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Advancements and Challenges in Integrating Renewable Energy Sources Into Distribution Grid Systems: A Comprehensive Review

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The issues in integrating renewable energy sources (RES) into distribution grid structures are thoroughly examined in this research. It highlights how important this integration is to updating the energy system and attaining environmental goals. The study explores the specific problems confronted by means of on-grid power structures, along with overall performance metrics and compatibility issues. Additionally, it presents a thorough assessment of the attributes of various RES hybrid systems, together with technology from the fields of solar, wind, batteries, and biomass. To be able to spotlight the significance of innovative solutions inside the dispersed technology environment, the integration of RES with combined heat and power system structures is investigated. This study addresses the numerous problems with RES integration into the grid to better comprehend their intricacies. The viability of RES integration is supported by real-world case studies that provide operational examples of dispersed generation systems. The study concludes by discussing the technical, financial, and grid-related problems associated with distributed generating systems' limits and highlighting the contribution of cutting-edge technology and artificial intelligence to their removal. In conclusion, the report highlights the development toward smarter grids and improved distributed generating capacities as the essential component of a robust and sustainable energy future. [DOI: 10.1115/1.4065503]

Keywords: renewable energy sources, distribution grid systems, smart grid integration, artificial intelligence, performance metrics, case studies, alternative energy sources, energy storage systems, power cogeneration

Introduction

Renewable energy sources (RES) like hydropower, biomass, wind, and solar photovoltaic (PV) are increasingly being used in smart grid (SG) systems, particularly in industrialized and developing nations [1]. Hydroelectric power currently accounts for 83% of renewable energy sources used in electricity generation. However, distributed generation systems may cause voltage fluctuations, excessive heat, and reversing power flow, necessitating grid strengthening [2].

Renewable energy adoption is influenced by factors like dependability, security, technology improvements, legislative limits, and carbon emissions uncertainties [3]. Figure 1 demonstrates the categorization of distributed generations (DGs) with respect to their impact on grids. DG techniques are being integrated into power systems to address outdated infrastructure, capacity limitations, and energy market competitiveness. However, voltage regulation may limit DG's spread. Power quality is also a concern, and maintaining grid stability while minimizing costs is crucial for DG penetration [4]. The integration of numerous DG sources has an effect on the distribution of power in the power system in many ways. From the perspective of distribution, DGs can be divided into two categories: output-controlled DGs and output uncontrollable DGs. Micro-turbines, biomass generation, and various other generating units utilizing conventional generation technology make up the majority of controllable DGs. Wind-based power generation, small hydro-based power generation, PV-based power generation, and combined heat and power system (CCHP)-based power generation are examples of uncontrollable DGs. Controllable DGs could be thought of as conventional generations that have little effect on conventional dispatch techniques. Uncontrollable DGs demand generation forecasting, which can be challenging given how closely related they are to the weather and other unpredictability. The reliability of load forecasting will also be impacted by the

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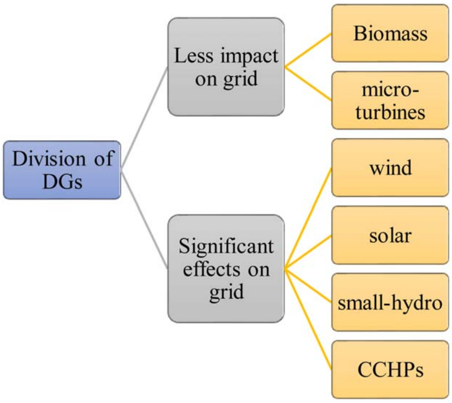

Fig. 1 Division of different DG resources based on their impacts on gird integration

intermittent production of those uncontrollable DGs that are linked to the same electrical substations as loads. Additional reserves are required for distributed renewable energy sources in the event that their outputs do not match the load patterning, in order to reduce both the variations induced by the renewable sources and the load fluctuations [5].

The utilization of renewable energy sources, particularly solar, wind, and CCHP, is being emphasized in smart grid systems at the outset of the study. It talks about the difficulties in power system operators that are having with distributed generation technologies and stresses how crucial it is to keep the grid stable. Reliability, security, technological improvements, and concerned about emissions reduction are some of the factors that have fueled the growth in the penetration of renewable energy sources. The modification from centralized infrastructure to decentralized generating emphasizes the important function that transmission and distribution networks perform. The paper additionally delves into the concept of "smarter grids" as a means to make certain stability whilst minimizing charges. It presents a comprehensive overview of different forms of distributed technology, such as solar-driven, wind, and CCHP systems. The ability of solar PV and onshore wind is provided with projections for future growth. Ultimately, the paper recognizes the restrictions of distributed generation structures, encompassing technical, economic, and grid-related demanding situations and the way those demanding situations are addressed by the employment of artificial intelligence (AI).

Background

Centralized power plants have traditionally been critical for the electrical grid, imparting fuel for the transmission and distribution structures [6]. But, economies of scale faltered in the late 1960s, making it not possible to supply cost-effective and dependable power to remote regions [7]. The twenty-first century's shift to sustainable energy requires a significant overhaul of the industry, focusing on distributed generation for efficiency, flexibility, and cost-effectiveness [8]. Decentralized generation technologies, such as solar modules [9], small-scale wind turbines [10], and CCHP systems [11], can generate electricity close to the point of consumption and can be integrated into microgrids [12], providing clean and reliable power to a wider range of customers [13].

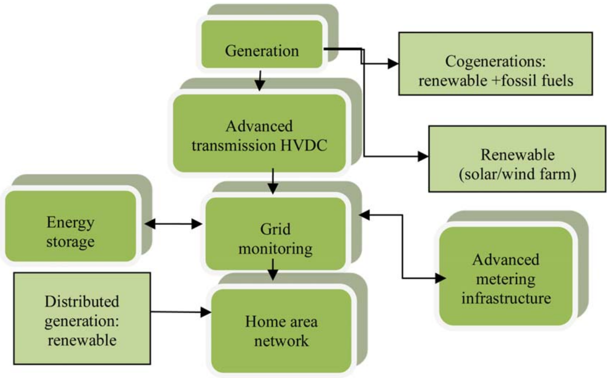

Fig. 2 Schematic representation of power distribution

The network of electrical power systems which include power generating source, transmission and distribution-based lines, and the utility or consumption system. Electric power-producing systems have typically been established away from areas of utilization or consumption, along with the electric grid interconnecting the two [14], as shown in Fig. 2. Electric power networks are divided into two groups based on the devices or components used along with their functionality, i.e., traditional or conventional grid and smart grid [15]. There are many factors that impact the ability of the traditional grid by not acquiring the demand successfully for reliable power distribution. Thus the development of smart grids took place, which is equipped with advanced sensors, controlling devices (FACTS, SVS, STATCOMs, D-STATCOMS), automated switches, substations, and other technologies to address issues of traditional grids. The traditional power grid is composed of a number of interconnected electrical power system components, including transformers, alternators, transmission lines, and different electrical loads designed to transmit electricity from a source of production to a destination of use [16]. Automated devices, smart power meters, automated substations, smart distribution systems, smart producing stations, various forms of automation sensors, etc., are the main elements of a smart grid. Smart grid is an advanced version of a traditional power distribution system that offers more dependable and steady supply of electricity. Such grids are the network of electricity that can monitor the actions of systems that are associated with the grid and propose real-time data on all activities occurring within the power system. This encompasses two different infrastructures, i.e., a power infrastructure for the flow of electricity and a communication-based infrastructure for providing information. Because of such an establishment, a smart grid incorporates the flow (i.e., bidirectional) of information and power, i.e., information coming from customers and delivered to power-generating stations. The fundamental idea behind DG is straightforward: rather than producing power centrally and then transporting it over great distances to the end user, DG involves producing electricity close to the site where it will be consumed.

Types of Decentralized

Depending on the ability to produce both actual and reactive power, DG units are divided into four classes [17]: Micro-turbines and solar PV systems are two examples of type 1 DGs that only provide active power (P). Distribution network operators are responsible for guaranteeing the profitability of their business in terms of MWh, but they may not be able to support voltage, especially when the decentralized network is unable to provide the required reactive power. Synchronous generators and a PV array connected to a voltage source inverter are examples of type 2 DGs that have the ability to produce both active power (P) and reactive power (Q). The only purpose of type 3 DGs, comprising synchronous compensators, static capacitors, and other such devices, is to generate reactive power (Q). Reactive power performs a crucial role in magnetically attracting the rotor circuit in type 4 DGs, which include wind turbines incorporating induction generators, necessitating their use. Generators like these deliver active power concurrently.

The variety of DG that has to be incorporated into the grid can be described as either a PV or PQ bus relying on its intrinsic capacity, particularly at the distribution side. The constant PQ (load bus) model is typically suitable for the distribution system load flow investigation since the capacity of DGs is typically less in size on compared it with traditional power sources. As mentioned above, DG systems come in a variety of forms, but they all aim to lessen the effect of the production of electricity on the environment, increase grid stability and security, and cut down on transmission and distribution losses. Distributed generation can lessen the environmental impact of centralized generating by reducing the amount of electricity that must be generated at centralized power facilities. RES including solar and wind can be used to generate power in residential as well as business structures, particularly by utilizing existing, affordable distributed generating systems. A CCHP, for instance, can be used by distributed generating systems to collect energy that might otherwise be lost. Distributed production decreases or even fully eliminates “line loss” (energy lost in the power transmission system) by utilizing local energy resources. In-depth analysis is necessary to fully grasp the functionality of each type.

Solar Energy-Based Distribution Generation Systems. Sunlight is the source of solar energy after conversion. This energy was turned into direct photovoltaic energy that was focused indirectly. By the utilization of mirrors, lenses, or tracing systems, solar concentration systems, which harness vast amounts of sunshine, get energy through a narrow beam. The photoelectric effect is used in photovoltaic technology to transform light into electric current (Fig. 3). The first commercialized solar power concentrated plant was built in the 1980s. Featuring 354 MW, the Mojave Desert in California is host to the most massive concentrated solar panel installation in the world. The other two largest solar power plants in Spain are Solnova and Andasol, both having a capacity of roughly 150 MW. On the other hand, the Agua Caliente Solar-based Project in the United States has a capacity of more than 250 MW, and the Charanka Solar Park in India that has a capacity of roughly 221 MW, are the most massive photovoltaic power plants in the world, respectively [18].

Solar energy now holds a position of critical importance within the field of renewable energy thanks to the quick growth of PV technological advances during the past few decades [19]. Figure 3 shows a streamlined version of a grid-connected PV distribution system to address this. A single-phase voltage source converter is used to provide solar PV electricity inside the grid whenever a single-stage structural photovoltaic system is linked to the distribution system. The synchronism among the converter power and the grid as well as the regular monitoring of the PV array’s global maximum power point tracker (MPPT) of operation are both guaranteed by this arrangement [20]. The ripple filter, the grid interface inductor, and the voltage source converter’s terminal output are all coupled at the point of common coupling (PCC). Through the use of a ripple filter, this configuration efficiently absorbs and subsequently reduces the switching ripples caused by the voltage source converters. Consequently, a control approach is implemented, with the primary objective being to supply the grid with power generated by the solar PV array at a power factor of 1.

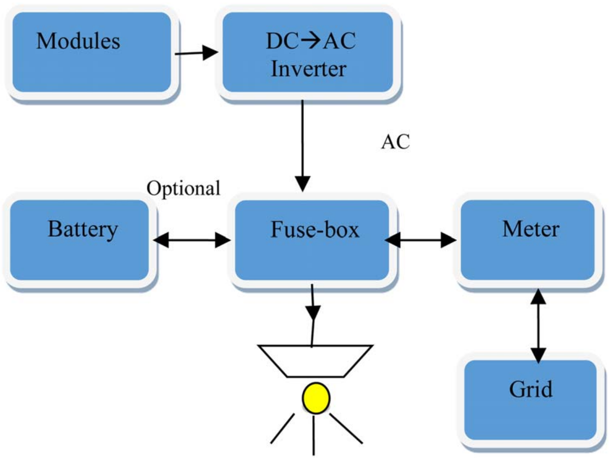

Fig. 3 Grid-connected photovoltaic distribution system for residential purpose

Meteorological factors like solar radiation (I) and ambient temperature (T) have a significant impact on the efficiency of PV modules. Solar radiation directly affects how much power a PV module produces. As a result, boosting solar radiation will result in higher output current, while lowering the temperature of the module’s cells will result in lower output voltage. Consequently, the formula for a PV module’s output power P_{pv} is given as [21]

$$P_{\mathrm{pv}}(t) = P_{\mathrm{mpp}} + \frac{I(t)}{I_{\mathrm{std}}} - \alpha_t [T_c(t) - T_{\mathrm{std}}] \tag{1}$$

Here maximum power point is denoted by P_{mpp}, α_t is representing temperature coefficient of the photovoltaic module, std is used for standard testing condition [22]. To evaluate the output power of the system, when η is the efficiency of energy conversion in the inverter, the following formulas are used:

$$P_{\mathrm{out}}(t) = P_{\mathrm{pv}}(t) \times \eta(t) \tag{2}$$

$$\eta(t) = [P_{\mathrm{in}}(t) - P_{\mathrm{Loss}}(t)] \times P_{\mathrm{in}}(t) \tag{3}$$

However, the output uncertainty issue with solar photovoltaic technology, like that with other climate-dependent DG systems, can lead to both technical as well as financial problems if not adequately planned and developed. Due to the fluctuation of the electricity industry, DG owners and investors, rather than power system operators, can efficiently design the location and size of DGs under the current unbundling laws. Due to the accessibility of main energy sources like wind energy or solar energy, the accessibility of an adequate amount of land-based space, and further variables, choosing the best location may also provide challenges.

The systems exhibit a modest level of efficiency in terms of electrical production, with performance ratios ranging from 60% to 82.6%. While system efficiencies range from 15.47% to 16.97%, capacity utilization factors (CUF) show variation, reflecting variances in operational performance. Obstacles to decentralization, restrictions on land use, economic factors, and grid compatibility problems are the main restrictions as the information is provided in Table 1. The capacity utilization factors are largely consistent, which reflects steady energy production. System efficiencies vary widely, with the greatest value being 55%, which indicates significant improvements in energy conversion.

The performance ratios of thermal energy output systems, range from 82.55% to 95.92% according to Fig. 4, demonstrating efficient energy usage. The need for sophisticated tracking systems, sensitivity to temperature changes, and dependence on particular nanofluids are notable drawbacks.

Wind Energy-Based Distribution Generation Systems. Various renewable energy conversion systems come together to construct a distributed renewable energy accessibility structure. As a demonstration, the components of a wind energy conversion system include (i) electrical generators, (ii) wind turbines (WTs), (iii) closed-loop controllers, and (iv) power electronics converters. Permanent magnet synchronous generators (PMSGs), which have a variable speed functioning, quick dynamic response, minimal noise, excellent reliability, a higher proportions of torque-to-current, and affordable converter with respect to cost, have become the most advanced variable speed generators. The pitch angle, DC-link voltage, active and reactive power compensation, total harmonic distortion (THD) mitigation, mechanical and electrical torque speed, and MPPT are the main conversion system

Table 1 Performance measures and compatibility issues with on-grid solar power systems

On-grid	Energy output type (electrical/ thermal)	Energy produced (kWh)	Performance ratio (PR %)	CUF (%)	Efficacy of system (%)	Limitation (integration challenges)	Ref.
On-grid	Electrical	467.2	80.68	15.25	15.47	Decentralized installations, land use limitations, and economic limitations	[23]
On-grid	Electrical	107.326	79.94	24.65	16.32	Power generation was not constant	[24]
On-grid	Electrical	1461	82.6	75.7	—	Financial uncertainty	[25]
On-grid	Electrical	144.73	60.0	—	—	Performance ratio of the plant is medium	[26]
On-grid	Electrical	139,125	80.29	18.83	16.72	Limited to small-scale grid-connected PV system	[27]
On-grid	Electrical	1535	77	17.50	16.97	Lack of grid compatibility	[28]
On-grid	Thermal energy	155.75	82.55	21.7	14.25	Reducing photovoltaic temperature boosts power output	[29]
On-grid	Thermal energy	157.32	95.52	—	13.1	Limited to nanofluids	[30]
On-grid	Thermal energy	1140.6	92.93	—	55%	Require a two-axis tracking system	[31]

variables that are dynamically controlled by closed-loop controllers. In response to the transiently variable wind, the energy generated from wind turbines is commonly calculated using the Weibull probability density function (PDF) [32].

$$f(\nu) = \frac{L_s}{c}\left(\frac{\nu}{c}\right)^{k_s-1}\exp\left[-\left(\frac{\nu}{c}\right)^{k_s}\right] \tag{4}$$

where in from the above equation, the scale parameter is denoted by c, and the shape parameter is denoted ask. When there is extensive knowledge of a region's wind regime, the L shape variable can be set to 2. The Rayleigh-PDF is the Weibull-PDF in that case [32]. A comparative analysis of three distinct hybrid energy systems, each combining solar PV and wind elements with unique supplementary components is provided in Table 2. These configurations have been specifically designed to cater to varying energy demands and supply conditions.

$$f(\nu) = \frac{2\nu}{c^2}\exp\left[-\left(\frac{\nu}{c}\right)^{2}\right] \tag{5}$$

The comparison of the hybrid systems reveals distinct strengths and applicability for specific energy projects. PV–wind–battery hybrid system offers a balanced mix of solar and wind power with notable battery capacity, making it suitable for grid stabilization and energy storage. Solar PV–wind–biogas–vanadium redox flow battery (VRFB) incorporating biogas and VRFB, excels in versatility and resilience, making it apt for applications demanding robust energy storage solutions. PV–wind hybrid system stands out for its high renewable energy generation capacity, particularly from PV and wind sources. However, it lacks an integrated energy storage component, making it better suited for scenarios where immediate storage needs are minimal or can be supplemented externally.

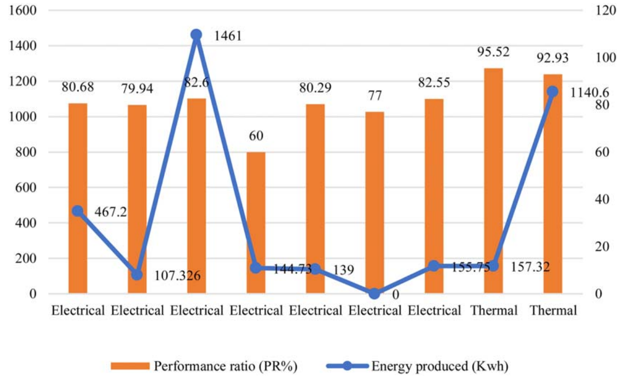

Fig. 4 Comparative analysis of performance ratio and energy output for different on-grid solar power systems

CCHP-DCs. Sustainable development faces challenges due to fossil fuel shortages and climate change. Solar technologies are becoming crucial for future energy systems, leading to research on hybrid CCHP systems [36]. These systems combine renewable, clean energy with fuel-powered systems, offering improved efficiency, lower emissions, lower prices, and reliability [37]. CCHP structures use a minimum amount of fuel, trap heat, and steam for greater electricity, and can diminish greenhouse fuel emissions. Additionally, they provide safety and dependability, even in screw-ups or grid outages [38]. These revolutionary electricity systems integrate RES, energy storage structures, and operational techniques to fulfill numerous energy demands even as minimizing environmental impact.

At the same time, the research presented within the table demonstrates the marvelous competencies of distributed generation CCHP systems, it is vital to acknowledge certain barriers. In the first place, the mixing of solar-driven power tower concentrators (SPTC) within the first system, although enhancing energy efficiency and emissions depletion, comes at an accelerated cost. This increases issues about the financial viability of such advanced technology, particularly in eventualities with budgetary constraints. Second, though the second system achieves self-sufficiency for cooling, heating, and electricity, its applicability can be contingent on precise geographical and climatic conditions. Moreover, the cost-effectiveness of the configuration is contingent on adopting the full-time loading (FTL) strategy, which might not continually align with operational options.

Statistical Information. Despite challenges like global warming and energy depletion, there is an increasing demand for electricity, leading to a growing interest in renewable energy sources like heat, solar, and wind [42]. By 2019, there were over 630 GW of installed solar PV capacity worldwide. China has invested over $50 billion in upgrading its PV supply capacity, creating over 300,000 manufacturing jobs [43]. Decentralized PV capacity is expected to increase by over 250% by 2024, with distributed uses accounting for 45% of the expansion [44]. Onshore wind capacity is projected to increase 57% to 850 GW by 2024, with China dominating the deployment. Offshore wind power is expected to quadruple, reaching 65 GW, and making up over 10% of global wind-generating capacity by 2024 [45].

Table 2 Comparison of parameters for different renewable energy hybrid systems

Parameter	Ref. [33] PV–wind–battery hybrid system	Ref. [34] Solar PV–wind–biogas–VRFB	Ref. [35] PV–wind hybrid system
PV array capacity	3.84 kW	1 kW	—
Battery capacity	9.8 kWh	VRF battery (1 kW)	—
Max power per PV module	213 W	250 W	415 W
PMSG rated power	3 kW	1 kW, biogas engine-generator (15 kVA)	—
PMSG rated speed	360 rpm	10 m/s, biogas engine-generator (1500)	—
Load power requirement	2 kW	7.5 kW	357.8 kW
Solar power available	4.8 kW	10 kW	173.3 kW
Wind power available	4.9 kW	1 kW	168.5 kW
Biogas power	—	12 kW	15 kVA
Biogas generator speed	—	1500	—
Excess power to batteries	7.7 kW	6 kW	—
SOC upper limit	80%	90%	—

Limitations of the Distributed Generation Systems. As discussed earlier, there are some limitations in grid-distributed generation systems with connecting it with renewable energy resources. Thus, this section will discuss different types of limitations that are categorized as, technical, intermittency, and Variability, grid integration, economic, etc., and further impact of grid on these limitations will be discussed. The primary consequences of solar panel integration may include voltage variations and unpredictability, harmonics in electrical (current) I and (voltage) V, preventing grid islanding, and additional power quality concerns, such as fluctuations and strain on distribution transformers. One of the most important factors in the distribution feeding system is elevated voltage [46]. Voltage fluctuation can be measured from the equation given as follows:

$$\Delta V_{oa}^{r} \leq -\left[\frac{(\Delta P_a R_{oa} - \Delta Q_a X_{oa})V_a^r + (\Delta P_a X_{oa} + \Delta Q_a R_{oa})V_a^i}{(V_a^r)^2 + (V_a^i)^2}\right] \tag{6}$$

Here ΔP_a and ΔQ_a are real and reactive power at two different nodes (R_{oa} and X_{oa}) connecting with the line, V_a^r is the real component of voltage whereas (V_a^i) is the imaginary component of voltage.

$$\Delta V_{oa}^{i} \leq -\left[\frac{(\Delta P_a X_{oa} + \Delta Q_{aR_{oa}})V_{oa}^r - (\Delta P_a R_{oa} + \Delta Q_a X_{oa})V_a^i}{(V_a^r) + (V_a^i)}\right] \tag{7}$$

$$\Delta V_o \leq \sum_{\alpha \epsilon A} -\frac{\Delta S_a Z_{oa}}{V_a^*} \tag{8}$$

$$\Delta V_{oa} = \Delta V_{oa}^r + i\Delta V_{oa}^i \tag{9}$$

$$\Delta V_{oa}^i = -\frac{1}{V_a}[\Delta P_a(R_{oa}\cos\theta_a - X_{oa}\sin\theta_a) - \Delta Q_a(R_{oa}\sin\theta_a + X_{oa}\cos\theta_a)] \tag{10}$$

$$\Delta V_{oa}^i = -\frac{1}{V_a}[\Delta Q_a(R_{oa}\cos\theta_a - X_{oa}\sin\theta_a) - \Delta P_a(R_{oa}\sin\theta_a + X_{oa}\cos\theta_a)] \tag{11}$$

The study provided in Ref. [46] examines the influence of varying intensities of PV reaching on a low-voltage delivery network during the summer and winter seasons. At 5% PV penetration, inverters have a limited impact on voltage regulation. At 10% penetration, they reduce capacitor size by 40%. At 30–50% penetration, PV inverters could offer full voltage support. However, at 50% penetration, voltage exceeds safe levels, highlighting the need for mitigation. Integrating renewable energy system strategy was suggested in Ref. [47], which includes solar power, wind power, and biogas, has the lowest levelized cost of energy (LCOE) of \$0.207 /kWh in the absence of policy involvement and drops to \$0.12 /kWh considering policy involvement and carbon abatement cost. Sensitivity research showed that National Petroleum Council (NPC) is the most susceptible to load variations. A grid-connected PV inverter is frequently required in order to generate <5%, THD of its full-rated electrical power [48]. The upfront capital costs associated with installing DG systems, especially renewable sources like solar panels or wind turbines, can be substantial. This can be a barrier for widespread adoption. Incorporating DG through solar PV panels and a wind turbine proves to be a non-dispatchable DG solution, while a dispatchable DG is represented by a diesel generator, as demonstrated in the study [49]. To mitigate disruptions caused by fluctuations in solar radiation, an energy storage system with an optimized battery energy storage system size is also integrated. The proposed energy management system yields substantial savings of 668.8 CC/day (\$) in grid electricity expenses, resulting in a 36.6% reduction of costs for the campus microgrid. This underscores the effectiveness of DG installations in minimizing overall electricity expenditures. Analyzed the economic outlook for the campus to produce the best results for the UET Taxila Campus. The sizing and management of building photovoltaic grid-connected systems in Pakistan are shown in a study that was given in Ref. [50]. The study revealed that initial investment comprises land and equipment costs. Land cost is set at \$25,000 / MW. Equipment cost ranges from \$2.6M/MW to \$3.1M/MW for plants of 2600–3100 MW. Large-scale plants cost \$1.57M/MW. Bahawalpur offers a profitability index of 11.50% for Multan Electric Power Supply Company (MEPCO), but this drops to 4.35% for Islamabad Electric Power Supply Company (IESCO) and further to 3.07% for Lahore Electric Power Supply Company (LESCO).

Grid Impacts

Limitations of Load Profiles and Demand Patterns in Distributed Systems. Distributed energy resources (DERs) have received a lot of attention recently as a result of the speedy implementation of power capacity and growth into distribution systems. Although Ref. [51] also mentions demand-response strategies, power electronics, and electric vehicles (EVs) that are connected to power grids. Distributed generation and energy storage technologies are the main components of DERs. DERs pose a threat to the whole operating system because of their diverse supply of energy from sources of renewable energy, the unpredictable nature of charging EVs, and end-user exponentially integrating power electronic devices [51]. Due to restrictions on conventional power supplies, especially for thermal power generation because of carbon emissions, the generation and transmission capacity of the present electricity grid system is developing slowly [51]. Effective load scheduling plans including renewable energy are necessary to maintain societal wealth and quality of life [52]. This entails taking into account initiatives like encouraging intelligent loads and energy-efficient building materials [53], as well as establishing efficient load scheduling [54] and optimization strategies [55]. End-users may now adjust their loads because of the development of demand response via SGs, which has helped to address these issues.

Issue With Reliability and Resilience. Modernization of the grid emphasizes improving grid resilience, which is crucial for reliable architectures [56]. Distribution system operators use reliability indicators like customer average interruption duration index (CAIDI) and system average interruption duration index (SAIDI) to demonstrate power outage management. Resilience is essential for electrical power distribution networks to absorb [57], recover from, and adapt to disturbances. Microgrids are less capable of managing unforeseen situations due to their primarily routine operations [58].

Environmental Factors With Respect to Carbon Emissions. Reducing carbon footprints in carbon emissions of the production of electricity presents an opportunity to alleviate pollution from fossil fuel combustion and contribute to the mitigation of climate change. Fossil-based power systems often require less initial infrastructure funding than renewable alternatives [59]. The study described in Ref. [60] offers the first thorough, integrated life-cycle assessment of the long-term, widespread adoption of electricity generation from renewable sources as well as carbon dioxide (CO_2) capture and storage for fossil fuel generation. The ability of EVs could potentially have the most impact on the integration of renewable energy sources into the current power system. The most commonly measured output when analyzing the environmental effects of switching to grid-powered EVs is CO_2 emissions. The amount of CO_2 emissions related to transportation has reportedly decreased by 85% in Denmark as a result of cooperation between the country's electric power and transportation sectors [61]. In Montana, it is anticipated that installing a 2 kW solar system will reduce emissions by 0.68 lbs of nitrogen oxides and 3643 lbs of CO_2, which is equal to the carbon dioxide produced by driving an average passenger car 4553 miles. This action has the potential to cut CO_2 emissions by an amount equal to an acre of trees' annual absorption rate. Furthermore, Ireland's power grid experienced an estimated 9% decrease in CO_2 emissions with the addition of 800 MW of wind energy (which symbolizes over 11% of the country's installed capacity) [62]. A decentralized grid (DG) has favorable environmental effects as well as a number of technical benefits, such as decreased line losses, improved voltage profile, higher efficiency, and grid reinforcement [63]. The research conducted in Ref. [64] evaluates the economic viability of compressed air energy storage structures for decentralized energy-generating sources in the islanded mode. It demonstrates that, while the initial expenses are greater, the long-term advantages include higher productivity and operational profit. Shunt capacitors can also be used to increase voltage profile and minimize loss, but when paired with DG, these advantages are amplified compared to the former. Peak load production and base load power supply can both be included in the use of DG. Table 4 highlights key restrictions and their potential effects on the grid's integration of DG systems.

Technical constraints, such as rapid capacity growth, may strain the grid. Voltage variations and harmonics can affect grid reliability and power quality. Inadequate grid islanding protection poses a risk during islanding events. Power quality issues, like flicker, can negatively impact end-users. Increased line losses may reduce system efficiency. DER integration may challenge grid operations. High initial installation costs, especially for large-scale plants, may hinder adoption, though DG implementation can ultimately lead to reduced grid electricity expenses.

Case Studies

Case Study: Optimal Configuration of a Hybrid Renewable Energy System for a Medium-Sized Workshop in Ardabil, Iran Highlight Successes and Challenges in Different Regions or Industries. A hybrid renewable energy system was developed to power a medium-sized workplace in Ardabil, Iran, using the windy climate for solar and wind energy [65]. The system included a 13.0 kW diesel generator, 1 kW PV array, two 3 kW wind turbines, and a 6.13 kW system converter. Twenty-seven strings of 1 kWh lead-acid batteries were added for energy storage. The system produced the lowest LCOE at $0.462/kWh, with an expected daily average of 11.02 kWh/day.

Case Study: Techno-Economic Feasibility of a Grid-Tied Hybrid Microgrid System in KallarKahar, Pakistan. The experiment investigates the feasibility of a grid-tied hybrid microgrid system near Chakwal, Pakistan, which uses renewable energy sources like wind, photovoltaic, and biomass [66]. The system combines advanced wind, photovoltaic, and biomass resources, and uses optimization techniques to distribute power effectively. The system can produce over 50 MW of electricity, with an estimated cost of 180.2 million USD to handle a peak load of 73.6 MW. The study also assessed the area's yearly solar insolation and wind power density and speed for sustainable wind power production.

Case Study: Integration of Photovoltaics as a Demand-Side Management Tool: A Real-Time Test Case Study in the Odisha Grid System, India. This study explores the potential of integrating PV into demand-side management strategies, focusing on energy conservation and seamless integration of renewable energy [67]. Real-time data from the Odisha grid system in India support the viability of this approach, showing a substantial reduction in peak loads through large-scale PV adoption. The study also highlights the potential for installing numerous grid-tied solar power plants to reduce peak demand by up to 25 MW.

Addressing the Challenges of Distributed Generations With Artificial Intelligence Applications in Grid Integration. Solar power's exponential expansion over the past decade has led to challenges in power system operation due to its unpredictability and locational specificity [68]. AI techniques, such as machine learning (ML), deep learning, ensemble learning, and metaheuristic learning, can help address these issues [69]. Load forecasting, a key area of smart grid technologies, has seen significant advancements, with deep learning approaches integrating machine learning concepts. A study demonstrates the effectiveness of a deep neural network strategy for short-term load forecasting, with high prediction accuracy [70]. Long short-term memory was the strategy with the smallest load forecasting error out of the three used. A symmetric mean absolute percentage error of 0.2307 (11.54%), a mean absolute error of 0.0896 (8.96%), and a root mean square error of 0.14065 (14.07%) are used to quantify this achievement [71].

The study in Ref. [72] describes a solar-driven energy forecasts and demand-side predictions technique based on the support vector regression analysis and data from office buildings' energy use. It increases productivity in hot climates and presents a method for optimizing temperatures set points in air conditioning units. The potential for collaboration between human inspectors and AI in preventive maintenance was investigated in Ref. [73], particularly when it comes to diagnosing bearing faults in wind farms using endoscopic photos. The trial, which had 2301 images from 138 wind turbines, used 54 inspectors. Generalists saw greater advancements (24.6% and 25.3%, respectively) when compared with specialists (4.7% and 6.4%, respectively).

Grid Optimization and Control Using Reinforcement Learning or Deep Reinforcement Learning. It is possible to think about creating an effective smart grid system as a mathematical control optimization problem. To address this issue, a number of strategies have been offered, including linear and dynamic programming, as well as heuristic techniques like particle swarm optimization (PSO), genetic algorithm, and gaming theory [61]. Modern distribution networks are experiencing frequent, considerable voltage swings as a result

Table 3 Analyzing performances of integrating CCHP with renewable energy

Study	System description	Performance metrics	Key findings
Wang et. al. [39]	Decentralized generation solar-depending CCHP gas turbine system with SPTC integration, absorption chiller, and heat storage tank	Energy efficiency: Cooling mode—83.6% Heating mode—66.0% Exergy efficiency: Cooling mode—24.9%, Heating mode—25.7% Carbon emission reduction: approx. 41.0%	SPTC integration improves efficiency and reduces emissions, but increases cost
Lorestani and Ardehali [40]	Autonomous RE-CCHP system utilizing PV + WT + electrical energy storage (EES) + thermal energy storage (TES) + combined heat and advanced vattery system (CHABS) + electrolyzer and gydrogen-based (EH). Two operational strategies: Following electric load (FEL) and FTL.	Maximum cooling load: 139 kW Maximum heating load: 114 kW Maximum electricity load: 56 kW	Cost-effective configuration: PV + WT + EES + TES + CHABS + EH based on FTL strategy. Electric chiller utilization is not needed. Achieves self-sufficiency for cooling, heating, and electricity demands.
Yan et al. [41]	Parametric life-cycle assessment of CCHP-RES-energy storage system with micro-turbines, solar PVs, lithium-ion batteries, and auxiliary components. Comparison with centralized conventional energy generation	46% reduction in global warming, 98% decrease in water usage, 90%met electricity demand. Breakdown: turbine (58%), solar and storage (34%), grid (8%)	High electricity demand satisfaction achieved. Reduces environmental impact. Life-cycle costs are higher for medium offices. Affordable for small and large offices.

Table 4 Challenges and considerations for distributed generation integration

Limitations	Impact on grid
Technical limitations	Quick capacity growth may strain the grid
Voltage variations (e.g., ±5 V)	Voltage instability affects grid reliability
Current and voltage harmonics	Harmonics can lead to power quality issues
Grid islanding protection	Lack of protection during islanding events
Power quality issues (e.g., flicker)	Poor power quality affects the consumer experience
Line losses	Increased line losses may reduce efficiency
System functionality	DER integration may challenge grid operations
Economic factors	Initial installation costs (e.g., $2.6–3.1M/MW for large-scale plants) can be a barrier to adoption. DG can reduce grid electricity costs.

of the spike in the use of renewable generators and electric vehicles [74]. Although deep reinforcement learning-based grid control solutions have made significant progress, their capacity to quickly adapt to changing grid operational settings and contingencies limits their usefulness in the actual world [75].

An ML strategy for predicting smart grid stability is introduced in a paper published in Ref. [76]. This calls for the use of multilayer perceptron classifiers (MPC), gradient boost trees, random forests, and logistic regression. When features are chosen using the binary PSO features selection, the MPC yields the highest accuracy prediction (93.8%). The efficiency of ML-hybrid models in assessing landslide susceptibility for catastrophe identification and risk management is also evaluated in Ref. [77]. The research generates six susceptibility maps based on an analysis of 155 landslides in Tongchuan City, situated in China, utilizing 12 evaluation parameters. Particularly in Loess tableland regions, the RS-Random Forest model based on slope units exhibits good prediction capability, with an accuracy of 80.0%. The study in Ref. [78] shows exactly how fuzzy systems with expertise can employ collecting data system observations to pinpoint problem modes in components and sensors by comparing observed data to predicted values via fuzzy logic. Additionally, Ref. [79] develops a ground-breaking method for early fault diagnosis and detection in microgrids, concentrating on three fault types: photovoltaic, capacitor, and sensor faults. For real-time decision-making, this model-free method uses a fuzzy inference technique similar to an expert system. The technology improves fault management in microgrid systems by having quick detection times that range from 0.0063 s to 0.0913 s. Last but not least, Ref. [80] suggests using a Q-learning algorithm to control energy flow within a solar microgrid. By learning from mistakes, the agent manages to maintain a healthy state of charge (SOC) above 20% and a constantly high water tank level. When compared to demand, the microgrid provides considerable load coverage, falling short by barely 0.8%. This ground-breaking method shows promise for effective energy flow control in solar microgrids [80].

Within the realm of grid management and stability enhancement, a mosaic of ingenious methodologies emerges, each tailored to address specific challenges within conventional grid systems.

Conclusion

The challenges involved in incorporating RES into distribution grid systems are carefully laid out in this research. It starts by outlining the significance of this integration and highlighting how important it is to the transformation of the energy setup. In order to support the debate, numerous useful tables are included. Challenges for on-grid solar power systems are shown in Table 1, with performance metrics and compatibility problems highlighted. Table 2 compares the parameters for various hybrid RES, including solar, wind, battery, and biomass. Table 3 provides performance indicators for integrating CCHP systems with RES. This emphasizes the significance of novel approaches in the landscape of distributed generation, promoting the investigation of workable and effective energy solutions. Table 4 offers a structured view of the complex problems with renewable energy (RE) integration into the grid, furthering the discussion's thoroughness. The development of smarter grids and improved distributed generation capacities ultimately holds the key to a resilient and sustainable energy future. Collectively, these tables strengthen the analysis in the paper by providing empirical data, comparisons, real-world examples, and innovations that add to the content and make the analysis a well-supported and thorough examination of this crucial energy transition.

The novelty of this study lies in the discussion of a multifaceted strategy for incorporating DG resources into electricity grids, encompassing technological, economic, and operational constraints. It provides a thorough overview and innovative strategies for better recognizing and maximizing renewable energy systems inside the current grid architecture. This technique not only enhances academic understanding, but also provides practical recommendations for optimizing implementation.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

No data, models, or code were generated or used for this paper.

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