



A Case Study Of Integration Of Variable Renewable Energy Resources Into Power Systems

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Abstract: India is actively contributing to the global push for clean, affordable, and sustainable energy, aiming to meet the UN Sustainable Development Goals by 2030. Recently, significant progress in solar energy generation has been made under the National Solar Mission, which targets 50% of energy from sustainable sources by 2030. Despite a solar power generation potential of 115.97 TWh and an estimated 280-300 GW in floating solar power, much of this remains untapped. Current installations are mostly in states like Madhya Pradesh and West Bengal, highlighting a vast opportunity for further development. However, only a small portion of this potential has been tapped, with current installations primarily in Madhya Pradesh, West Bengal, Andhra Pradesh, Kerala, Telangana, Bihar, and Rajasthan. Despite the considerable capacity available, the actual installed capacity remains limited, highlighting a substantial opportunity for further development and investment in floating solar power projects across the country. This paper introduces a novel controller that enhances the performance of a solar-wind hybrid power system by combining solar and wind energy for electricity generation. The system optimizes resource use, boosting efficiency and reliability compared to single-source generation. It is suitable for both industrial and domestic applications. The research focuses on developing combined solar-hydro power plants in India, where solar potential is high but underutilized. This hybrid system aims to produce low-cost electricity, increase renewable energy penetration, and mitigate the environmental and financial costs of conventional plants.

Key Words: Floating solar power plant, Solar-hydro power plants, Solar potential, Variable energy resources, National solar mission.

1.1 Introduction

The integration of variable renewable energy sources, like solar and wind, into existing power systems offers a mix of opportunities and challenges. As the world increasingly shifts towards sustainable energy solutions, understanding the intricacies of incorporating these intermittent sources while ensuring grid stability and reliability becomes essential. This paper delves into these complexities, exploring both the technical and operational hurdles. This case study explores the technical, economic, and environmental impacts of integrating VRE into power systems, highlighting innovative solutions and strategies to enhance grid flexibility and resilience.

Renewable energy sources like solar and wind are inherently variable and unpredictable, posing challenges for grid operators who must ensure a constant and reliable energy supply. The intermittency of these resources necessitates advanced grid management techniques, energy storage solutions, and smart grid technologies to

balance supply and demand effectively. This research examines successful integration efforts from various regions and countries, providing real-world examples and best practices.

From a technical perspective, integrating VRE requires significant upgrades to the existing grid infrastructure, including advanced sensors, real-time monitoring systems, and automated controls that can respond quickly to fluctuations in energy production. Additionally, the effectiveness of energy storage solutions, such as batteries and pumped hydro storage, in mitigating the variability of renewable sources will be analyzed.

Economically, the transition to renewable energy offers both opportunities and challenges. Initial investments in renewable infrastructure and grid upgrades can be substantial, but long-term benefits include reduced operational costs, lower greenhouse gas emissions, and increased energy security. This study will explore the cost-benefit analysis of integrating VRE, considering factors such as government policies, subsidies, and market dynamics.

Environmental impacts are another critical aspect of integrating VRE. The transition to renewable energy can significantly reduce the carbon footprint of power generation, contributing to global efforts to combat climate change. However, the environmental implications of manufacturing and disposing of renewable energy technologies, such as solar panels and wind turbines, must also be considered.

By examining these multifaceted aspects, this case study aims to provide a comprehensive analysis of the benefits and challenges associated with integrating variable renewable energy resources into power systems. The findings will offer valuable insights for policymakers, engineers, and stakeholders involved in the transition to a sustainable energy future.

1.2 Literature review

Integrating variable renewable energy resources (VRE) such as solar and wind power into existing power systems presents numerous technical, economic, and environmental challenges. This literature review explores the complexities of incorporating these intermittent energy sources while maintaining grid stability and reliability. It examines the advancements in grid infrastructure, energy storage solutions, economic implications, and environmental impacts. By analyzing real-world examples and successful integration efforts, this review aims to provide a comprehensive understanding of the best practices and strategies for enhancing grid flexibility and resilience.

1.2.1 Technical Aspects of VRE Integration:

Grid Infrastructure and Management

Integrating VRE into existing power grids necessitates significant upgrades to infrastructure, including advanced sensors, real-time monitoring systems, and automated controls. According to Lasseter et al. (2002), smart grid technologies are essential for enhancing grid reliability by enabling real-time adjustments to energy production and consumption. These technologies help balance supply and demand effectively, accommodating the variability and unpredictability of solar and wind power.

Smart grids incorporate information and communication technologies (ICT) to create a more flexible and responsive power system. As described by Faria et al. (2010), these grids can integrate various energy sources, including VRE, and provide real-time data to optimize energy distribution. The implementation of smart grids significantly enhances the efficiency and reliability of power systems with high VRE penetration.

Energy Storage Solutions

To manage the variability of renewable energy sources effectively, energy storage systems are vital. Denholm and Hand (2011) emphasize the critical role of batteries and pumped hydro storage in stabilizing energy output. These systems capture surplus energy during peak production times and release it when production dips, thus ensuring a reliable power supply. The effectiveness of these storage solutions is further supported by Ibrahim et al. (2008) and Hittinger et al. (2015), who explore various energy storage technologies and their applications in renewable energy systems.

Battery storage systems, particularly lithium-ion batteries, have emerged as a viable solution for short-term energy storage. They provide rapid response to fluctuations in energy production and consumption, making them suitable for integrating VRE. Pumped hydro storage, on the other hand, offers large-scale energy storage capacity, making it ideal for balancing long-term variations in renewable energy supply.

Hybrid Systems

Hybrid systems that combine different renewable energy sources, such as solar and wind or solar and hydro, can optimize resource utilization and improve overall efficiency. The study by IRENA (2017) shows that hybrid systems can provide a more stable and reliable energy supply compared to single-source systems. Additionally, Liu et al. (2010) emphasize the potential of hybrid systems to enhance energy security and reduce dependency on conventional power plants.

Hybrid renewable energy systems can effectively manage the intermittency of VRE by leveraging the complementary nature of different energy sources. For instance, solar and wind power generation often exhibit opposite patterns of availability, with solar energy being more abundant during the day and wind energy peaking at night. By integrating these sources, hybrid systems can provide a more consistent energy output.

1.2.2 Economic Aspects of VRE Integration: Cost-Benefit Analysis

The integration of VRE into power systems involves significant initial investments in renewable infrastructure and grid upgrades. Borenstein (2008) provides a comprehensive cost-benefit analysis of solar photovoltaic (PV) electricity production, illustrating the economic advantages of transitioning to renewable energy. While the upfront costs of renewable technologies can be substantial, the long-term benefits include reduced operational costs, lower greenhouse gas emissions, and increased energy security.

The cost-effectiveness of VRE integration is influenced by several factors, including technological advancements, economies of scale, and government incentives. As renewable energy technologies become more efficient and affordable, the economic case for VRE integration strengthens. Additionally, the declining costs of energy storage solutions, such as batteries, further enhance the economic viability of renewable energy systems.

Government Policies and Incentives

Government policies and regulatory frameworks play a significant role in facilitating the integration of VRE. Mitchell et al. (2006) and Bird et al. (2016) highlight the importance of supportive policies in promoting renewable energy adoption. Incentives such as feed-in tariffs, tax credits, and renewable energy certificates can drive investment in renewable technologies and accelerate their deployment.

Feed-in tariffs (FITs) guarantee a fixed price for the electricity generated from renewable sources, providing financial stability for investors. Tax credits reduce the initial capital expenditure required for renewable energy

projects, making them more attractive to developers. Renewable energy certificates (RECs) create a market for trading renewable energy attributes, incentivizing the production of clean energy.

Market Dynamics

The integration of VRE into power systems is also shaped by market dynamics. The transition to renewable energy can disrupt traditional energy markets, requiring adjustments in market structures and pricing mechanisms. Studies by Rühl et al. (2012) and Hirth (2013) explore the impact of VRE on energy markets, emphasizing the need for flexible market designs that can accommodate the variability of renewable energy sources.

The integration of VRE can lead to price volatility in electricity markets due to the intermittent nature of renewable energy production. To mitigate this volatility, market mechanisms such as capacity markets and ancillary services can be implemented. Capacity markets provide financial incentives for maintaining adequate generation capacity, while ancillary services ensure the stability and reliability of the grid.

Economic Opportunities

Despite the challenges, the integration of VRE presents significant economic opportunities. The renewable energy sector can create new jobs, stimulate economic growth, and enhance energy security. The International Renewable Energy Agency (IRENA) (2017) reports that the renewable energy sector employed over 10 million people worldwide in 2016, with the potential for further job creation as the sector expands.

The economic benefits of VRE integration extend beyond the energy sector. By reducing reliance on fossil fuels, countries can decrease their exposure to volatile global energy markets and enhance their energy independence. Additionally, the environmental benefits of renewable energy, such as reduced air pollution and improved public health, can result in substantial economic savings.

1.2.3 Environmental Aspects of VRE Integration

Carbon Footprint Reduction

One of the primary environmental benefits of VRE is the significant reduction in carbon emissions. The transition to renewable energy contributes to global efforts to combat climate change. Jacobson and Delucchi (2011) demonstrate that widespread adoption of renewable energy can drastically reduce the carbon footprint of power generation. This is further supported by studies from the Intergovernmental Panel on Climate Change (IPCC) (2018), which emphasize the urgency of reducing greenhouse gas emissions to mitigate climate impacts.

The carbon footprint of renewable energy technologies, such as solar panels and wind turbines, is significantly lower than that of fossil fuel-based power plants. By replacing conventional power generation with VRE, countries can achieve substantial reductions in carbon dioxide emissions, contributing to international climate goals.

Environmental Implications of Renewable Technologies

While VRE has clear environmental benefits, the production and disposal of renewable energy technologies also have environmental implications. Studies by Fthenakis and Kim (2011) and McDonald and Pearce (2010) examine the life cycle environmental impacts of solar panels and wind turbines. These studies highlight the need for sustainable manufacturing processes and end-of-life management strategies to minimize the environmental footprint of renewable technologies.

The production of solar panels involves the extraction and processing of raw materials, which can have environmental impacts such as habitat destruction and water pollution. Additionally, the disposal of solar panels at the end of their life cycle poses challenges related to waste management and recycling. Wind turbines also have environmental impacts, including noise pollution and wildlife disturbances. Sustainable practices in manufacturing, operation, and disposal are essential to mitigate these impacts.

Broader Environmental Benefits

Beyond carbon footprint reduction, the integration of VRE offers broader environmental benefits. The reduction in air pollution from replacing fossil fuel-based power generation with renewable energy can lead to improved public health. Studies by Garud and Purohit (2007) and Shaikh (2017) highlight the health benefits of reduced air pollution, including lower rates of respiratory and cardiovascular diseases.

The transition to renewable energy also conserves natural resources by reducing the demand for fossil fuels. By harnessing energy from the sun and wind, countries can decrease their reliance on finite resources and promote the sustainable use of natural assets. Additionally, renewable energy projects can contribute to biodiversity conservation by promoting land use practices that protect natural habitats.

Case Studies of Environmental Impact

Case studies from various regions provide insights into the environmental impacts of VRE integration. For example, Ramachandra et al. (2011) examine the hotspots of solar potential in India, highlighting the environmental benefits of large-scale solar projects. Similarly, Rafique et al. (2020) assess the environmental impact of solar energy deployment in Pakistan, demonstrating the positive effects on air quality and public health.

These case studies underscore the importance of considering environmental impacts in the planning and implementation of renewable energy projects. By adopting best practices and sustainable strategies, countries can maximize the environmental benefits of VRE integration.

1.3 Methodology:

System Configuration and Design

This study focuses on the Pawana Dam hydroelectric power plant, located on the Pawna River in Maval taluka, approximately 40 kilometers from Pimpri Chinchwad city. Constructed between 1963 and 1972, the dam spans 1329 meters in length and stands 42.37 meters high. It has a gross storage capacity of 0.24 cubic kilometers, forming the foundation for Pawna Lake, an artificial reservoir created by the dam's backwaters. The Pawna Dam serves dual purposes of hydroelectric power generation and water supply, with a significant power generation capacity of 1250 MW. To maximize solar energy utilization, we propose installing floating photovoltaic arrays in the reservoir. This approach not only protects the dam's structure from potential shallow water damage but also preserves the site's tourism appeal.

Optimal Location for Floating Solar PV Arrays

To effectively harness solar energy, we propose the installation of floating photovoltaic (PV) arrays within the reservoir. The ideal location for these arrays is at the center of the lake, which serves two main purposes: it prevents potential damage to the dam's structure caused by shallow depths near the shoreline, and it preserves tourist spots that contribute to the local economy.

Benefits of Floating PV Plants

Water Conservation: Floating PV plants can significantly reduce water loss through evaporation, with the extent of savings dependent on the surface area covered by the arrays and prevailing climate conditions.

Cleaning Efficiency: According to the Council on Energy, Environment, and Water (CEEW), cleaning a plant requires approximately 7000 to 20000 liters of water per MW. In a floating PV system, cleaning water can be reused, leading to cost savings and efficient water management.

Improved Water Quality: By shading the water surface, floating PV arrays inhibit algae growth, contributing to better water quality.

Reduced Evaporation and Heat Excursion: The presence of floating PV panels helps prevent water evaporation and excessive heating of the water body.

Solar PV and Wind Integration

India's solar energy potential is vast, with over 300 sunny days and 2300–3200 sunshine hours annually. The average daily and annual solar radiation (GHI) ranges from 1.1 to 5.9 kWh/m² and 414.6 to 2159 kWh/m² respectively, comparable to solar radiation levels in tropical and subtropical regions.

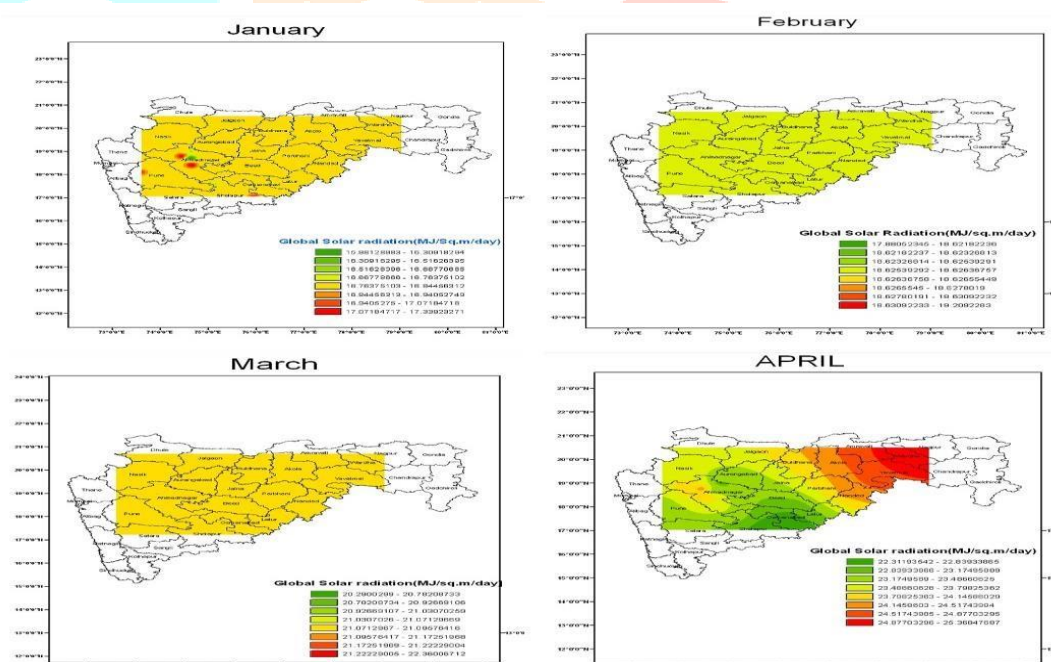


Fig 1: Solar radiation data

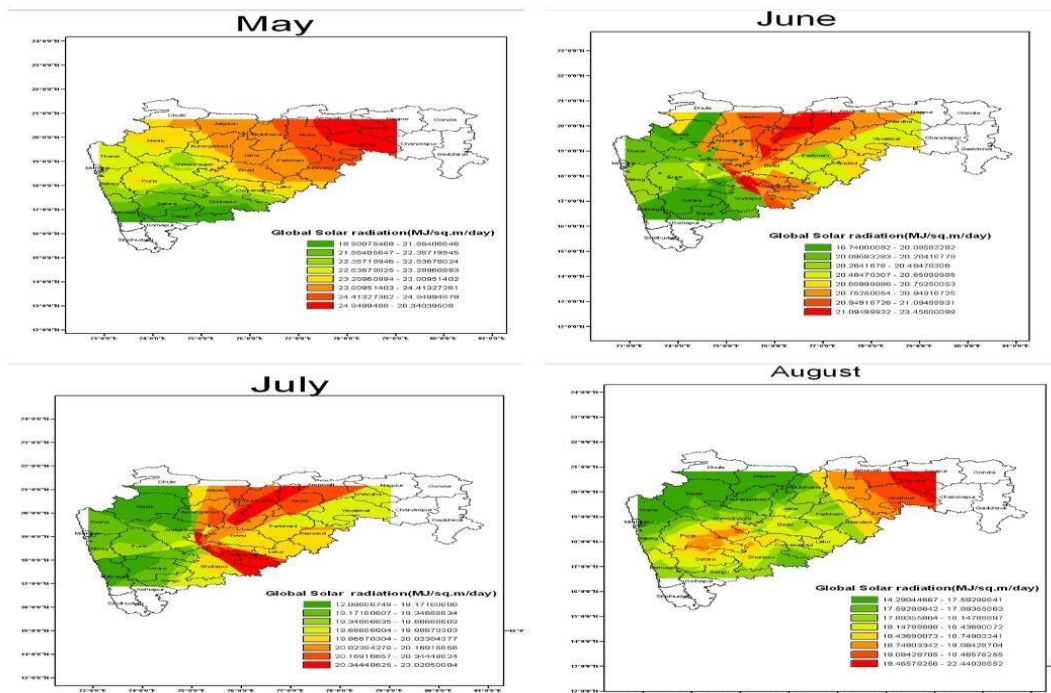


Fig 2: Solar radiation data

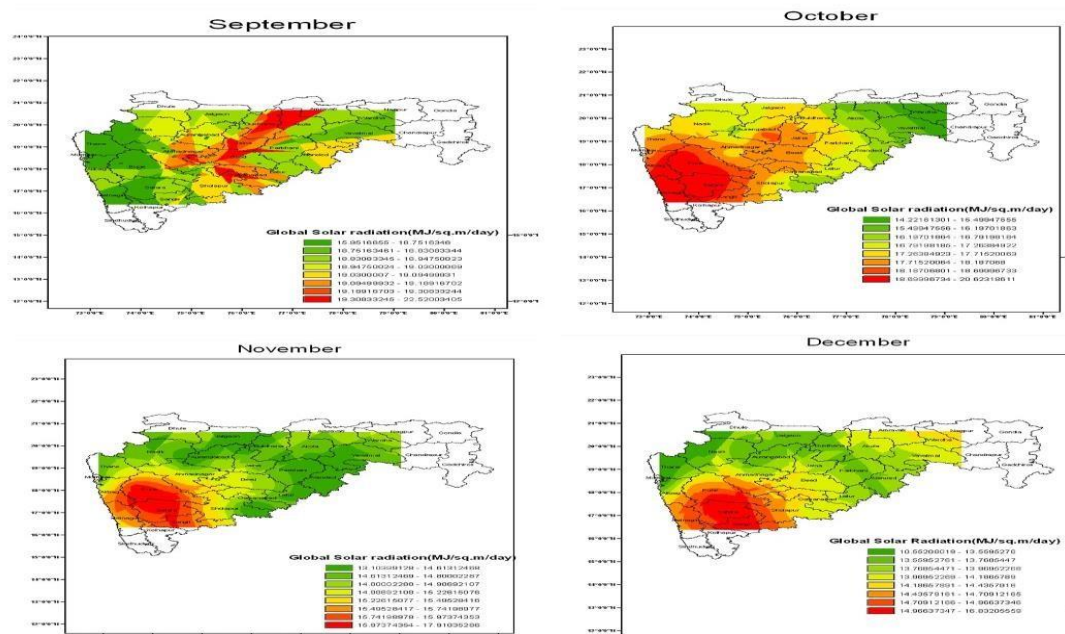


Fig 3: Solar radiation data

The Pawna Dam area experiences global solar radiation of around 16.7 – 16.8 MJ/sq.m per day. During peak summer months, ample solar radiation and clear skies are available to generate energy. The terrain at 3580 feet above sea level is also conducive to wind energy generation, as the open expanse of the reservoir provides an opportunity for wind energy integration. Adequate wind flow allows wind turbine systems to generate electricity efficiently, necessitating a feasibility study to determine the optimal wind turbine setup for the site.

Grid Integration and Control Strategies

Hybrid Approach: Considering the importance of water resources for public use and emergency storage, a solar/wind hybrid system is well-suited. During monsoon seasons, when water availability is abundant, energy can be produced from all three sources simultaneously.

Existing Grid Infrastructure: The existing grid connection infrastructure at the Pawana Dam power station is advantageous, requiring no substantial investment for basic connectivity. Integrating different energy sources into a common grid ensures efficient supply.

Energy Storage: Implementing energy storage solutions, such as batteries, enhances the project's financial viability. Excess energy can be stored for commercial purposes or emergencies, expanding the project's scope.

Economic and Environmental Aspects

The growing global concern about environmental issues and the gradual depletion of fossil fuels have spurred research and innovation in renewable energy. Solar energy, wind power, and hydropower are poised to play pivotal roles in meeting future energy needs. Integrating photovoltaic (PV) and wind systems offers a promising avenue for maximizing energy production, complementing each other in terms of energy availability with minimal economic impact.

Complementary Energy Production: Solar radiation dominates during the day and summer months, while wind energy compensates for the absence of solar production at night and during winter. Combining PV and wind technologies ensures a more consistent and reliable energy output.

Unpredictability and Auxiliary Systems: The inherent unpredictability of renewable sources necessitates auxiliary energy systems. Diesel generators, fuel cells, and battery storage systems can mitigate energy fluctuations and enhance system reliability.

Hybrid Systems: Integrating PV and wind technologies into hybrid systems addresses challenges related to high initial investments, maintenance costs, and depreciation. Researchers often assess the economic and energy efficiency of hybrid systems compared to standalone PV or wind installations. Finding the optimal configuration—such as the right number of PV panels and wind turbines—is crucial.

Storage Solutions

Stand-Alone Systems: When both solar and wind energy sources are insufficient, storage systems become essential. Batteries can store excess energy during peak production for use during low-production periods.

Grid-Connected Systems: In grid-connected setups, any energy deficit can be compensated by drawing power directly from the grid. Conversely, surplus energy produced by the system can be channeled back into the grid or stored for later use.

Diverse Storage Technologies: Beyond batteries, other storage methods—such as hydraulics, thermal storage, compressed air, hydrogen electrolysis, and fuel cells—are being explored for integration with hybrid systems.

Recommendations

Research and Consideration: Given the critical need for sustainable power generation and meeting climate goals, it is essential to conduct further research and explore hybrid energy systems. Comprehending the full range of advantages and environmental benefits these systems offer is crucial for advancing sustainable energy solutions.

Pilot Projects: Initiating pilot projects at existing hydroelectric sites, and converting them into variable renewable energy systems, is a practical step. These projects require manageable investments and provide opportunities for system refinement. Successful pilots can instill confidence for broader implementation.

Multi-Renewable Approaches: For new projects, consider integrating multiple renewable sources from the outset. This holistic approach optimizes energy production and resilience.

In summary, the integration of PV, wind, and storage technologies holds immense promise for sustainable energy generation. By embracing these innovations, we can move toward a greener and more resilient energy future.

1.4 Working System:

Working Principle: The proposed system operates on the principle of generating energy (specifically electricity) from multiple available sources. In our proposed system, solar energy will serve as the primary, continuous source of electricity generation. Complementing this, wind and hydro sources will be strategically integrated. To manage and synchronize the power input to the grid, inverters will be employed, ensuring efficient load sharing by slightly adjusting the voltage.

Case 1: In this scenario, the infrastructure for basic grid connectivity already exists—for example, in hydropower stations. The financial viability of such a case is very promising, making it suitable for use as a pilot project to achieve the desired results.

Case 2: In contrast, when no prior infrastructure is available for grid connectivity, proper financial support becomes crucial to consider variable renewable energy resources.

At the initial stage, integrating variable sources like solar and wind with a hydropower station is the most feasible and practical approach.

If we start with a small-scale domestic plant with Solar-Wind-Hydro sources then using a battery storage bank as an anchor for the system is the best way to handle load. For each energy source, you use a dedicated charge controller to feed the one battery bank, and for your supply a single inverter is all that's required, as long as it's capable of supplying the required load

1.5 Conclusion:

Integration of VRE into the Pawana Dam hydroelectric power plant would demonstrate the technical feasibility, economic viability, and environmental benefits of such projects. Advanced grid management technologies, effective energy storage solutions, and hybrid systems would optimize resource utilization and enhance the reliability of the power supply. Supportive government policies and incentives have driven investment in renewable energy, creating new economic opportunities and reducing the carbon footprint of power generation.

This study offers crucial insights for policymakers, engineers, and stakeholders engaged in the transition to sustainable energy. By tackling the technical, economic, and environmental challenges of integrating variable

renewable energy resources, the Pawna Dam project exemplifies a model for future renewable initiatives. Ongoing research and development in hybrid renewable systems promise to further improve grid flexibility and resilience, securing a reliable and sustainable power supply for the future.

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