An overview of the existing and future state of the art advancement of hybrid energy systems based on PV-solar and wind

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Abstract

Increasing solar and wind power use in existing power systems could create significant technical issues, especially for grids with poor connectivity or stand-alone systems needing more adequate storage capacity. This is due to the unpredictable and intermittent nature of solar and wind power. The intermittent nature of solar and wind resources can be reduced by integrating them optimally, making the entire system more reliable and cost-effective to operate. The advantages and disadvantages of hybrid wind and solar energy integration systems are discussed in this research. The impact of voltage and frequency oscillations and harmonics is amplified in weak grids, affecting both grid-connected and stand-alone systems. This may be fixed by ensuring that hybrid systems are well designed, equipped with cutting-edge quick reaction control capabilities, and optimized. This review offers an overview of existing advances in PV-solar and wind-based hybrid energy systems while exploring potential future developments. Further, this review also provides an overview of the primary studies published on optimum design considerations for compactness, topologies for power electronics, and control. As the global energy environment shifts toward sustainability and resilience, this review helps researchers, policymakers, and industry stakeholders understand, adapt, and enhance PV-solar-wind hybrid energy systems.

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1 INTRODUCTION

Energy seems crucial to a nation's progress, therefore it must be saved as efficiently as possible. However, in addition to developing technology to generate energy from all hydrocarbons in an eco-friendly manner, energy assets should be preserved as efficiently as is feasible. Energy alone drives the economy [1, 2]. The main disadvantages of solar and wind systems are their lack of reliability and efficiency [3]. To meet energy market demands, renewable energy technology has grown significantly. Petroleum consumption drains our foreign currency reserves. The optimal solution to these challenges lies in renewable energy [4]. The world's fossil fuel sources are fast depleting [5]. Renewable energy was previously recognized. Over the past 30 years, a variety of renewable energy solutions have been researched, developed, tested, and implemented. India, with 15% of the world's population, is one of the fastest-growing energy users [6]. Fossil fuels produce greenhouse gases which contribute to global warming [7]. Numerous studies predict these energy sources will soon run out. This encourages most industrialized and growing nations to switch to renewable energy technologies. This is done to meet the growing economic demand for electricity and improve power infrastructure efficiency. The best arrangement calls for hybrid energy systems, which use photovoltaic, wind, diesel engine, and battery-connected power sources to generate electricity. The system uses wind speed, sun radiation, wind rates, and meteorological data. Hybrid energy system optimization reduces total cost, present values, greenhouse gas emissions, power system failure likelihood, energy cost, and annualized system cost [8]. This makes the system cheaper for residential use. The adaptive genetic algorithm (GA) uses source chromosomes like number of battery banks, PV array ratings, wind turbine capacity, system initialization cost, diesel generator rated power, and operation and maintenance cost to produce results. The algorithm finds the best solution for the lowest operational maintenance cost. An improved GA program for small applications to electrify rural locations has been developed using the matrix laboratory (MATLAB) toolbox to reduce the cost of the proposed hybrid energy system. This program's goal is cost reduction.

Renewable energy sources have steadily increased their global energy supply in recent years [9]. Energy storage must be connected to energy system management since it is extremely dynamic and sensitive to many conditions. Individualized energy management solutions can optimize energy transfer between electric drivetrain components. To boost wind energy absorption while enabling power systems, lowering wind power's key drawback of fluctuating renewability might make it easier to continue their typical modes of work and ensure the integrity of their useful facilities [10]. Thus, energy storage could increase the grid's adaptability and create a quick power reserve to minimize grid imbalances. Real-time stochastic power management uses the SPSA algorithm to find the optimum securities for HESS elements. This technique determines the optimal HESS component proportions. The grid's power matrix is used to smooth the battery's output to reduce cycling oscillations which have decreased compared to the initial wind power profile. The data show that the suggested technique reduces power fluctuations at the grid interface by more than 81% in 90% of the days analyzed compared to the wind-produced profile. The flywheel's working mode also varies, although the SPSA's goal is to reduce battery consumption by 65%. The suggested method achieves the provided aims in all simulated analyses, proving trustworthy, easier, and faster than alternative methods. Further research will apply this power management strategy to WECS and HESS circumstances and other renewable energy system designs. The designs are implemented to minimize system cost [11]. The renewable energy-based winding system for the investigated network would determine how many wind turbines and panels are needed to minimize power costs and energy costs owing to energy not given inside the channel. The proposed system's cost includes the net present value of all maintenance and operating expenses and the raw cost of energy, which covers the initial investment.

Hybrid renewable energy systems (HRES) optimize power generation by combining renewable sources. These systems use multiple technologies to overcome each energy source's constraints and provide more electricity efficiently and consistently. Tawfik et al. [12] optimize an energy management system in a Mediterranean port using solar and wind energy. Results show solar panels generate sufficient power, while simulated wind arrays show improved performance. Kiehbadroudinezhad et al. [13] studied a multi-objective optimization problem which combines life cycle cost, environmental impacts, and system reliability. A division algorithm is proposed for faster and more flexible solutions. A study of Larak Island, Iran, shows the proposed algorithm is more cost-effective and eco-friendlier than genetic and artificial bee swarm algorithms. HRES reliability is a significant benefit since wind turbines can provide power when solar panels are impractical due to nightfall or overcast conditions. Diverse energy sources often maximize energy conversion, making use of current conditions. Since renewable resources are free, the initial expenses of putting up these systems are offset by lowering operational costs over time. HRES is eco-friendly and minimizes fossil fuel use and greenhouse gas emissions. Hybrid systems also improve load management by smoothly integrating batteries and other storage options. Real-world benefits of HRES are transforming energy access and delivery. HRES delivers electrification to isolated populations without power. HRES-powered microgrids provide uninterrupted power in grid-unstable areas. The industrial sector uses HRES more frequently to reduce energy expenses and encourage sustainability. Contemporary urban projects use hybrid energy to power large neighborhoods and complexes. Some public transit systems are switching to hybrid renewable energy, which minimizes operational costs and environmental impacts.

Wind and solar energy are well-established forms of renewable energy due to their extensive utilization [14]. Their complementary production patterns ensure a constant energy supply. Recently developed technologies have increased efficiency and lowered expenses. The use of these methods simultaneously improves land efficiency and provides ecological benefits.

A photovoltaic power station, wind farm, and energy storage device with a manageable capacity arrangement are needed to make a hybrid wind-photovoltaic-storage power system economically viable [15]. So, we propose a new energy storage technology that combines wind, solar, and gravitational energy. The storage of energy is vital for extensively utilizing renewable energy sources. Location and building size limit energy storage solutions such as compressed air and battery systems. One of a gravity energy storage system's benefits in hilly areas is its ability to use the terrain.

Mountain height stores GESS energy. Using a numerical method, wind and solar power plants can provide renewable energy to ordinary families [16]. A non-dominated sorting genetic algorithm assessed the ecological and economic optimum for four hybrid energy system scenarios. Synchronously using optimization goals and sensitivity analysis, the system was designed to meet established requirements. The environmental goal was to reduce carbon dioxide emissions; hence a lot of renewable energy was used. Thus, hybrid renewable energy systems have shown great potential in application, which has led to a trend toward distributed power production as a more stable and consistent energy source. A strategy for optimizing and improving micro-grid HRES by implementing optimization algorithms is by utilizing a non-dominated sortation evolutionary algorithm to find a combination that meets ecological and economic goals with constrained abilities. This research sought to create a hybrid power system that met end-user needs and maximized efficiency.

2 HYBRID ENERGY SYSTEM

Decades of research in all applications have shown hybrid energy system capacity. Solar-wind hybrid energy systems are a technological innovation because they are renewable and sustainable for human civilization. Wind and solar energy are free. Hybrid energy systems have been used to restructure network infrastructure and identify the ecosystem's many components for solar-powered smart cities. Advanced algorithms and methodologies have improved the hybrid system's efficiency. Thus, Sureshand Meenakumari [8] propose an enhanced GA-based novel technique for the design optimization of hybrid energy systems, which

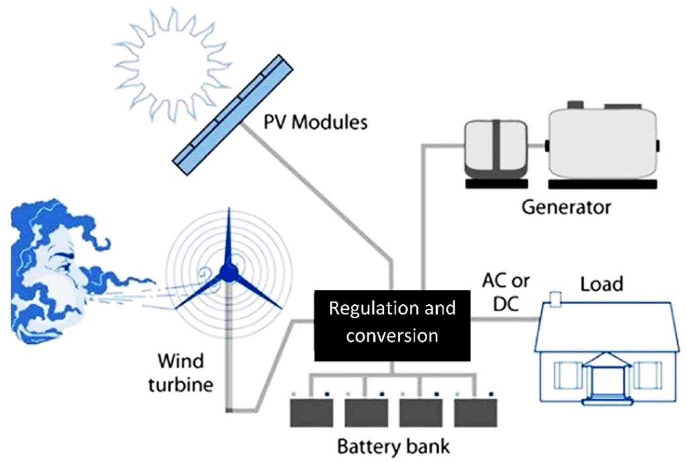

Figure 1. *Illustrates the Hybrid Solar-Wind energy system ([17]) .*

includes diesel generator, solar PV, wind, and battery storage systems for power generation. The suggested system uses sun radiation and wind velocity data (available from NASA). Hybrid energy system optimization reduces total expense, cost of present values, greenhouse gas emissions, loss of power system, energy cost, and annualized rate system cost. This makes technology more affordable for family use. Figure 1 illustrates the Hybrid Solar-Wind energy system.

Indonesia has both the longest coastline and most islands. Its coastline spans 81 000 kilometers and 17 058 islands. Indonesia's water covers 5.8 million square kilometers, 75% of its land area. So, Setiawan et al. [18] suggest that the dual input buck-boost converter will utilize the PID approach to regulate the voltage to 14 V used to charge the battery from the wind turbine generator and photovoltaic module. A mechanical catamaran system will feature a photovoltaic panel and wind turbine generator. The ship's model propulsion system will employ battery power. This study found that solar and wind turbine generators can yield 774 Wh. The simulation shows that the PI controlled system takes 35 milliseconds to set, while the PID control system takes 11 milliseconds. Abd Ali et al. [19] proposed and simulated the hybrid system for wind and solar energy conversion. Al Najaf, in southern Iraq, will employ the solar modules and wind power facilities to generate green energy. Thus, the average monthly solar radiation intake was detected and expected to be 6.5–7 kW h/m^2 while the average annual wind speeds were 3.8 meters per second. Research found that Iraq's solar and wind power potential could assist in meeting some regions' electricity needs. Due to alternative and renewable energy system unpredictability, it must share renewable energy sources. Talaat et al. [20] explored whether it is possible to combine a variety of renewable energy sources, taking into account the operational reserve established during the implementation phase. The reserve boosts the hybrid renewable energy system's efficiency and dependability. A microcontroller merges all three types into one and calculates the operational reserve for each. Buck-Boost converters power this controller. Zhu et al. [21] proposes integrating a wind-solar hybrid power

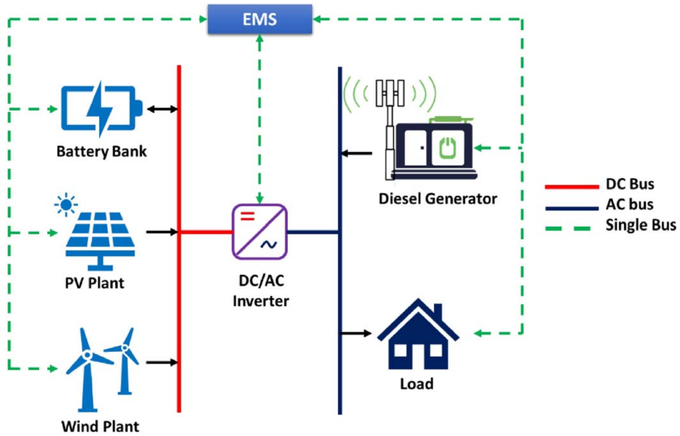

Figure 2. *Battery-PV-Wind Hybrid system [23] .*

generating system with a supercapacitor hybrid energy storage system. This method could boost energy storage and electricity production. This procedure maximizes energy storage and power stability using conductance-fuzzy dual-mode control and the static wind correction mechanism. MATLAB studied the optimal hybrid energy storage system setup model. Agyekum et al. [22] investigated the technology and economic viability of a commercial hybrid power plant in southern Ghana to generate electricity. It determines the best photovoltaic and wind-DG-battery hybrid system designs. Energy infrastructure feasibility studies evaluate pay-back time, internal rate of return, total expenses, and LCOE. The Battery-PV-Wind hybrid system diagram is illustrated in Figure 2.

Standalone hybrid systems based on a renewable source could provide continuous and stable electricity in remote areas not connected to the grid. Xu et al. [24] found that these locations are commonly in hard-to-reach places. The PV and wind power stoppage rate is calculated on new indices when developing the photovoltaic hybrid energy system. In a few MOPSO cycles, a single-goal optimization model can be built up. The wind farm, photovoltaic plant, concentrated solar power plant, electric heater, inverter, and battery model [25] is being researched. Various LCOEs and PSPs determine the best system configuration and design concerns. A CSP plant, photovoltaic system, and inverter can achieve a 10% LPSP and 0.1484 dollars per kilowatt-hour LCOE using power cycle output priority.

Solar and wind power consumption is rising due to the desire to reduce our environmental footprint while also expanding. To reduce power supply stochasticity, Jamshidi et al. [26] offers a hybrid system with solar and wind generators. PV, battery, wind, diesel hybrid systems include PV arrays, wind turbines, batteries, a standby diesel generator, converters, and other equipment. These components generate, store, and manage electricity. Conventional fossil fuel–based power generation is the main cause of global environmental degradation, which will only worsen in the near future. Thus, Naeem et al. [27] offer an algorithm to choose the best places for supporting solar and wind energies. Due to recent environmental legislation aimed at reducing greenhouse gas emissions and pollution and the world's rising energy demand, renewable energy generation must increase. According to Barelli [28], intelligent power management systems and flywheel-battery technologies reduce power profile changes at the grid by more than 80%. This study examines the LCOE of a 2 MW wind generation plant with flywheel and lithium-ion battery hybrid energy storage. Hybrid energy storage uses flywheels and lithium-ion batteries. NMC battery technology with a mechanical flywheel, along with the 'Fast Reserve' service, can reduce LCOE by over 5% compared to the lack of energy collection.

3 ENERGY STORAGE FOR HYBRID SYSTEMS

The renewable hybrid system prioritizes energy storage. Thus, Guo et al. [29] developed a robust dynamic-wavelet-enabled wind power smoothing technique by hybrid energy storage system (HESS) of super-capacitors and batteries. Robust coefficients can handle the robustness-economic gain tradeoff. Figure 3 shows how HESS technology integrates a hybrid system to improve energy storage.

Due to the power requirements of wireless base stations, rural telecommunications networks cannot expand without energy. Zhao et al. [31] proposes a hybrid energy supply system for rural mobile base stations that uses renewable sources like photovoltaics, wind, and adiabatic compressed air. Solar and wind energy are widely used. Pressurized gas energy storage smooths intermittent renewable sources. Portfolio management and energy storage site management are important since Brazil's energy mix includes more renewable sources. Thus, Antunes et al. [32] propose a study that examines the universal nature of photovoltaic and wind creation in the Brazilian North. Energy storage can mitigate the impact of unreliable natural resources on electricity sources. Figure 4 below shows several photovoltaic (PV) technologies, including the two systems evaluated for this study, a single-axis tracker and a 12° fixed-tilt system.

For load frequency stability, Mudi et al. [33] explore isolated hybrid power systems (HPSs) with risk management of energy storage devices and renewable energy sources utilizing proper control methodologies. The PID controller gains were set using the MVO method. The test systems' dynamic performance was assessed under various operating conditions and situations. Mudi et al. [33] also suggest a hybrid energy storage system (HESS) using batteries and a hydrogen conversion system (HCS) to solve this problem. Thus, a single energy storage cannot generate a fully functional and reliable off-grid renewable energy (RE) system without a large generator and store capacity. Gupta et al. [34] studied a hybrid pumped and battery storage (HPBS) system to improve off-grid RE system sustainability and dependability. A HES with supercapacitors and batteries interfaced with most multi-input converters handles power changes from wind, sun, and unexpected load disruptions. Thus, Ravada et al. [35] introduced a revolutionary integrated converter construction that

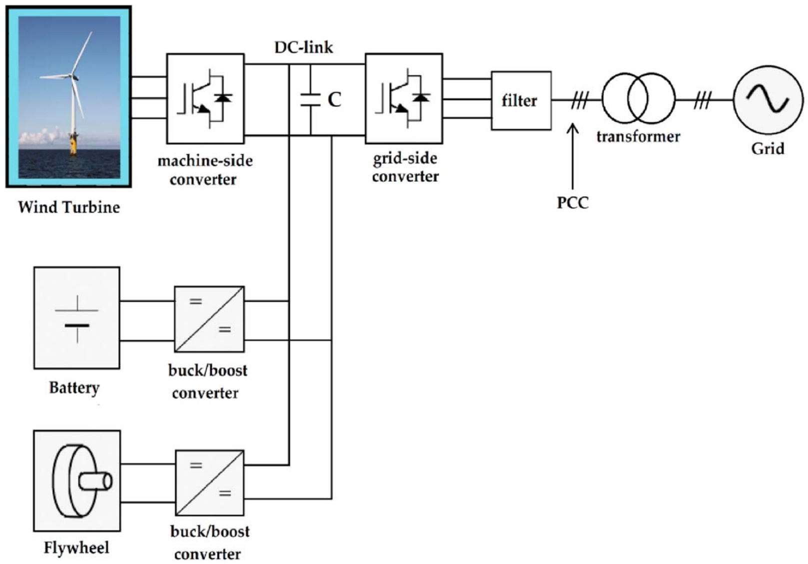

Figure 3. *Representation of wind power system integrated with the HESS [30].*

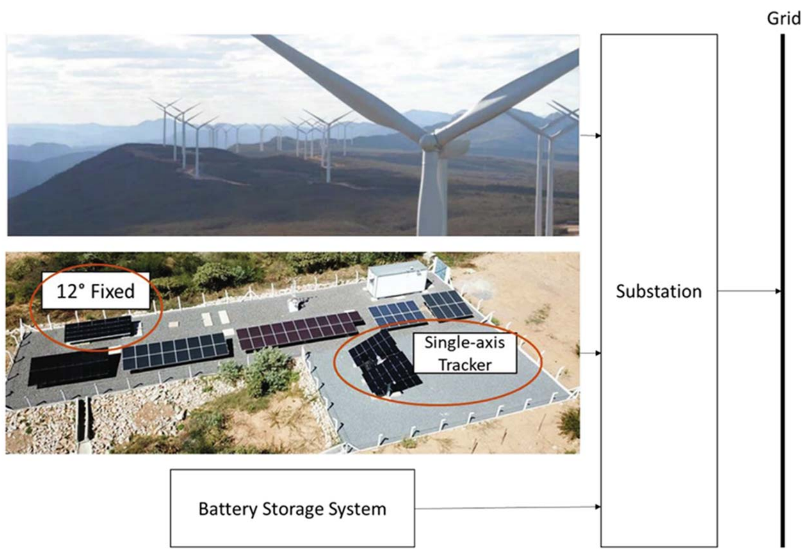

Figure 4. *Two PV systems (12° fixed tilt and single-axis tracker) are tested here amongst a variety of other PV technologies [32] (Adopted with permission from Elsevier BV. with License Number: 5718890894994)*

uses several energy sources and hybrid energy storage (HES) for DC microgrids. ESDs enable independent renewable microgrids to power their loads at all times [35]. In a HESS, many ESDs contribute their benefits. Unlike the FLC algorithm, the AFLC reduces the detrimental impacts of excessive or insufficient ESD usage. Javed et al. [36] studied solar energy and hydrogen storage devices in electrical networks to improve the hybrid energy storage system. Hydrogen fuel cells and batteries are examples. The hydrogen storage technology, which stores electricity as hydrogen, reduces this uncertainty. The proposed wind-solar-thermal energy storage system includes an electric heater, power block, heater exchanger, and thermal energy storage framework [37]. This work uses multi-objective particle swarm optimization to discover the optimal capacity, Pareto front, and decision-making approach. When transmission channel loss and energy cost are low, the best system goals for rebuilding a thermal power plant are to maximize utilization and to maximize communication routes.

Governments are aggressively seeking eco-friendly and cost-effective energy sources to meet demand and provide energy security. Al-Ghussain et al. [38] propose hybridizing renewable energy systems (RESs) and merging them with energy storage systems to improve RES dependability and reduce energy demand-generation mismatches. In this study, adding PHS and HFC to a PV/Wind hybrid systems increased the demand–supply ratio from 46.5% to 89.4% and the RES fraction from 62.6% to 91.8% at 0.175 USD/kWh. A demo feasibility study is used to provide a

Table 1. *Overview of the Solar-Wind Hybrid System and its storage of energy*

[Ref.]	Hardware/Components/ Software used	Microcontroller/ Algorithm used	Applications
[39]	Solar PV Battery Storage System Wind Turbine MATLAB	Genetic Algorithm	A GA-based new approach for designing hybrid energy systems that supply electrical power using a diesel engine, wind, solar PV, and battery storage systems.
[40]	PV Panel Wind Turbine Buck-Boost Converter	PID Controller	The dual input buck-boost converter will control energy from the wind turbine generator and solar module using the PID approach to charge the battery at 14 V.
[19]	PV System MATLAB	Hybrid Controller	Designed and simulated a hybrid wind-sun energy system. Solar panels and wind turbines generate green energy.
[41]	Battery-supercapacitor Wave Energy Converter Hybrid Energy Storage System	Buck-Boost converter	To combine a variety of renewable energies using the operational reserve established during installation.
[42]	MATLAB Supercapacitor	Conductance-fuzzy dual-mode control technique	This supercapacitor-hybrid energy system approach may increase energy storage and power production.
[29]	Supercapacitors	Hybrid energy storage system (HESS)	Dynamic wavelets smooth wind power. It uses dynamic wavelets and the hybrid energy storage system (HESS) to smooth wind power.
[32]	PV Panels using a single-axis tracker	Curtailment optimization	Research on the universality of solar and wind generation in the Brazilian North and how energy storage may reduce the limits imposed by the dependability of related natural resources.
[31]	Compressor	Hybrid energy supply system Adiabatic compressed air	Using photovoltaics, wind, and adiabatic compressed air to power a remote mobile base.
[43]	Ultra-capacitor Double-layer capacitor	Isolated hybrid power systems Load frequency control Optimization	Risk management may work for hybrid power systems with renewable energy and energy storage. This study examined standalone HPS modeling load–frequency stability with different ESD settings.

method for scaling RES components in a microgrid utilizing ESS in various configurations. Table 1 illustrates the overview of the Solar-Wind Hybrid System and its storage of energy.

4 APPLICATION, COMMERCIALIZATION AND ERECTION COST OF WIND-SOLAR HYBRID SYSTEMS

Modern families need clean grid electricity, so a numerical approach was developed to optimize wind-solar energy systems. The wind-solar hybrid system has many economic uses. Water energy, especially from rivers, may assist most rural areas. Seasonal changes are difficult. Hot, dry conditions hamper the system's energy and water flow. These energy sources could be used in power plants to generate electricity, solving the problem and expanding renewable energy potential. Iran's abundant solar and wind energy can be exploited during electricity shortages. Hoseinzadeh et al. [44] used Homer Software to simulate a power plant to find the most technically and economically advantageous hybrid to account for river flow and solar energy swings. The results show that energy shortage solutions need economic study first.

Rising energy demand, environmental consciousness, and energy market innovation make renewable energy technologies more desirable and significant in the global energy balance [45]. Recent advances in hybrid renewable energy systems suggest a shift toward distributed power production as a more stable and predictable energy source. This paper described microgrid HRES efficiency-boosting methods. Thus, Jaszczur et al. [46] propose using an optimization function in a non-dominated sorting genetic algorithm to find the ideal financial and environmental arrangement. This study linked two goals that HRES modeling can reasonably analyze costs and emissions.

To evaluate system performance and validate energy balance-based battery and energy management models, Liu et al. [47] tested a PV and battery storage combination to increase self-use and optimal utilization. TRNSYS with jEPlus + EA linked modeling and optimization. After considering renewable energy's benefits—lower carbon footprint, transmission loss, network development costs, etc.—the levelized cost of energy (LCOE) is calculated. Abdelsalam et al. [48] built a numerical model and tested two layouts: one with direct heat exchange and one with indirect heat exchange using submerged heat exchangers. The solar percentage, which measures solar thermal energy input to the load, gives a different perspective on the two systems.

The world is currently focused on greener energy sources for energy security and sustainable development. But massive urbanization has caused energy supply and demand mismatches. Thus, Kumar et al. [49] created diesel generator alternatives. This study examines the techno-economic feasibility of upgrading hybrid energy systems for urban distributed power production. Techno-economic feasibility studies must examine energy technology investments to maximize resource efficiency. Despite the intermittent nature of renewable energy resources, hybrid renewable

Figure 5. *Various barriers associated with HRES.*

energy systems provide the most consistent and reliable load supply [50]. The HOMER software mimics the load of a Tehran residential complex supplied by several off-grid hybrid RESs. NPC-based best-available power supply systems were introduced after significant research and computation. Top models were compared. The model without wind turbines has a lower NPC than the one with.

Liu et al. [25] examined the commercial environmental performance of hybrid photovoltaic-wind-battery-hydrogen systems for powering conventional high-rise housing complexes utilizing a strong multi-objective design optimization and parametric analysis technique. Figaj et al. [51] studied TRNSYS's dynamically simulated solar heating and cooling system for serially coupled thermal collectors and dish concentrators. Experiments verify dish concentrator configuration and solar collector. Using various configurations of solar energy collecting devices and thermally powered chillers, a smart house cooling and solar heating system was constructed and dynamically simulated.

These systems are used in many places. Rural and distant areas without reliable traditional energy benefit greatly from HRES. Modern urban infrastructure, especially green buildings, integrates HRES for sustainable energy. Island communities are switching from standard fossil fuels to renewable energy sources (HRES) to gain economic and environmental advantages. The energy-intensive industrial sector is using HRES for reliable power [52]. HRES is utilized by academic organizations for both energy and advanced research purposes. Tourism, especially eco-resorts, is using HRES to improve sustainability. HRES adoption is part of a global shift toward clean, flexible, and reliable energy [43].

Numerous key aspects have shaped HRES commercialization. Wind, solar, hydro, and biomass technologies have improved, making hybrid systems more effective. The substantial cost reductions in these technologies have made HRES more economically appealing. Tax incentives, grants, and government subsidies have promoted renewable energy options. The economic appeal of HRES has increased due to improved energy security and reliability from their combined sources. Renewable energy's promise spurs private sector investments in HRES research and deployment.

The costs associated with erecting a solar power facility vary and are influenced by various factors [53]. Understanding site circumstances and material and service market rates is essential for accurate financial forecasting [54]. Expect a higher investment for a larger facility with more energy output. Equipment costs are of utmost importance. Solar panels' efficiency and type—monocrystalline, polycrystalline, or thin-film—determine their price. However, wind turbine prices depend on design (horizontal or vertical), capacity, and tower height. Inverters, batteries, and controllers, which convert and store energy, cost money depending on quality and ability. Site-specific factors like geography can affect costs [55]. Flat ground is cheaper to prepare than mountainous or wooded areas. Ground-mounted systems may require piling, and rooftop systems can affect house prices. Integrating with the grid requires infrastructure and safety standards, which incur costs. Other project development expenditures include planning, design, environmental assessments, and expert advice. Utility-scale solar plants cost $1000 to $3000 per kW in 2021, while wind installations cost $1200 to $2500. Due to economies of scale, hybrid arrangements may save money on inverters and grid integrations.

5 BARRIERS IN HYBRID RENEWABLE ENERGY SYSTEMS

Hybrid Renewable Energy Systems (HRES) offer various benefits, but they encounter specific barriers that hinder their extensive use. There are various barriers that can be identified, which are illustrated in Figure 5.

Compared to conventional energy sources, hybrid renewable energy systems can be expensive, especially in homes [56]. Investing in sustainable energy alternatives may be more appealing to potential users due to the upfront cost. Integrating multiple energy sources into a system presents technological problems [57]. Hybrid systems must deal with intermittent and balance varied energy sources, requiring new control and management systems. Land and space constraints can also hinder HRES implementation. Individual renewable technologies like solar and wind may require a lot of land, but combining them can worsen geographical limits, especially in densely populated areas. HRES systems use components from several technologies, each with maintenance demands, causing dependability and maintenance concerns. One component's failure might impair system performance. In some locations, the lack of trained personnel in hybrid system design, installation, and maintenance can hinder their use. Some countries or regions need more supportive policies or incentives for HRES adoption, and bureaucratic hurdles may impede permitting and installation.

Many HRES use energy storage technologies like batteries to maintain energy supply, complicating matters. Current energy storage technologies may be expensive, short-lived, and insufficient for more extensive applications [58]. HRES integration with power grids may be complex since grids may need help handling renewable energy variability or significant changes to support hybrid systems. Economic barriers may arise when HRES is not cost-effective, especially when cheaper, subsidized, non-renewable energy sources are accessible [49]. Social and cultural preferences for traditional energy sources over hybrid systems can also prevent technology adoption. The manufacturing and disposal of components like solar panels and batteries may have environmental implications, causing stakeholder debate and dispute. Advancements in technology and a growing demand for sustainable energy sources are diminishing these restrictions [60]. Nevertheless, every location and country will encounter obstacles when implementing hybrid renewable energy systems.

6 SUMMARY, CONCLUSIONS, AND FUTURE SCOPE

Solar and wind power are intermittent and inconsistent, which could provide technological issues for weak networks or isolated systems without appropriate storage. Solar and wind integration can reduce system dependence and operational costs. This study examines the pros and cons of hybrid wind-solar energy systems. Voltage and frequency variations and harmonics affect both grid-connected and stand-alone installations, but a weak grid exacerbates them. Hybrid systems that are well-designed, optimized, and feature cutting-edge rapid response control may help. In-depth study on optimal size design, power electronics topologies, and control is summarized here. This review paper discusses solar-wind hybrid systems' energy storage and household usage. Solar-wind hybrid energy systems reduce monthly electricity costs in the most economical way. They provide clean, renewable, non-polluting electricity and avoid the exorbitant expenditures of bringing grid power lines to remote areas. This article provides energy analysts and specialists with recommendations for installing a solar-wind irrigation system for irrigation water. MPPT controllers track wind energy conversion system peak power production. Hill-climb search, power signal feedback control, and tip speed ratio are wind energy MPPT processor subfields to optimize energy output, monitor solar radiation and alter photovoltaic panel orientation. Maximum Power Point Trackin g is a clever automated system like IoT devices that tracks the module without moving it.

AUTHOR CONTRIBUTIONS

Manzoore Elahi M. Soudagar (Conceptualization, Data curation , Resources , S. Ramesh (Funding acquisition , Investigation , T. M. Yunus Khan (Conceptualization , Data curation), Naif Almakayeel (Conceptualization , Data curation), R. Ramesh (Conceptualization , Investigation , Methodology), Nik Nazri Nik Ghazali (Conceptualization , Data curation , Investigation), Erdem Cuce (Conceptualization , Data curation , Formal analysis), and Sagar Shelare (Conceptualization , Methodology , Writing—original draft , Writing—review & editing).

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REFERENCES

[1] Khan FA, Pal N, Saeed SH. Optimization and sizing of SPV/wind hybrid renewable energy system: a techno-economic and social perspective. *Energy* 2021;**233**:121114.
[2] Khan FA, Pal N, Saeed SH. *et al.* Techno-economic and feasibility assessment of standalone solar photovoltaic/wind hybrid energy system for various storage techniques and different rural locations in India. *Energy Convers Manag* 2022;**270**:116217.
[3] Baddadi S, Skouri S, Ayed R. *et al.* Performance investigation of an innovative solar heating unit for a powered self-sustained solar dryer. *Appl Therm Eng* 2023;**233**:121173.
[4] Gorjian A, Rahmati E, Gorjian S. *et al.* A comprehensive study of research and development in concentrating solar cookers (CSCs): design considerations, recent advancements, and economics. *Sol Energy* 2022a;**245**:80–107.
[5] Jathar LD, Ganesan S. Assessing the performance of concave type stepped solar still with nanoparticles and condensing cover cooling arrangement: an experimental approach. *Groundw Sustain Dev* 2021;**12**:100539.
[6] Al-Turjman F, Qadir Z, Abujubbeh M. *et al.* Feasibility analysis of solar photovoltaic-wind hybrid energy system for household applications. *Comput Electr Eng* 2020;**86**:106743.
[7] Gorjian S, Hosseingholilou B, Jathar LD. *et al.* Recent advancements in technical design and thermal performance enhancement of solar greenhouse dryers. *Sustainability* 2021;**13**:7025.
[8] Suresh M, Meenakumari R. An improved genetic algorithm-based optimal sizing of solar photovoltaic/wind turbine generator/diesel generator/battery connected hybrid energy systems for standalone applications. *International Journal of Ambient Energy* 2021;**42**:1136–43.
[9] Barelli L, Ciupageanu DA, Ottaviano A. *et al.* Stochastic power management strategy for hybrid energy storage systems to enhance large scale wind energy integration. *Journal of Energy Storage* 2020;**31**:101650.
[10] Jathar LD, Ganesan S. Assessing the performance of concave type stepped solar still with brick, sand, and concrete pieces. *International Journal of Ambient Energy* 2022a;**43**:3468–84.
[11] Eslami E, Ahmadi KM. Optimal design of solar–wind hybrid system-connected to the network with cost-saving approach and improved network reliability index. *SN Applied Sciences* 2019;**1**:1–12.

[12] Tawfik M, Shehata AS, Hassan AA. *et al.* Renewable solar and wind energies on buildings for green ports in Egypt. *Environ Sci Pollut Res* 2023;**30**:47602–29.

[13] Kiehbadroudinezhad M, Merabet A, Rajabipour A. *et al.* Optimization of wind/solar energy microgrid by division algorithm considering human health and environmental impacts for power-water cogeneration. *Energy Convers Manag* 2022;**252**:115064.

[14] Chandrakant NK, Jathar L, Shelare SD. *et al.* Parametric analysis and optimization of 660 MW supercritical power plant. *Energy* 2023;**280**:128165.

[15] Hou H, Xu T, Wu X. *et al.* Optimal capacity configuration of the windphotovoltaic-storage hybrid power system based on gravity energy storage system. *Appl Energy* 2020;**271**:115052.

[16] Jaszczur M, Hassan Q, Palej P. *et al.* Multi-objective optimisation of a micro-grid hybrid power system for household application. *Energy* 2020;**202**:117738.

[17] Hybrid Wind and Solar Electric Systems. (22 C.E.). https://www.energy.gov/energysaver/hybrid-wind-and-solar-electric-systems

[18] Setiawan B, Putra ES, Siradjuddin I. *et al.* Optimisation solar and wind hybrid energy for model catamaran ship. *IOP Conference Series: Materials Science and Engineering* 2021;**1073**:012044.

[19] Abd Ali LM, Al-Rufaee FM, Kuvshinov VV. *et al.* Study of hybrid wind–solar systems for the Iraq Energy Complex. *Applied Solar Energy (English Translation of Geliotekhnika)* 2020;**56**:284–90.

[20] Talaat M, Elkholy MH, Farahat MA. Operating reserve investigation for the integration of wave, solar and wind energies. *Energy* 2020;**197**:117207.

[21] Zhu R, Zhao AL, Wang GC. *et al.* An energy storage performance improvement model for grid-connected wind-solar hybrid energy storage system. *Computational Intelligence and Neuroscience* 2020;**2020**:1–10.

[22] Agyekum EB, Nutakor C. Feasibility study and economic analysis of stand-alone hybrid energy system for southern Ghana. *Sustainable Energy Technologies and Assessments* 2020;**39**:100695.

[23] Bouchekara HREH, Sha'aban YA, Shahriar MS. *et al.* Sizing of hybrid PV/battery/wind/diesel microgrid system using an improved decomposition multi-objective evolutionary algorithm considering uncertainties and battery degradation. *Sustainability* 2023;**15**:11073.

[24] Xu X, Hu W, Cao D. *et al.* Optimized sizing of a standalone PV-wind-hydropower station with pumped-storage installation hybrid energy system. *Renew Energy* 2020;**147**:1418–31.

[25] Liu J, Cao S, Chen X. *et al.* Energy planning of renewable applications in high-rise residential buildings integrating battery and hydrogen vehicle storage. *Appl Energy* 2021;**281**:116038.

[26] Jamshidi S, Pourhossein K, Asadi M. Size estimation of wind/solar hybrid renewable energy systems without detailed wind and irradiation data: a feasibility study. *Energy Convers Manag* 2021;**234**:113905.

[27] Naeem A, Ul Hassan N, Arshad N. Design of Solar-Wind Hybrid Power System by using Solar-Wind Complementarity. *Proceedings of 2020 4th International Conference on Green Energy and Applications, ICGEA 2020* 2020;100–5.

[28] Barelli L, Bidini G, Ciupageanu DA. *et al.* Integrating hybrid energy storage system on a wind generator to enhance grid safety and stability: a Levelized cost of electricity analysis. *Journal of Energy Storage* 2021a;**34**:102050.

[29] Guo S, He Y, Pei H. *et al.* The multi-objective capacity optimization of wind-photovoltaic-thermal energy storage hybrid power system with electric heater. *Sol Energy* 2020;**195**:138–49.

[30] Barelli L, Pelosi D, Ciupageanu DA. *et al.* HESS in a wind turbine generator: assessment of electric performances at point of common coupling with the grid. *In Journal of Marine Science and Engineering* 2021;**9**.

[31] Zhao P, Xu W, Zhang S. *et al.* Technical feasibility assessment of a standalone photovoltaic/wind/adiabatic compressed air energy storage based hybrid energy supply system for rural mobile base station. *Energy Convers Manag* 2020;**206**:112486.

[32] Antunes CR, Rafael do Nascimento L, Rüther R. The complementary nature between wind and photovoltaic generation in Brazil and the role of energy storage in utility-scale hybrid power plants. *Energy Convers Manag* 2020;**221**:113160.

[33] Mudi J, Shiva CK, Vedik B. *et al.* Frequency stabilization of solar thermalphotovoltaic hybrid renewable power generation using energy storage devices. *Iranian Journal of Science and Technology - Transactions of Electrical Engineering* 2021;**45**:597–617.

[34] Gupta A, Kumar R, Maurya A. *et al.* A comparative study of the impact on combustion and emission characteristics of nanoparticle-based fuel additives in the internal combustion engine. *Energy Sci Eng.* 2024;**12**:284–303.

[35] Ravada BR, Tummuru NR, Ande BNL. Photovoltaic-wind and hybrid energy storage integrated multi-source converter configuration for DC microgrid applications. *IEEE Transactions on Sustainable Energy* 2021;**12**:83–91.

[36] Javed MS, Zhong D, Ma T. *et al.* Hybrid pumped hydro and battery storage for renewable energy based power supply system. *Appl Energy* 2020;**257**:114026.

[37] Galbally J, Marcel S, Fierrez J. Biometric antispoofing methods: a survey in face recognition. *IEEE Access* 2014;**2**:1530–52.

[38] Al-Ghussain L, Samu R, Taylan O. *et al.* Sizing renewable energy systems with energy storage systems in microgrids for maximum cost-efficient utilization of renewable energy resources. *Sustain Cities Soc* 2020;**55**:102059.

[39] Suresh M, Meenakumari R. An improved genetic algorithm-based optimal sizing of solar photovoltaic/wind turbine generator/diesel generator/battery connected hybrid energy systems for standalone applications. *International Journal of Ambient Energy* 2021;**42**:1136–43.

[40] Setiawan B, Putra ES, Siradjuddin I. *et al.* Optimisation solar and wind hybrid energy for model catamaran ship. *IOP Conference Series: Materials Science and Engineering* 2021;**1073**:012044.

[41] Talaat M, Elkholy MH, Farahat MA. Operating reserve investigation for the integration of wave, solar and wind energies. *Energy* 2020;**197**:117207.

[42] Barelli L, Ciupageanu DA, Ottaviano A. *et al.* Stochastic power management strategy for hybrid energy storage systems to enhance large scale wind energy integration. *Journal of Energy Storage* 2020;**31**:101650.

[43] Gorjian S, Ahmed M, Fakhraei O. *et al.* 2022). Chapter 8. Solar desalination technology to supply water for agricultural applications. In Gorjian S, Campana PE (eds). *Solar Energy Advancements in Agriculture and Food Production Systems*. Academic Press. 271–311.

[44] Hoseinzadeh S, Ghasemi MH, Heyns S. Application of hybrid systems in solution of low power generation at hot seasons for micro hydro systems. *Renew Energy* 2020;**160**:323–32.

[45] Shelare SD, Aglawe KR, Matey MS. *et al.* Preparation, applications, challenges and future prospects of nanofluid materials with a solar systems in the last decade. *Materials Today: Proceedings* 2023a. https://doi.org/10.1016/j.matpr.2023.06.160.

[46] Jaszczur M, Hassan Q, Palej P. *et al.* Multi-objective optimisation of a micro-grid hybrid power system for household application. *Energy* 2020;**202**:117738.

[47] Liu J, Wang M, Peng J. *et al.* Techno-economic design optimization of hybrid renewable energy applications for high-rise residential buildings. *Energy Convers Manag* 2020;**213**:112868.

[48] Abdelsalam MY, Teamah HM, Lightstone MF. *et al.* Hybrid thermal energy storage with phase change materials for solar domestic hot water applications: direct versus indirect heat exchange systems. *Renew Energy* 2020;**147**:77–88.

[49] Kumar D, Tewary T. Techno-economic assessment and optimization of a standalone residential hybrid energy system for sustainable energy utilization. *Int J Energy Res* 2022;**46**:10020–39.

[50] Abbaszadeh MA, Ghourichaei MJ, Mohammadkhani F. Thermoeconomic feasibility of a hybrid wind turbine/PV/gas generator energy system for application in a residential complex in Tehran, Iran. *Environmental Progress and Sustainable Energy* 2020;**39**:1–12.

[51] Figaj R, Zoładek M. Experimental and numerical analysis of hybrid solar heating and cooling system for a residential user. *Renew Energy* 2021;**172**:955–67.

[52] Jathar LD, Ganesan S, Palanimuthu L. Performance assessment of concavetype stepped desalination unit with nanoparticles and varying water

depth: an experimental approach. *International Journal of Ambient Energy* 2022;**43**:5041–54.
[53] Jathar LD, Ganesan S, Shahapurkar K. *et al.* Comprehensive review on the prediction of thermal behavior of solar stills with diverse designs. *AIP Conference Proceedings* 2020;**2247**:30004.
[54] Gajbhiye TS, Waghmare SN, Sirsat PM. *et al.* Role of nanomaterials on solar desalination systems: a review. *Materials Today: Proceedings* 2023b. https://doi.org/10.1016/j.matpr.2023.04.532.
[55] Shelare S, Kumar R, Gajbhiye T. *et al.* Role of geothermal energy in sustainable water desalination—a review on current status, parameters, and challenges. *Energies* 2023c;**16**:2901.
[56] Jathar LD, Ganesan S. Statistical analysis of brick, sand and concrete pieces on the performance of concave type stepped solar still. *International Journal of Ambient Energy* 2022b;**43**:3727–43.
[57] Gajbhiye TS, Nikam KC, Kaliappan S. *et al.* Sustainable renewable energy sources and solar mounting systems for PV panels: a critical review. *AIP Conference Proceedings* 2023a;**2800**:020066.
[58] Jathar LD, Ganesan S, Gorjian S. An experimental and statistical investigation of concave-type stepped solar still with diverse climatic parameters. *Cleaner Engineering and Technology* 2021;**4**:100137.
[59] Shelare SD, Belkhode PN, Nikam KC. *et al.* Biofuels for a sustainable future: examining the role of nano-additives, economics, policy, internet of things, artificial intelligence and machine learning technology in biodiesel production. *Energy* 2023b;**282**:128874.
[60] Gajbhiye T, Shelare S, Aglawe K. Current and future challenges of nanomaterials in solar energy desalination Systems in Last Decade. *Transdisciplinary Journal of Engineering & Science* 2022;**13**: 187–201.