasize sophisticated forecasting, AI-enhanced grid management, and cyber-physical resilience, while also fostering community-level integration of distributed resources. Researchers have an equally important role in advancing methodologies to assess the value of flexibility, developing novel storage and hybrid systems, and examining the social and psychological dimensions of renewable adoption. In conclusion, advancing grid flexibility requires a multidimensional approach that unites technology, finance, regulation, and social equity. When executed proficiently, flexibility strategies will facilitate significant renewable integration while fostering resilient, inclusive, and sustainable energy systems that can address the demands of a low-carbon future.

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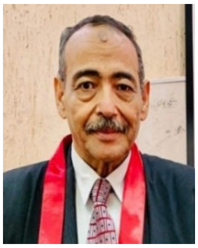

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