A Comprehensive Survey on Hybrid Renewable–VSDG Power Systems for Remote Electrification

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ABSTRACT

This paper presents a comprehensive review of hybrid renewable–diesel power systems for remote electrification and sustainable energy generation. The rapid increase in global energy demand and environmental concerns associated with fossil fuel-based electricity generation have accelerated the development of renewable energy technologies such as solar photovoltaic (PV), wind energy, and hybrid power systems. Hybrid renewable-diesel systems combine renewable sources, diesel generators, energy storage systems, and advanced power management strategies to ensure reliable and cost-effective electricity supply in remote and off-grid regions. This paper reviews system configurations, hybrid combinations, constant and variable speed diesel generator technologies, energy storage systems, and intelligent power management strategies. Detailed hybrid configurations such as PV–diesel, PV–wind–diesel, and PV–VSDG–Li-ion systems are discussed with figures. Research gaps including limited work on variable speed diesel generators, optimized power management systems, and battery-less hybrid systems are identified. The survey concludes with future research directions for sustainable rural electrification.

Keywords: Hybrid Power System, Solar PV, Diesel Generator, Variable Speed Diesel Generator, Lithium-ion Battery, Remote Electrification, Renewable Energy

1. INTRODUCTION

Energy or power has been one of the most widely used and essential concepts throughout human history, playing a crucial role in social and economic development. Over the past few decades, the demand for electrical energy has increased significantly due to rapid growth in commercial, industrial, and domestic activities. Since the Industrial Revolution in the late 18th century, human progress has been closely linked to the availability and use of energy resources. Modern societies depend heavily on energy to sustain economic growth, improve living standards, and support technological advancements. Many countries, including India, rely extensively on fossil fuels such as coal, oil, and natural gas for electricity generation. To meet the growing demand for power, large-scale fossil fuel-based power plants have been established, particularly in developing nations where industrialization and urbanization are expanding rapidly [1], [2].

In remote and rural areas with low population density and limited access to national power grids, diesel-based mini-grids are often used as the primary source of electricity [3][4]. Diesel generators are widely adopted because they are relatively affordable, easy to install, and readily available in the market. As a result, many rural communities depend on privately owned diesel generators to supply electricity for households, small businesses, and community services. These generators provide a reliable solution in areas where grid extension is difficult or economically unfeasible [5-8]. However, this heavy dependence on fossil fuels for energy generation has raised serious concerns about sustainability, environmental degradation, and long-term energy security.

The continuous increase in global energy consumption and extensive use of fossil fuels have accelerated the depletion of natural resources and caused severe environmental impacts. Every stage of fossil fuel utilization, including exploration, extraction, processing, transportation, and combustion, poses significant risks to both human health and the environment. The combustion of fossil fuels releases harmful and toxic gases such as carbon dioxide, sulfur dioxide, nitrogen oxides, and particulate matter into the atmosphere. These emissions contribute to air pollution, global warming, and climate change, which threaten ecosystems, biodiversity, and human well-being. Greenhouse gas emissions from fossil fuel-based energy production are widely recognized as a major driver of global climate change, making the transition to cleaner energy sources increasingly urgent [9].

According to the International Energy Agency's (IEA) Medium-Term Oil Market Report 2022, global oil demand growth is expected to slow by the end of this decade due to increasing environmental awareness, rising oil prices, and the availability of cost-effective alternative energy sources. Although the IEA has projected an increase in global oil demand by approximately 960,000 barrels per day, the overall growth trend is expected to weaken over time. The report also highlights that strong supply, particularly from North America's ongoing oil production expansion, may push the global oil market toward an inflection point [10]. After this point, oil demand growth is likely to decelerate due to environmental concerns, economic pressures, and the gradual shift toward renewable and sustainable energy technologies. This transition reflects the growing global commitment to reducing fossil fuel dependence and promoting cleaner, more sustainable energy systems for future development.

2. LITERATURE REVIEW

Many researchers and environmentalists agree that fossil fuel–based electricity generation must be reduced to address climate change and lower carbon dioxide emissions. The depletion of fossil fuel resources is another major environmental concern. However, only a few recognize that existing fossil fuel power generation systems can be upgraded with modern technologies at relatively low additional costs to reduce fuel consumption and emissions [11][12]. Since traditional power plants have been operating for many decades, replacing them completely with modern systems will take a long time. During this transition period, advanced technologies such as high-efficiency and variable speed diesel generators can significantly reduce fuel consumption compared to conventional constant-speed generators, thereby improving overall efficiency [13][14].

In several developed countries, local authorities have the flexibility to adopt alternative and environmentally friendly energy generation systems to meet increasing electricity demand. Among advanced fossil fuel technologies, nuclear power has gained considerable attention because of its low carbon emissions during electricity production. However, major nuclear accidents such as Three Mile Island (1979), Chernobyl (1986), and Fukushima (2011) have raised serious concerns regarding the safety and reliability of nuclear power plants for commercial use.

According to BP's Energy Outlook (2014), global energy demand is expected to increase significantly due to rapid economic growth in emerging economies. BP projected that energy demand would grow by approximately 36% between 2011 and 2030. Without continuous improvements in energy efficiency, electricity supply would need to expand at a much faster rate to sustain economic development. The report also highlights the importance of innovation and efficiency in energy production, including the exploration of unconventional oil and gas resources and the reduction of carbon emissions. The overall conclusion is that future energy demand can be met through technological advancements and the development of renewable energy systems with minimal greenhouse gas emissions [15].

Scientific studies indicate that atmospheric carbon dioxide levels exceeded 400 parts per million (ppm) by 2020, which is the highest level recorded in millions of years. Researchers believe that greenhouse gas emissions are a major cause of climate change and rising sea levels, emphasizing the urgent need for effective solutions to this global problem. Considering the advantages and limitations of different energy generation methods, renewable energy systems are often integrated with conventional power sources to form hybrid power systems [16][17]. These systems can be connected to the grid or operated in off-grid mode with diesel generators and energy storage systems controlled by supervisory controllers. The most practical approach to reducing greenhouse gas emissions is to combine renewable energy with conventional generation systems. From a reliability perspective, many studies recommend hybrid systems that integrate renewable energy sources with fossil fuel generators to ensure stable and efficient power supply.

Since ancient times, the Sun has been regarded as the primary source of life on Earth, and with industrial development, solar has become recognized as a major source of energy. Global solar irradiation maps provided by the International Renewable Energy Agency (2021) highlight regions with high solar insolation, indicating areas where photovoltaic (PV) power generation can be most effective. Modern technologies enable solar energy to be harnessed even in cloudy conditions, making it widely used for electricity generation, heating, and water desalination. Solar power is mainly generated through two technologies: photovoltaic (PV) systems, which convert sunlight directly into electricity, and concentrated solar power (CSP), which uses mirrors to produce steam for turbine-driven electricity generation [18][19]. Developed in 1954, PV technology has become one of the fastest-growing renewable energy sources. Solar PV systems can be integrated with diesel generators for commercial or mini-grid applications, particularly in developing countries like India. Falling costs, long lifespans, and scalability make solar energy a key solution for sustainable power generation.

3. HYBRID POWER SYSTEM CONFIGURATIONS

3.1 Series connected hybrid system configuration

Rapid advancements in green technologies have enabled renewable energy generators to harness natural resources with improved efficiency and flexibility. Although modern renewable generators and power conversion units enhance energy harvesting, the actual energy delivered to consumers depends largely on the energy flow path and component arrangement within a hybrid power system. A typical hybrid system may include diesel generators, photovoltaic (PV) systems, wind turbines, and battery storage, which can be interconnected in different ways [20]. These configurations are generally classified into series and parallel arrangements, as discussed in previous studies.

In a series configuration, also known as a DC-coupled system, all components are connected through a DC bus. The inverter and battery bank must be sized to meet peak load demand, as power from both PV and diesel generators passes through the battery before reaching the load. Frequent battery usage reduces battery lifespan and lowers overall system efficiency due to repeated energy cycling, making this configuration less efficient in long-term operation.

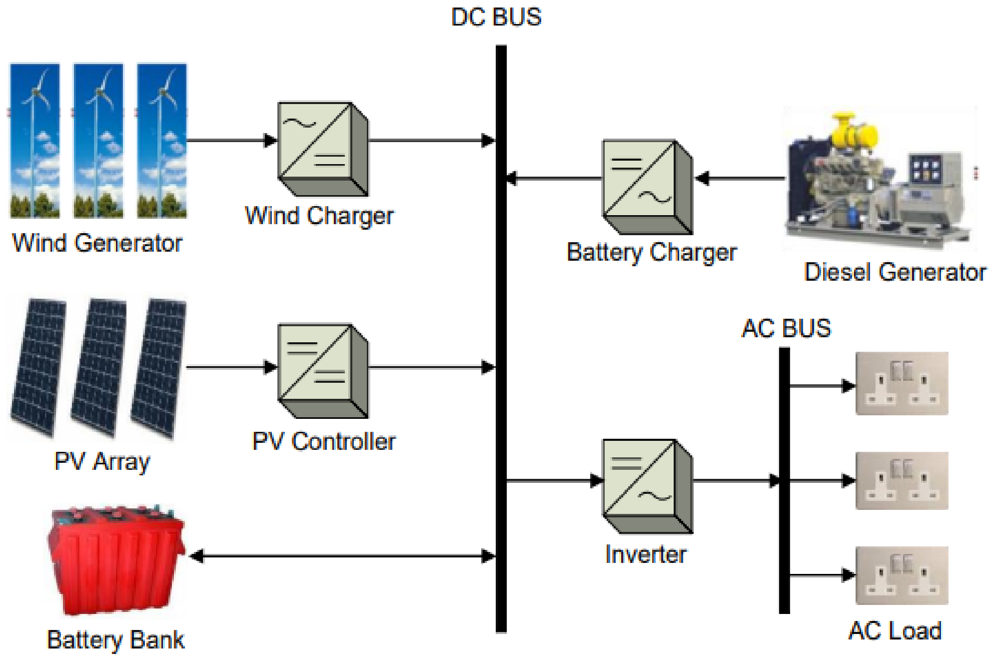

Fig1: Series hybrid energy configuration

3.2 Parallel connected hybrid power system configuration

The parallel configuration is suitable for DC, AC, or mixed bus hybrid power system designs, as discussed in earlier studies shown Fig2. This configuration allows different energy sources to be connected so that generators can directly supply load demand. Unlike the series configuration, renewable energy sources and diesel generators in a parallel system can deliver power directly to AC or DC loads without passing through the battery, improving overall efficiency. Excess energy produced is stored in the battery for peak shaving, which helps supply additional power during high-demand periods, such as evening peak loads. In terms of controllability, the parallel configuration offers greater flexibility, allowing advanced control strategies to efficiently dispatch and manage different energy sources. Because of its operational flexibility, direct power supply capability, and efficient control of dispatchable components, the AC-coupled parallel hybrid power system is selected for detailed analysis and discussion in this thesis.

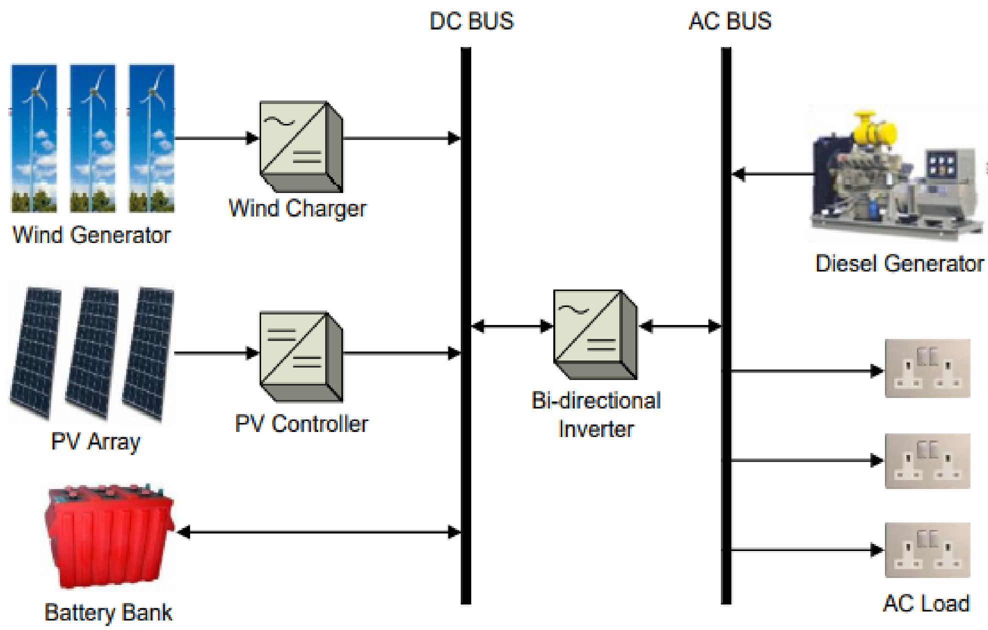

Fig2: Parallel hybrid energy configuration

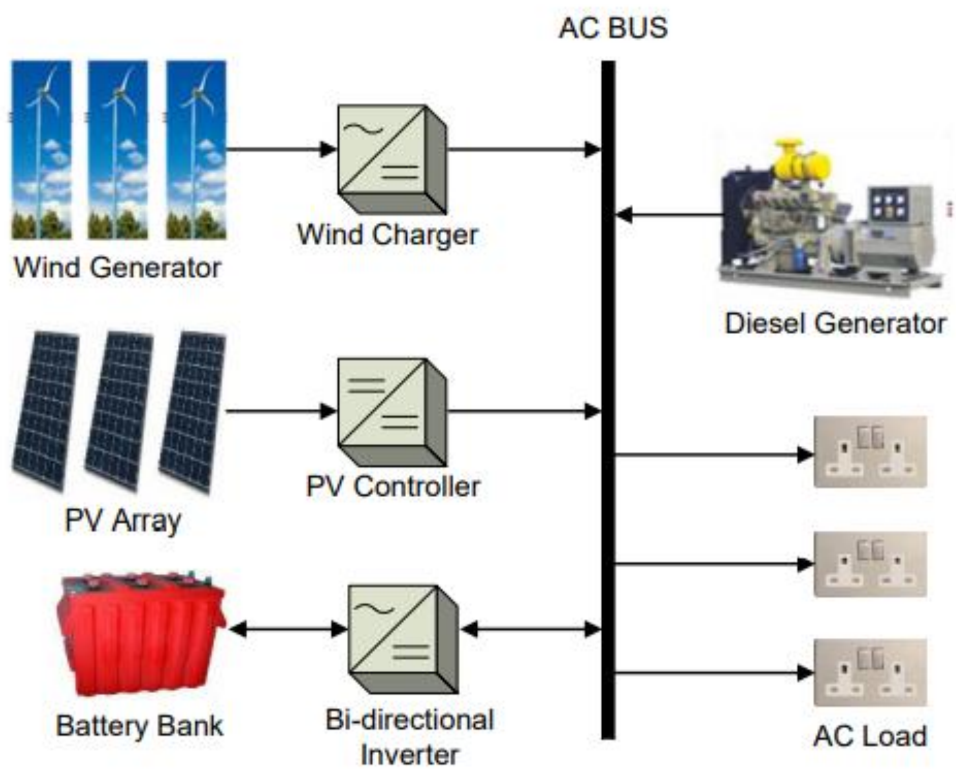

Fig3: Hybrid energy system connected to an AC bus

4. CONSTANT SPEED DIESEL GENERATOR (CSDG) AND VARIABLE SPEED DIESEL GENERATOR (VSDG)

From the previously discussed hybrid system configurations, fossil fuel–based diesel generators, typically constant speed diesel generators (CSDGs), are often required to operate alongside renewable energy sources to ensure a reliable power supply to consumers. Despite their widespread use, CSDGs have several operational limitations. Traditionally, a CSDG is designed and sized to meet peak load demand, which usually occurs only for a short duration during daily operation [21]. As the name suggests, a CSDG operates at a constant rated speed regardless of load variations and is generally recommended to run above a minimum load level of 30–50% of its rated capacity. Manufacturers suggest this operating range to avoid engine-related issues such as hydrocarbon buildup, glazed piston rings, and cylinder wall damage caused by prolonged low-load operation. Continuous operation at low load and constant speed can result in inefficient fuel combustion, premature engine aging, and reduced system flexibility, making CSDGs less suitable for modern hybrid power systems.

To address these limitations, the development of variable speed diesel generators (VSDGs) has gained significant attention in recent years. VSDGs are designed to automatically adjust engine speed according to power demand, making them suitable for both standalone and hybrid energy systems [22][23]. Typically, a VSDG employs a doubly fed induction generator driven by an internal combustion engine, allowing flexible and efficient operation under varying load conditions. This technology helps mitigate the issues associated with CSDGs, particularly under light load conditions, where VSDGs maintain satisfactory performance and efficiency.

Several studies have compared CSDGs and VSDGs in terms of performance and economic benefits [24]. Research by Pena et al. (2008) and Nayar (2008) [25] highlights the advantages of variable speed engine operation in overcoming the operational constraints of constant speed systems. Unlike CSDGs, which must operate above 40% of rated power, VSDGs can function efficiently over a wide operating range, allowing optimal power extraction and improved system performance under low-load conditions.

A key advantage of VSDGs is their ability to operate at optimal engine speed depending on load demand, leading to higher fuel efficiency and reduced operational costs (Regen Power Pvt. Ltd., 2010) [26][27]. The engine operates at lower speeds during low power demand and increases speed when higher power is required, ensuring efficient fuel consumption. This flexibility also enhances the integration of renewable energy sources in hybrid systems by allowing better coordination between diesel generators and renewable power generation.

Furthermore, VSDGs reduce the negative effects associated with low-load operation in CSDGs and can extend engine lifespan by operating at lower speeds during reduced load conditions. Overall, variable speed diesel generators provide improved fuel efficiency, operational flexibility, enhanced renewable energy utilization, and longer engine life, making them a more suitable alternative to conventional constant speed diesel generators in modern hybrid power systems.

5. ENERGY STORAGE SYSTEMS

Most hybrid power systems discussed in the literature rely on large energy storage units to store excess renewable energy and meet peak load demand. Although various hybrid system structures and operational strategies have been explored, the high initial cost of large battery banks makes such systems less suitable for small and medium-scale remote applications. The total installation cost increases due to battery housing, auxiliary components, transportation, and installation, and becomes even higher with greater renewable energy penetration. Batteries are also the most sensitive components in hybrid systems, requiring continuous monitoring of state of charge (SoC) to avoid overcharging or deep discharging [28]. Their relatively short lifespan, typically five to ten years, and the lack of proper recycling and disposal facilities in many developing countries add further challenges.

Energy storage systems are often integrated with diesel generators to manage load variations and reduce transient effects. However, conventional charging strategies may lead to energy overflow and losses due to inefficient charging and discharging processes. Among available battery technologies, lithium-ion batteries are increasingly preferred because of their high energy density, longer lifespan, flexibility, and lower operational costs, making them more suitable for hybrid solar, wind, and diesel generator systems.

6. POWER MANAGEMENT STRATEGIES

Power management strategy plays a crucial role in ensuring satisfactory performance of hybrid power systems, particularly in remote area applications, as it directly affects fuel consumption and diesel generator lifespan. Simple and robust hybrid systems that combine renewable energy generators with diesel generators, without complex control or large energy storage systems, are often considered more practical for remote electrification. Systems with high renewable energy penetration usually require large battery banks and complex control mechanisms, which increase cost and operational difficulty. Therefore, several studies have proposed hybrid systems without energy storage elements, demonstrating their feasibility through wind–diesel and renewable–diesel retrofit systems [29][30].

Hybrid power system control strategies are generally classified into dynamic strategies, which maintain voltage and frequency stability, and dispatch strategies, which manage power flow and system balance. Various optimisation and intelligent control methods, including genetic algorithms, fuzzy logic, and neural networks, have been developed to improve fuel efficiency and system performance. However, most existing research focuses on conventional constant speed diesel generators, with limited studies on variable speed diesel generators (VSDGs).

This research addresses this gap by proposing off-grid PV–VSDG hybrid configurations for rural electrification, offering flexible control, reduced fuel consumption, minimal power electronics, and improved reliability while avoiding the complexity of multi-renewable systems.

7. CONCLUSION

A reliable and cost-effective power supply is essential for remote hamlets to meet basic energy requirements such as electricity, water supply, and communication services. Traditionally, constant speed diesel generators (CSDGs) have been used to provide dependable power for small lighting loads and communication towers in such areas. However, the rapid development of photovoltaic (PV) and other renewable energy technologies has transformed the global power sector. In India, several regions with high solar irradiation and wind potential have been identified, leading to increased research focus on solar- and wind-based renewable energy systems. The advancement of power electronic technologies has enabled hybrid systems that combine renewable energy sources with diesel generators, using both AC and DC bus configurations reported in various studies. To enhance system reliability, energy storage systems are often integrated, but this increases circuit complexity and overall cost. Additionally, conventional CSDGs suffer from low efficiency at part-load operation, making them uneconomical for community power supply where load demand varies throughout the day. In this context, variable speed diesel generators (VSDGs) offer a suitable alternative, as they can operate efficiently under varying load conditions.

Integrating PV systems with VSDGs further improves energy efficiency, reduces fuel consumption, and lowers carbon emissions. Advanced power electronic converters enable variable voltage and frequency generation to be converted into stable grid-compatible power. However, incorporating multiple renewable energy sources into hybrid systems increases the complexity of power management and control. Although some studies report improved efficiency in hybrid systems without battery cycling, detailed parametric analysis of VSDGs and effective power flow management algorithms remain limited in the literature. Furthermore, the integration of lithium-ion batteries with VSDGs presents a promising alternative to conventional lead-acid battery and CSDG systems due to higher efficiency and longer lifespan. Therefore, the development of effective power management and control strategies for PV–VSDG and VSDG–lithium-ion battery hybrid systems for remote hamlet electrification represents a significant research gap and a potential solution for reliable and sustainable power supply.

References

[1] Arriaga, Mariano & Canizares, Claudio & Kazerani, Mehrdad; “Renewable Energy Alternatives for Remote Communities in Northern Ontario, Canada”, *Sustainable Energy, IEEE Transactions*, 8, 661-670,2013

https://doi.org/10.1109/TSTE.2012.2234154

[2] Dominic Fong; “Sustainable Energy Solutions for Rural Areas and Application for Groundwater Extraction”. *Global Energy Network Institute (GENI),* 2014

Available: http://www.geni.org/

[3] Miriam Madziga , Abdulla Rahil, Riyadh Mansoor; “Comparison between Three Off-Grid Hybrid Systems (Solar Photovoltaic, Diesel Generator and Battery Storage System) for Electrification for Gwakwani Village, South Africa” *Int. Journal of Environments*,7, 1-21,2018

https://doi.org/10.3390/environments5050057

[4] Qolipour, M.; Mostafaeipour, A, Tousi, M.O; “Techno-economic Feasibility of a Photovoltaic-Wind power plant construction for electric and hydrogen production: A Case Study” *Renew. Sustain. Energy* Rev.1, 113–123, 2017.

https://doi.org/10.1016/j.rser.2017.04.088

[5] Hope, G.; Gilding, P.; Alvarez, J; “Quantifying the Implicit Climate Subsidy Received by Leading Fossil Fuel Companies; Working Paper No. 2” *Cambridge Judge Business School*: Cambridge, UK, 2015.

[4] Birudula Anil Kumar ; Raghu Selvaraj ; Thanga Raj Chelliah ; U. S. Ramesh; “Improved Fuel-Use Efficiency in Diesel-Electric Tugboats With an Asynchronous Power Generating Unit” *IEEE Transactions on Transportation Electrification*, 5, 565 – 578, 2018.

https://doi.org/10.1109/TTE.2019.2906587

[6] Tajuddin Waris, C.V.Nayar; “Variable Speed Constant Frequency Diesel Power Conversion System Using Doubly Fed Induction Generator (DFIG)” *IEEE Power Electronics Specialists Conference*, 8, 2728- 2734, 2010.

https://doi.org/10.1109/PESC.2008.4592357

[7] Srishti Singh, Prerna Gaur, Madhur Kapoor, Sankalp Goel, Satinderpal Singh and Sonali

Negi, “Design and implementation of a prototype hybrid micro grid model for available weather conditions” *Int. J. Renewable Energy Technology*. 10. 93-117,2019. https://doi.org/10.1504/IJRET.2019.10017694

[8] Lim, P. and Nayar, C; “Modelling and Simulation of Photovoltaic-Variable Speed Diesel Generator Hybrid Power System for Off-Grid Rural Electrification” *International Journal of Energy Science*. 2, 5-14, 2020. http://www.ijesci.org/paperInfo.aspx?ID=5967#Abstract

[9] P.Y. Lim and C. V Nayar, “Control of Photovoltaic -Variable Speed Diesel Generator battery -less hybrid energy system for remote area applications” *Energy Conference and Exhibition, 2010 IEEE International,* 7, 223 -227,2010. https://doi.org/10.1109/ENERGYCON.2010.5771736

[10] Yoshio Nishi; “The Development of Lithium Ion Secondary Batteries*” The Japan Chemical Journal Forum and John Wiley & Sons*. 11, 406–413, 2001 https://doi.org/10.1002/tcr.1024

[11] Mohammad Zeeshan; “Optimisation of energy storage for an electricity system in the Indian scenario”. *International Journal of Renewable Energy Technology*, 8 3/4, 254 – 267, 2017. https://doi.org/10.1504/IJRET.2017.088967

[12] A. G. Bakirtzis and E. S. Gavanidou; “Optimum operation of a small autonomous system with unconventional energy sources” *Electric Power Systems Research*, 23, 93-102, 1992. https://doi.org/10.1016/0378-7796(92)90056-7

[13] International Energy Agency, *World Energy Investment Outlook*. 2022. https://doi.org/10.1787/7a0d89ff-en

[14] M. Ozcan; “Assessment of renewable energy incentive system from investors' perspective”. *Renewable Energy*, 71, 425-432, 2018. https://doi.org/10.1016/j.renene.2014.05.053

[15] J. Paska and T. Surma; “Electricity generation from renewable energy sources in Poland”. *Renewable Energy*, 71, 286-294, 2014. https://doi.org/10.1016/j.renene.2014.05.011

[16] E. I. Baring-Gould, et al. *Worldwide Status of Wind-Diesel Applications*. 2004.

https://citeseerx.ist.psu.edu/document?doi=45a257cf8ed98bdb3a6927ac11ee47054c49760f&repid=rep1&type=pdf

[17] International Renewable Energy Agency (IREA), *Renewable Capacity Statistics* 2021. https://www.irena.org/publications/2021/March/Renewable-Capacity-Statistics-2021

[18] Sandhya Madan, Swetha Manimuthu, Dr. S. Thiruvengadam; "History of Electric Power in India (1890 – 1990)". *IEEE Conference on the history of Electric Power*, 7, 152-165, 2007. https://doi.org/10.1109/HEP.2007.4510263

[19] S. Mukhopadhyay and B. Singh; "Distributed generation — Basic policy, perspective planning, and achievement so far in india". *IEEE Power & Energy Society General Meeting*, 6, 1-7, 2009. https://doi.org/10.1109/PES.2009.5275741

[20] [Online]. Available: http://powermin.nic.in/

[21] [Online] Executive summary power sector-14. Available: http://www.cea.nic.in/

[22] [Online] Performance and achievement of Indian power sector during the year 2012-13 and future planning, Indian power sector scenario, 2013. Available: http://powermin.nic.in/

[23] S. N. Singh, Bharat Singh and Jacob Stergaard; "Renewable Energy Generation in India: Present Scenario and Futrue Prospects". *Power & Energy Society General Meeting, PES '09. IEEE*, 2, 26-30, 2009 https://doi.org/10.1109/PES.2009.5275448

[24] Dr. Tarlochan Kaur; "The Indian Power Sector – A sustainable way forward". *IEEE IPEC 2010 conference*, 666-670, 2010. https://www.proceedings.com/content/010/010424webtoc.pdf

[25] Raina, G., & Sinha, S. (2019) Outlook on the Indian scenario of solar energy strategies: Policies and challenges. *Energy Strategy Reviews,* 331–341, 2019. https://doi.org/10.1016/j.esr.2019.04.005

[26] Yadav, P., Davies, P. J., & Sarkodie, S. A; "The prospects of decentralised solar energy home systems in rural communities: User experience, determinants, and impact of free solar power on the energy poverty cycle". *Energy Strategy Reviews*, 100424.

https://www.sciencedirect.com/science/article/pii/S2211467X19301166

[27] Edward W Constant; “Why evolution is a theory about stability: constraint, causation, and ecology in technological change”. *Research Policy*, 31, 8–9, 1241-1256, 2002. https://doi.org/10.1016/S0048-7333(02)00061-6

[28] C. V. Nayar, S. J. Phillips, W. L. James, T. L. Pryor, and D. Remmer; “Novel wind/diesel/battery hybrid energy system”. *Solar Energy*, 51, 65-78, 1993. **https://doi.org/10.3390/en14248276**

[29] H. Dehbonei, C. V. Nayar, and L. Chang; “A new modular hybrid power system”. *IEEE International Symposium on Industrial Electronics, ISIE '03*, 2, 985-990, 2003. DOI Bookmark: 10.1109/ICCIMA.2007.83

[30] B. Wichert, *Control of photovoltaic-diesel hybrid energy systems*. PhD, Dept. Elect. & Comp. Eng., Curtin University of Technology, Perth, 2000. DOI:10.4324/9781315074405-162