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An Integrated Paradigm: A Holistic Review on Stability, Economic, and Intelligent Dimensions of Wind-Solar-Storage Systems

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Abstract. Both wind energy and solar energy have their own fluctuations. If they are used separately, they will cause some hard to suppress impacts on the stability of power grid and power quality. To address this issue, Wind–Photovoltaic–Storage Systems (WPSS) have been introduced to enhance the stability, flexibility, and reliability of modern power infrastructures. This paper provides a comprehensive discussion of WPSS, beginning with their fundamental principles—including their operating mechanisms, functional roles, and adaptability within microgrids—and further examining their overall performance and potential applications. For example, how they can be stable amid changes, how they can keep the cost low and how they can work smartly. Better scheduling plans combined with electricity market rules can also play an effective role in enhancing the overall efficiency and reducing the cost. It is an effective way to balance power generation, the grid, load and storage. It can also integrate more amount of renewable energy into the grid safely. Based on above analysis, this research establishes one single framework that connects system design and market operation. It provides a complete solution to enhance WPSS from both technical and economic aspects. As one key technology to build new power system, WPSS plays an important role. The next stage of development should focus on reducing energy storage costs, improving electricity market mechanisms, and implementing smarter multi-stage dispatching strategies in practical projects.

Keywords: Wind–Photovoltaic–Storage Systems, Power system stability and flexibility, Renewable energy integration

1. Introduction

Against the backdrop of rapid economic growth, coupled with the urgent need to address climate change and the support of stronger policies behind the scenes, global electricity demand has been continuously increasing. Under such circumstances, to solve the problem of energy security and achieve the transition to clean energy at the same time, increasing a large amount of wind power generation and solar power generation has become a very crucial approach. As a result, many countries have begun to vigorously promote wind power - photovoltaic - energy storage systems.

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The major policy efforts such as the Energy Storage Challenge initiated by the United States in 2020 and China's 14th Five-Year Plan for Renewable Energy Development launched in 2022 are both advancing rapidly [1, 2]. By mid-2024, China's installed capacity of renewable energy has reached 1,653 gigawatts, accounting for more than half of the total power generation. This is the first time that the power generation has exceeded that of coal-fired power. Such rapid growth is actually attributed to improvements made in other fields. For instance, there have been enhancements in energy storage, better power conversion technology, and more intelligent microgrid control. All these improvements have made the entire energy system more flexible and easier to manage. To support such a transformation, State Grid Corporation of China has formulated a five-year spending plan worth 250 billion US dollars. Among this plan, 45 billion US dollars is specifically allocated for the modernization of the smart grid.

Although this has been developed, the rising trend towards the utilization of variable renewable sources of energy is extremely daunting in terms of technical aspects. Currently, the second and third leading sources of electricity in China are wind and solar energy. They however are unpredictable which not only threaten the stability of the power grid but also the power dispatching is difficult than ever before and they put the stability of the whole system to test. Consequently, it is highly essential to pay attention to the research of the integration and optimization of the use of Wind–Photovoltaic–Storage Systems (WPSS) By doing that, it will be possible to get more electricity using renewable energy resources, facilitate the process of energy conversion and decrease the usage of fossil fuels, and, in the end, meet the carbon targets. The cooperation of WPSS and smart grids offers the valuable assistance in developing further power infrastructures and ensuring the energy security. This paper will make full introduction to the technology of WPSS and its use in solving these burning problems and facilitating energy sector development.

2. Principle of wind–solar–storage power generation technology

Wind-solar-energy storage power generation integrates wind energy, solar energy and energy storage into a single system. It mainly takes advantage of the natural compatibility between wind and sunlight to provide stable renewable energy. The storage part in this system can eliminate the fluctuations between the amount of energy generated and the amount of energy required. Wind can convert flowing air into electrical energy, and solar panels achieve the same function of converting other forms of energy into electrical energy as wind power generation by capturing sunlight. The storage system will absorb excess electricity when the power is sufficient, and release the stored electricity when the power is insufficient. When several energy sources and devices work together like this, the power grid can become more reliable and flexible. It can also reduce the intermittent and unstable characteristics of wind and solar power generation. Such a setup is the key to establishing a modern power system that uses local energy.

2.1. Principle of photovoltaic power generation

In the wind-solar hybrid power generation system, also known as WPSS, the photovoltaic (PV) part can directly convert sunlight into electrical energy. As shown in Figure 1, the silicon semiconductor PN junction utilizes the photovoltaic effect. This effect is that when sunlight hits the surface of the silicon semiconductor PN junction, the PN junction will absorb the light energy. After absorbing light energy, the electrons inside the PN junction will gain energy and be excited. This changes the way charges diffuse. Due to the presence of an internal electric field, positively charged holes will drift to the P region and accumulate there, while electrons will enter the N region with a negative

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charge. This situation will generate a voltage on the PN junction. If the external circuit is connected, the voltage will drive the current to flow, thus converting solar energy into electrical energy [3].

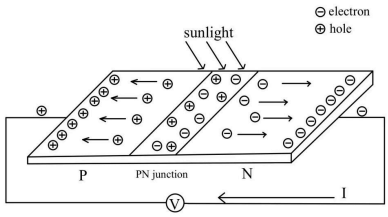


Figure 1. Formation of the PN junction

The output characteristics of PV cells are influenced by ambient temperature and solar irradiance, exhibiting pronounced nonlinear behavior. Under normal operating conditions, their physical equivalent model is typically simplified as a constant current source in parallel with a diode, with additional series and parallel resistances included in the circuit. The parallel diode represents the unidirectional conduction characteristic of the photovoltaic current, while the series and parallel resistances describe the equivalent resistive effects within the PV system [4].

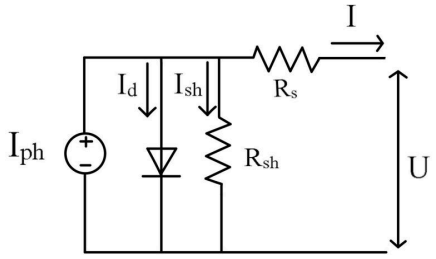


Figure 2. Equivalent circuit

As shown in Figure 2, the output current I of a PV cell can be expressed as:

$$I = I_{ph} - I_d - I_{sh} \tag{1}$$

Where I_{ph} is the photogenerated current, which depends on ambient temperature and irradiance, expressed as:

$$I_{ph} = \left[I_{sc} + (T - T_r)\right] \frac{S}{1000} \tag{2}$$

Here, I_{sc} is the short-circuit current, N is the temperature coefficient of the short-circuit current, S is the current irradiance, T is the current temperature, and T_r is the reference temperature (25 °C). I_d is the diode current, which can be obtained from the diode's current–voltage characteristic:

$$I_d = I_0 \exp\left(\frac{qU_j}{AKT} - 1\right) \tag{3}$$

Where I_0 is the reverse saturation current, q is the electron charge, U_j is the voltage across the diode, A is the diode ideality factor, and K is the Boltzmann constant. I_{sh} is the current flowing

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through the parallel resistance R_{sh}, which according to Kirchhoff's law is given by:

$$I_{sh} = \frac{U_j}{R_{sh}} \tag{4}$$

$$U_j = U + IR_s \tag{5}$$

Where U is the PV cell output voltage and R_s is the series equivalent resistance.

To adapt the model for engineering practice, simplifications are typically applied: since the parallel resistance R_{sh} is very large, I_{sh} can be neglected; and because the series resistance R_s is very small, it can be approximated that $I_{ph}=I_{sc}$. Consequently, the final simplified output current equation is obtained as:

$$I = I_{sc} - I_0\left\{\exp\left[\frac{qU}{AKT}\right] - 1\right\} \tag{6}$$

2.2. Principle of wind power generation

The wind power generation system primarily consists of a wind turbine module and a generator module. The wind turbine module captures wind energy through its blades and converts it into mechanical energy. As the turbine rotates, this mechanical energy is transmitted to the generator module. The generator module, based on the principle of electromagnetic induction, converts the input mechanical energy into clean electrical energy [5]. Because the wind turbine generates three-phase alternating current (AC), at the beginning, it needs to be converted into direct current (DC) through a rectifier circuit. Then, the converted DC will be sent to the wind energy, solar energy and energy storage DC microgrid controller. After a series of processing, the DC can be directly used to charge batteries. It can also be converted into a stable AC voltage by means of an inverter to provide power for AC loads [6].

Wind power generation devices can choose to use different power generation methods according to actual conditions. However, most of their basic components are actually the same. The function of the blades is to capture wind power and convert the captured wind power into mechanical energy. What the transmission system does is to transfer the energy from the blades to the generator. The function of the speed control system is to keep the energy input to the generator in a stable state all the time. The permanent magnet synchronous direct drive generator is the most core part of the entire system, and its task is to convert mechanical energy into electrical energy [7]. The tower holds up the generator unit, while the yaw system keeps blades facing the wind for best energy capture. An overspeed protection system stops the turbine from spinning too fast in strong winds, protecting the equipment. In aerodynamics, the power a wind turbine can pull from the wind follows a basic equation:

$$P = \frac{1}{2}\pi\rho r^2 v^3 \tag{7}$$

In the formula, ρ represents the air density (1.29 kg/m³ under standard conditions),r is the radius of the wind turbine blades, and v is the instantaneous wind speed. In practical applications, however, the wind turbine experiences energy conversion losses due to factors such as frictional heating of the blades. Consequently, $C_p(\lambda, \beta)$ is introduced to account for these losses, yielding the formula for the actual output power:

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$$P = \frac{1}{2}\ \pi\rho r^2 v^3 C_p\left(\lambda, \beta\right) \tag{8}$$

The wind energy coefficient C_p mainly depends on the tip-speed ratio λ and the blade pitch angle β.

Due to unpredictability of wind and solar power, independent micro grids tend to experience power fluctuations. That is the reason why an energy storage system is required to stabilize the supply and demand of electricity and as a reserve source of power. In case when the generated electricity by renewable energy is more than the demand, The energy storage system will absorb the surplus electricity. The energy storage system will also emit the stored energy to maintain the normally operation of the load when there is an insufficient power generation. This will not only increase stability of the micro grid, but also make it more flexible.

In the modern setting, the more prevalent types of energy storage methods are lead-acid batteries, nickel-chromium batteries, lithium-ion batteries, and supercapacitors. The lead-acid batteries have become popular to hundreds of people because they enjoy long life, have large capacity, mature technology and are cheap. Li-Ion battery is becoming more and more popular because it is high in energy density and possesses a higher charging rate. Still, it is a disadvantage since Supercapacitors can store a relatively small amount of energy, yet they recharge quickly and have high power. Lead-acid batteries are still considered to be the best option of microgrid storage due to their cost and reliability among other aspects.

2.3. Principle of energy storage system

The ESS or energy storage system is important in the proper stable functioning of the wind power - photovoltaic - energy storage system or the WPSS. It behaves as an energy buffer where it is used to experience real time balance between power generation and power load. Whenever the quantity of power that is generated by the renewable energy is more than the real demand, then the ESS will absorb the additional power and fill itself. In the case where the power generation is less than ideal, it will discharge the energy that was stored in the past to compensate the lack of power generation. At the system level as a whole, ESS could also help the stability of the power grid to stabilize the power flow, adjust the frequency and support the voltage, etc. The functions play a very important role to enhance the safety and reliability of the power grid.

In general, energy storage technologies can be classified into two distinct categories according to their discharge time and the purpose of usage. The first is energy-oriented storage, e.g., lithium-ion battery or hydrogen storage, and can store so much energy within a matter of hours or even days. The other one is energy-centered storage. Flywheels and supercapacitors belong to this type. They suit well in bursts of short-term high-energy such that it takes in a few seconds up to several minutes. This is able to even out the fluctuation of the energy as well as enhance quality of electrical energy.

The most fundamental problem in the design of WPSS is the selection of the suitable energy storage technology as well as the optimal scale. This decision will play a decisive role in the price, dependability and time of the system.

3. Analysis of wind–solar–storage integrated smart grid systems

With the introduction of renewable energy match in the past few years, a greater number of renewable sources in the power grid, the studies on wind and solar energy storage devices are no longer concentrated on the enhancement of the one component, but has started revolving around the

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entire system. In present times, the focus of researchers on stability and the ability of economic benefits to be reflected has become the priority. Similar to this, coordination work shall also have to be done, but highly ingenious coordination work shall have to be conducted at the same time.

3.1. System stability: mitigating inertia-less operation

Renewable that is linked through inverters does not necessarily possess inertia which has posed a significant problem with grid stability. Hybrid energy storage or HESS is a technology that integrates technologies that are power based such as supercapacitors into the energy-based batteries to enable an important solution in the rapid control of the frequency and the voltage. Recently, Wang et al. [8] researched a grid-connected hybrid power plant that employed Vanadium REDOX flow batteries (VRFB) and supercapacitors. Their research findings revealed that this system improved damping and it was capable of responding to transient disturbances.

Another highly important change in the study to observe is that the storage devices of wind and solar energy that were formerly determined by deterministic methods years ago is now being changed to probability-based models. The use of probabilistic design and multi-mode levels of stability checks is highly essential to real-life reliability and strength because of the presence of system coupling and capacity restrictions.

3.2. Economic performance: achieving life-cycle value maximization

Taking the wind–photovoltaic–energy storage system as an example, its economic value was previously evaluated mainly through the payback period. This approach has now evolved toward a full life-cycle assessment, aiming to maximize system value over time. Hierarchical control is commonly employed, enabling the coordination of different types of energy storage technologies—such as long-term hydrogen storage and short-term battery storage—to achieve economic balance across multiple time scales and improve overall efficiency.

A significant advancement in this area is the application of economic model predictive control (MPC). This framework has been implemented in photovoltaic–hydrogen integrated systems. Guo et al. (2025) demonstrated that, compared with traditional configurations, this method can increase the proportion of self-consumed energy and improve long-term profitability, even under realistic weather conditions and fluctuating electricity prices [9].

Future research should place greater emphasis on accurately modeling energy storage degradation and incorporating external factors such as carbon pricing into system planning. Neglecting these considerations may result in suboptimal short-term scheduling and increased long-term costs. A comprehensive approach that integrates economic and sustainability considerations is essential for achieving balanced and resilient energy systems.

3.3. Intelligent operation: adaptive scheduling under uncertainty

The promotion of real-time and adaptive operation has integrated artificial intelligence technology into wind, photovoltaic and energy storage systems. Reinforcement learning and its new forms, such as meta-reinforcement learning, stand out because they have the ability to learn and fine-tune control strategies in highly uncertain environments. Shen et al. constructed a Meta-RL framework in 2024, which demonstrates this potential [10]. Their research found that this model can quickly adapt to new environments with almost no training data, thus reducing the cost of early trial and error.

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However, this study also points out the key gaps in this field, as artificial intelligence models generally operate like "black boxes", and applying them to large-scale engineering applications means solving three major problems. These three issues are respectively making the model easier for people to understand, enhancing the security and reliability of the system, and carefully checking whether the data-driven plan is in line with the physical limitations of the power grid.

3.4. Synthesis and future pathways

By looking at the progress made in system stability, economic planning and intelligent operation, it is clear that the wind energy - photovoltaic - energy storage system is developing towards a single and hierarchical optimization approach. In future work, stability control, economic dispatching and intelligent decision-making will no longer be treated as separate tasks. Instead, it will rely on a collaborative design approach that links control algorithms, energy storage Settings, and market strategies, integrating stable control, economic scheduling, and intelligent decision-making. With renewable energy systems becoming more complex and less predictable, there is a need to implement a hybrid system that balances between the traditional systems and the use of data-driven knowledge. They can make predictions more precise with a method, which accommodates machine learning and the opportunity-based analysis and is within the framework of real-world constraints. The other effective strategy is scaling up the test projects and this can help in bridging the gap between the concepts in the laboratory and real world. These pilot projects can help examine cross-disciplinary plans, measure the long-term impact of these plans on cost and stability, and also provide data for ongoing model updates. Hybrid control theory, energy economics and artificial intelligence will influence the future development direction of WPSS, that is, to create a stable, economical, flexible, clear system that can remain resilient even in uncertain situations.

4. Synergistic optimization of system configuration and market participation for renewable energy integration

4.1. A methodological framework for standalone hybrid system optimization

Establishing an independent hybrid power system is actually a rather challenging issue involving multiple aspects. To solve this problem, a relatively sensible approach needs to be adopted, which should be able to balance cost, reliability and its working effect. The proposed approach mainly consists of four components. The first component involves detailed stochastic modeling to characterize the inherent randomness within the system. The second part is a complete method capable of judging multiple targets at once. The third part is a relatively intelligent search algorithm. The fourth part is a planned comparison of different system designs.

It operates a combination of probability-based models to manage natural uncertainties in the generation of renewable and the demand of power. The intensity of sunlight which can be rather erratic is approximated by a Beta distribution, the parameters of shape are determined by historical average and variation data. This model then operates with temperature response of the panel in determining photovoltaic power output. A two-parameter Weibull distribution is used to show the changes in the wind speed with an addition of a height factor in a way that the height factor adjusts it to the actual weather conditions, considering the height of the turbine and this enhances the prediction of the non-linear power production. The randomness of electrical load is assumed to follow a normal distribution. Combined, the models ensure the optimization captures the actual system behavior much more than simple averages.

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The plan will have a holistic evaluation mechanism which extends beyond the cutting of cost. The system is designed such that it has four big indicators such as the Loss of Power Supply Probability (LPSP) to ensure reliability; the Loss of Energy Probability (LEP) to ensure efficiency; the System Energy Fluctuation Rate (K_f) to ensure stability and the Life cycle cost (LCC) to ensure the ownership cost as a total. With such a comprehensive approach, it will ensure that the best set-up would not only be cost-efficient but reliable and efficient too, including grid-stable.

To address this nonlinear and complex multi-objective optimization problem, an enhanced Natural Selection Particle Swarm Optimization (NSPSO) algorithm is employed. Such a combination prevents the pitfalls of PSO methods like being stuck in the early phases, and Genetic Algorithms like fine-tuning. This is obtained by way of a step of natural selection. A new round of this is followed by the stronger half of the swarm replacing the weaker half, and in spite of this, preserving the best position of each particle and the best position of the group. These maintains the group diverse and assists the search in being more in the direction of the most appropriate solutions. A weighted sum approach converts multi-goal task into the single-goal one. A penalty function ensures the rule of reliability (LPSP < 0.1) is adhered to. The weights are readjusted dynamically, using feedback of combined goal runs, to ensure that all measures of performance are given an equal opportunity.

The process of optimization proves to be effective, as it can be compared closely. Multi-objective setups are a superior balance using a slight increase in cost with significant improvements in energy utilization and system stability which identifies the constraints of mere cost reduction. Systems that have various types of parts, such as multiple wind turbines and solar panels, perform better than those that have just a single type of parts, since a combination of technologies in such a way allows them to cooperate more easily, and each other supports one another the most. Ultimately, a wind-solar-battery system is obviously less expensive and more reliable in comparison with ones based on the utilization of either wind or solar alone to achieve the same degree of reliability. Especially a solar-only system will require the extra panel and battery area to get through the dark such that they are now well beyond the cost of their own systems as well as not performing as well.

4.2. Optimization of market mechanisms for wind and solar energy storage

It has a mixture of probability-on-board models to take care of natural uncertainties of the production of renewable and power demand. A Beta distribution approximates the intensity of the sunlight that can be fairly quite unpredictable, the shape parameters are obtained with respect to historical average and variation values. This model then works by operating with temperature response of the panel in the determination of photovoltaic power output. It displays the variations of the wind speed with an addition of a height factor markedly on a two-parameter Weibull distribution and increases it by factoring the height of the turbine and this improves the prediction of the non-linear power generation. The fact that electrical load is random is assumed to follow a normal distribution. Together, the models provide an optimization that ensures that the actual system behavior is captured in a much better way than the simple averages.

The strategy has an overall evaluation system, which surpasses cost reduction. The system is developed having four major indicators such as the LPSP to guarantee reliability; the LEP to guarantee efficiency; the K_f to guarantee stability; and the LCC to guarantee ownership cost in totality. This comprehensive approach would ensure that the most suitable set-up would be affordable but also reliable and efficient besides being stable to the grid.

To effectively address this nonlinear and complex multi-objective problem, an improved NSPSO technique is employed. This combination prevents the popular issues of PSO, including being stuck

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in the early phase, and Genetic Algorithms, including fine-tuning. This is done by taking a step of natural selection. After each round, the swarm is replaced by the stronger half that, however, makes use of the best position of each particle and the best position of the group. This keeps the group diversified and helps the search be more towards the best suitable solutions. Weighted sum strategy transforms many-goal task to the one-goal one. A penalty function can be used to make sure that the rule of reliability (LPSP < 0.1) is followed. Readjustments of the weights are then carried out dynamically based on feedback of combined goal run to make sure that the various measures of performance are given equal opportunities.

The optimization process is the one where the process can be compared. Multi-objective configurations are an optimal tradeoff on slight rise in cost with immense gains in energy use and stability of a system that uncovers the limitation of pure cost cutting. Systems containing a multitude of types of parts like multiple wind turbines, solar panels or panels, work more effectively than the ones containing a single type of parts as a combination of technologies would have each other cooperating more readily, and as far as each other would be supporting each other the most. Finally, it is certain that a wind-solar-battery system is not only cheaper and more trustworthy but also in comparison to the systems that deem wind or solar as the sole factor in providing the same level of trust. Particularly a solar-only system will need the additional panel and battery space to have survived the dark so that they are now even worse than expensive than their own systems, to say the least.

5. Conclusion

To conclude, WPSS systems have obviously become an important means of stabilizing the power systems, improving the economic results, as well as ensuring the transition to smarter energy handling. An analysis of current studies reveals several important developments. As an example, hybrid configurations with a combination of batteries and supercapacitors contribute to a less jagged power line of the system, and to its overall reliability. Next are stratified economic plans that reconcile long and short terms storage, which causes greater cost containment, whilst employing more renewable energy. The stochastic -robust hybrid optimization based on market strategies also creates new revenue sources of WPSS installations in various electricity markets. Better still, artificial intelligence and reinforcement learning presently provide an excellent platform of intelligent, responsive functioning even in circumstances where circumstances are severely uncertain. Nevertheless, the barriers are still present, such as the prohibitive cost of storage, the shortness of battery duration, and the inadequate large scales deployment. In the future, it would work to reduce the costs that could be achieved by using technological innovation, enhance the market incentives to get the real worth of storage, and render intelligent scheduling models to the real world. Ultimately, more co-existence between technological advancements and policymaking will be fundamental towards the full deployment of WPSS across all smart grids in the future in a sustainable and environmentally friendly manner.

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

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