



Hybrid Solar-Wind-Storage Systems: Research on the Design, Modeling, and Optimization of Hybrid Renewable Energy Systems

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Abstract

Hybrid solar-wind-storage systems have gained significant attention in recent years as a promising solution to address the intermittency and variability inherent in individual renewable energy sources. These integrated systems combine solar photovoltaic (PV) and wind turbine generators, coupled with energy storage components, to provide a more reliable and cost-effective renewable energy supply.

This review paper provides a comprehensive overview of the research conducted on the design, modeling, and optimization of hybrid solar-wind-storage systems. It examines the key elements and architecture of these systems, including the selection and sizing of renewable energy generators, energy storage technologies, and power electronics interfaces. The paper discusses various modeling approaches, such as analytical, numerical, and hybrid techniques, used to simulate the dynamic performance of hybrid systems under different operating conditions.

Additionally, the review covers optimization strategies that aim to maximize the system's energy generation, minimize the levelized cost of energy, and ensure optimal operation and control. These optimization techniques leverage advanced algorithms, including metaheuristic methods, to find the most suitable configuration and parameters for hybrid systems based on techno-economic and environmental factors.

The paper also highlights the challenges and opportunities associated with the integration of hybrid solar-wind-storage systems, including grid integration, energy management, and the role of energy storage in enhancing system reliability and resilience. Finally, it provides insights into future research directions, such as the integration of artificial intelligence and machine learning algorithms for intelligent control and decision-making in these complex energy systems.

The comprehensive review of the research on hybrid solar-wind-storage systems presented in this paper serves as a valuable resource for researchers, engineers, and

policymakers working towards the widespread adoption of integrated renewable energy solutions.

Introduction:

The global energy landscape is undergoing a significant transformation, driven by the urgent need to address climate change and the growing demand for clean, sustainable energy sources. Renewable energy technologies, such as solar photovoltaic (PV) and wind power, have experienced a remarkable surge in deployment in recent years, playing a crucial role in this energy transition. However, the intermittent and variable nature of these individual renewable energy sources poses a challenge in maintaining a reliable and uninterrupted energy supply.

To overcome the limitations of standalone renewable energy systems, hybrid solar-wind-storage systems have emerged as a promising solution. These integrated systems combine multiple renewable energy sources, such as solar PV and wind turbines, with energy storage components, creating a more resilient and efficient energy generation and distribution network. By leveraging the complementary characteristics of solar and wind resources, as well as the energy storage capabilities, hybrid systems can provide a more stable and reliable supply of renewable energy, addressing the intermittency issues associated with individual renewable technologies.

The design, modeling, and optimization of hybrid solar-wind-storage systems have been the focus of extensive research in recent years. Researchers have explored various system configurations, component selection, and integration strategies to enhance the overall performance, efficiency, and cost-effectiveness of these integrated renewable energy solutions. Modeling and simulation techniques have been developed to accurately represent the dynamic behavior of hybrid systems, enabling the evaluation of their performance under different operating conditions and the optimization of their design and operation.

This review paper aims to provide a comprehensive overview of the research conducted on hybrid solar-wind-storage systems, with a particular focus on the design, modeling, and optimization of these integrated renewable energy systems. The paper will delve into the key components and architectures of hybrid systems, the various modeling approaches used to simulate their performance, and the optimization strategies employed to enhance their techno-economic and environmental performance. Additionally, it will discuss the challenges and opportunities associated with the integration of hybrid solar-wind-storage systems, as well as the future research directions in this rapidly evolving field.

By synthesizing the current state of research on hybrid solar-wind-storage systems, this paper aims to serve as a valuable resource for researchers, engineers, and policymakers

working towards the development and widespread adoption of integrated renewable energy solutions that can contribute to a more sustainable and resilient energy future.

II. Fundamentals of Hybrid Renewable Energy Systems

Hybrid renewable energy systems typically integrate two or more renewable energy sources, such as solar photovoltaic (PV) and wind turbines, coupled with energy storage components, to provide a more reliable and efficient energy supply. These integrated systems leverage the complementary nature of different renewable energy sources to overcome the inherent intermittency and variability associated with standalone renewable energy technologies.

A. Renewable Energy Sources

Solar photovoltaic (PV) systems

Conversion of solar radiation into electrical energy

Advantages: Modular, scalable, low maintenance, silent operation

Challenges: Dependence on solar irradiation, seasonal and diurnal variations

Wind turbine generators

Conversion of wind energy into electrical energy

Advantages: High energy yield, mature technology, cost-effectiveness

Challenges: Dependence on wind speed, intermittent nature, geographical constraints

B. Energy Storage Technologies

Electrochemical energy storage

Batteries (e.g., lithium-ion, lead-acid, flow batteries)

Advantages: High energy density, fast response, versatile applications

Challenges: Limited cycle life, safety concerns, cost

Mechanical energy storage

Pumped-storage hydropower, compressed air energy storage (CAES)

Advantages: High energy capacity, long-term storage

Challenges: Site-specific, high capital cost, geographic constraints

Thermal energy storage

Sensible heat storage, latent heat storage, thermochemical storage

Advantages: High energy density, long-term storage, low cost

Challenges: Limited applications, system complexity

C. System Architecture and Integration

Hybrid system configurations

Series, parallel, and hybrid configurations

Advantages: Improved energy generation, enhanced reliability, optimized resource utilization

Power electronics and control systems

Power converters, inverters, charge controllers

Energy management and control strategies

Optimization of system performance and efficiency

D. Techno-economic and Environmental Considerations

Levelized cost of energy (LCOE)

Capital expenditure, operating and maintenance costs, lifetime

Impact of system design and optimization on LCOE

Environmental impact

Greenhouse gas emissions reduction

Land use, water consumption, and material usage

The fundamental understanding of renewable energy sources, energy storage technologies, system architectures, and techno-economic and environmental factors is crucial for the design, modeling, and optimization of hybrid renewable energy systems.

III. Solar-Wind-Storage System Components

The key components of a hybrid solar-wind-storage system are the renewable energy generators (solar PV and wind turbines), energy storage systems, and the power electronics and control interfaces that enable the integration and management of the entire system.

A. Solar Photovoltaic (PV) Systems

PV module technology

Crystalline silicon (c-Si), thin-film, and emerging PV technologies

Efficiency, cost, and performance characteristics

PV array design

Sizing and configuration (series, parallel, tracking)

Shading effects and mitigation strategies

Power conditioning

Maximum power point tracking (MPPT) algorithms

Inverters and charge controllers

B. Wind Turbine Generators

Wind turbine technology

Horizontal axis, vertical axis, and small-scale wind turbines

Turbine characteristics, such as power curve and cut-in/out speeds

Wind resource assessment

Wind speed and direction measurements

Estimation of wind energy potential
Generator and power conversion
Permanent magnet synchronous generators (PMSG)
Doubly-fed induction generators (DFIG)
Power converters and grid integration

C. Energy Storage Systems

Electrochemical storage
Lithium-ion, lead-acid, and flow batteries
Capacity, power rating, efficiency, and cycling capabilities
Mechanical storage
Pumped-storage hydropower and compressed air energy storage (CAES)
Energy capacity, power, and response time
Thermal storage
Sensible heat, latent heat, and thermochemical storage
Applications in hybrid systems (e.g., solar thermal, waste heat recovery)

D. Power Electronics and Control Systems

Power conversion and conditioning
DC-DC, DC-AC, and AC-DC converters
Grid-tied and off-grid inverters
Energy management and control
Supervisory control and data acquisition (SCADA)
Energy management algorithms and control strategies
Grid integration and interconnection
Grid codes and standards
Synchronization, power quality, and grid stability
The selection, sizing, and integration of these key components are crucial for the design and optimization of hybrid solar-wind-storage systems to achieve optimal performance, reliability, and cost-effectiveness.

IV. System Design and Modeling

The design and modeling of hybrid solar-wind-storage systems involve the careful consideration of various factors to ensure the optimal performance, reliability, and cost-effectiveness of the integrated system. This section discusses the key aspects of system design and modeling approaches.

A. System Design Considerations

Resource assessment
Evaluation of solar irradiation and wind potential at the site
Complementarity of solar and wind resources

Load profile analysis
Estimation of energy demand and consumption patterns
Seasonal and diurnal variations
Component selection and sizing
PV array capacity, wind turbine rated power, and energy storage capacity
Matching the system components to the load and resource availability
System architecture and configuration
Series, parallel, or hybrid configurations of solar, wind, and storage
Optimization of system layout and interconnections
Power electronics and control systems
Selection of power converters, inverters, and charge controllers
Energy management strategies and control algorithms

B. Modeling Approaches

Solar PV system modeling
Single-diode or double-diode equivalent circuit models
Simulation of PV array performance under various operating conditions
Wind turbine modeling
Aerodynamic models, generator models, and power curve representations
Simulation of wind turbine power generation under varying wind speeds
Energy storage system modeling
Electrochemical, mechanical, and thermal energy storage models
Simulation of storage system charge/discharge cycles and efficiency
Hybrid system modeling
Integrated models combining solar, wind, and storage components
Simulation of system-level performance, including energy flows and losses
Optimization techniques
Multi-objective optimization methods (e.g., genetic algorithms, particle swarm optimization)
Techno-economic and environmental optimization of system design and operation

C. Simulation Tools and Software

Commercial software
HOMER, MATLAB/Simulink, PSCAD, and other simulation platforms
Open-source tools
Python-based frameworks (e.g., PyRen, PySAM)
Modeling and optimization libraries (e.g., Pandas, NumPy, SciPy)
The systematic design and comprehensive modeling of hybrid solar-wind-storage systems are crucial for evaluating their performance, optimizing their configuration, and ensuring their reliable and cost-effective operation.

V. Optimization Strategies

Optimizing the design and operation of hybrid solar-wind-storage systems is essential to enhance their performance, reliability, and cost-effectiveness. This section discusses various optimization strategies and techniques employed in the context of hybrid renewable energy systems.

A. Techno-economic Optimization

Levelized cost of energy (LCOE) minimization

Optimizing the system configuration and component sizing to reduce LCOE

Net present value (NPV) maximization

Evaluating the long-term financial viability and profitability of the system

Payback period reduction

Determining the optimal system design to shorten the investment payback period

B. Multi-objective Optimization

Conflicting objectives

Balancing the trade-offs between cost, reliability, and environmental impact

Optimization techniques

Genetic algorithms, particle swarm optimization, and other metaheuristic methods

Pareto-optimal solutions

Identifying the set of optimal solutions that represent the best compromise between multiple objectives

C. Energy Management Optimization

Load matching and grid integration

Optimizing the energy flow between the renewable sources, storage, and the grid

Demand-side management

Coordinating the energy consumption patterns to match the available renewable generation

Operation and dispatch strategies

Developing optimal control algorithms for the efficient operation of the hybrid system

D. Environmental Impact Optimization

Greenhouse gas emissions reduction

Minimizing the system's carbon footprint and environmental impact

Resource utilization optimization

Improving the efficiency of land use, water consumption, and material usage

E. Reliability and Resilience Optimization

Loss of power supply probability (LPSP) minimization

Ensuring a reliable energy supply and reducing the risk of power outages

Resilience to disruptions

Enhancing the system's ability to withstand and recover from unexpected events

F. Optimization Techniques and Tools

Analytical methods

Linear programming, dynamic programming, and other mathematical optimization techniques

Simulation-based optimization

Coupling system models with optimization algorithms in simulation environments

Hybrid optimization approaches

Combining multiple optimization techniques to leverage their respective strengths

The selection and application of appropriate optimization strategies are crucial for the design, operation, and management of hybrid solar-wind-storage systems to achieve the desired performance, economic, and environmental objectives.

VI. Integration Challenges and Solutions

The integration of hybrid solar-wind-storage systems involves several technical, operational, and grid-related challenges that must be addressed to ensure the seamless and reliable operation of these systems. This section discusses the key integration challenges and potential solutions.

A. Technical Challenges

Intermittency and variability

Addressing the fluctuations in solar and wind power generation

Effective energy storage and management strategies

Power quality and grid stability

Maintaining voltage and frequency regulation within acceptable limits

Ensuring smooth synchronization with the grid

System compatibility and control

Coordinating the operation of different system components

Developing robust control algorithms and energy management strategies

B. Operational Challenges

Resource forecasting and prediction

Improving the accuracy of solar irradiation and wind speed forecasts

Incorporating weather data and machine learning techniques

Energy storage management

Optimizing the charging and discharging cycles of energy storage systems

Balancing the trade-offs between energy efficiency, cycle life, and cost

Maintenance and reliability

Implementing preventive and predictive maintenance strategies

Enhancing the overall system reliability and resilience

C. Grid Integration Challenges

Grid codes and regulations

Complying with the technical requirements and standards set by utility providers

Addressing grid interconnection, power quality, and safety regulations

Grid stability and ancillary services

Maintaining grid frequency and voltage stability through active and reactive power control

Providing ancillary services, such as frequency regulation and voltage support

Grid modernization and smart grid integration

Leveraging advanced grid technologies, such as smart meters and energy management systems

Developing strategies for seamless integration with the evolving smart grid infrastructure

D. Solutions and Approaches

Advanced control and energy management systems

Implementing hierarchical control architectures (primary, secondary, and tertiary control)

Developing intelligent energy management algorithms and optimization techniques

Grid-friendly power electronics and grid support features

Designing power converters and inverters with advanced grid-support capabilities

Implementing low-voltage ride-through, reactive power control, and other grid-stabilizing features

Hybrid system modeling and simulation

Developing comprehensive system models to analyze and validate grid integration strategies

Leveraging simulation tools and hardware-in-the-loop testing for system validation

Collaboration and standardization

Fostering collaboration between renewable energy stakeholders, grid operators, and regulatory bodies

Establishing industry standards and guidelines for the integration of hybrid renewable energy systems

Addressing these integration challenges through innovative solutions, advanced control strategies, and collaborative efforts is crucial for the successful and widespread adoption of hybrid solar-wind-storage systems.

VII. Case Studies and Best Practices

This section presents case studies and highlights best practices in the implementation of hybrid solar-wind-storage systems, drawing insights from real-world applications and demonstration projects.

A. Case Studies

Remote Community Electrification
Hybrid system design and deployment in off-grid rural or island communities
Challenges and solutions in providing reliable and affordable energy access
Grid-connected Hybrid Power Plants
Integration of hybrid systems with the main electricity grid
Optimization of system configurations and energy management strategies
Commercial and Industrial Applications
Hybrid systems for on-site power generation and energy management
Addressing specific load profiles and energy requirements
Microgrid and Smart Grid Integration
Development of hybrid systems within the context of microgrid and smart grid environments
Leveraging advanced control and communication technologies
Hybrid System Demonstration Projects
Large-scale pilot projects to showcase the technical and economic feasibility
Collaboration between research institutions, industry, and regulatory bodies

B. Best Practices

Comprehensive System Design
Rigorous assessment of local resource availability and demand profiles
Optimal sizing and configuration of renewable energy components and storage systems
Integrated Energy Management
Deployment of advanced control and energy management algorithms
Coordination of renewable generation, storage, and grid interaction
Grid Compliance and Interconnection
Adherence to relevant grid codes, standards, and regulatory requirements
Ensuring seamless grid integration and stabilizing grid support capabilities
Lifecycle Considerations
Evaluation of system lifetime, maintenance requirements, and replacement strategies
Incorporating sustainable and environmentally-friendly design principles
Stakeholder Collaboration and Public Engagement
Fostering partnerships between project developers, utilities, and local communities
Addressing social, environmental, and economic impacts through stakeholder engagement

C. Lessons Learned and Recommendations

Insights gained from the implementation of hybrid systems in diverse applications
Strategies for overcoming technical, operational, and market-related challenges
Recommendations for future research, development, and deployment of hybrid renewable energy systems
The case studies and best practices highlighted in this section provide valuable insights into the real-world implementation of hybrid solar-wind-storage systems, guiding future projects and contributing to the widespread adoption of these integrated renewable energy solutions.

VIII. Future Trends and Emerging Technologies

The field of hybrid solar-wind-storage systems is rapidly evolving, with ongoing research and development driving the emergence of new technologies and innovative approaches. This section explores some of the key future trends and emerging technologies that are expected to shape the future of these integrated renewable energy systems.

A. Advancements in Energy Storage Technologies

- Improved battery chemistries and energy density
- Continued progress in lithium-ion, solid-state, and flow battery technologies
- Increased storage capacity and extended lifespan
- Diversification of storage solutions
- Integration of alternative storage technologies, such as hydrogen, compressed air, and thermal energy storage
- Hybridization of different storage systems for enhanced flexibility and reliability
- Intelligent energy storage management
- Advanced control algorithms and optimization techniques for optimal charging and discharging strategies
- Leveraging predictive analytics and machine learning for intelligent energy storage operation

B. Integrated Renewable Energy Forecasting and Prediction

- Enhanced solar and wind resource forecasting
- Incorporation of satellite data, numerical weather prediction models, and machine learning techniques
- Improved accuracy and granularity of short-term and long-term forecasts
- Holistic renewable energy prediction
- Joint forecasting of solar, wind, and other renewable energy sources
- Developing methods for capturing the spatial and temporal correlations between different renewable resources
- Uncertainty quantification and risk management
- Probabilistic forecasting and modeling of renewable energy uncertainties
- Optimization strategies for robust operation under variable renewable energy conditions

C. Advancements in Power Electronics and Grid Integration

- Grid-friendly power converter technologies
- Intelligent power converters with advanced grid support capabilities
- Seamless integration with smart grid infrastructure and ancillary services
- Distributed energy management and control
- Hierarchical control architectures for coordinated operation of hybrid systems
- Decentralized and distributed control approaches for enhanced resilience and scalability

Artificial intelligence and machine learning
Application of AI and ML techniques for optimal energy management and decision-making
Predictive maintenance and anomaly detection for improved system reliability

D. Sustainable and Circular Design Principles

Life-cycle assessment and environmental impact
Evaluation of the environmental footprint and sustainability of hybrid systems
Circular economy approaches for component reuse, recycling, and end-of-life management
Integrated hybrid system design
Holistic consideration of system components, materials, and manufacturing processes
Optimization of resource utilization and waste reduction throughout the system lifecycle
Sector coupling and energy system integration
Hybrid systems integrated with other energy sectors, such as transportation and heating/cooling
Synergies between renewable energy, energy storage, and other energy-intensive applications

E. Emerging Business Models and Market Structures

Innovative financing and investment mechanisms
Leveraging green bonds, crowdfunding, and other sustainable financing approaches
Exploring new ownership and revenue-sharing models for hybrid systems
Flexibility and market participation
Hybrid systems providing ancillary services and participating in energy markets
Adapting to evolving grid requirements and regulatory frameworks
Digitalization and energy data platforms
Integration of hybrid systems with digital energy platforms and data analytics
Enabling new services, such as virtual power plants and energy-as-a-service
These future trends and emerging technologies highlight the dynamic and evolving nature of hybrid solar-wind-storage systems, paving the way for increased efficiency, reliability, and sustainability in the renewable energy landscape.

IX. Conclusion

Hybrid solar-wind-storage systems have emerged as a promising solution for the integration of renewable energy sources and the provision of reliable, clean, and cost-effective electricity. The research and development efforts in this field have been instrumental in addressing the challenges associated with the variability and intermittency of solar and wind resources, as well as the need for energy storage to balance supply and demand.

This comprehensive review has explored the key aspects of hybrid solar-wind-storage systems, including:

Fundamental Concepts and System Architectures

The principles of hybrid renewable energy systems and their diverse configurations

Renewable Energy Resource Assessment and Forecasting

The importance of accurate characterization and prediction of solar and wind resources

Energy Storage Technologies and Integration

The role of various energy storage systems, their characteristics, and integration strategies

Modeling, Simulation, and Optimization Techniques

The advancements in computational methods for the design and optimization of hybrid systems

Control and Energy Management Strategies

The development of advanced control algorithms and energy management approaches

Economic and Environmental Considerations

The techno-economic analysis and environmental impact assessment of hybrid systems

Case Studies and Best Practices

Insights gained from real-world implementation and lessons learned from demonstration projects

Future Trends and Emerging Technologies

The evolving landscape of energy storage, renewable energy forecasting, grid integration, and sustainable design principles

By synthesizing the current state of research, this review has provided a comprehensive understanding of the multifaceted aspects of hybrid solar-wind-storage systems. The insights and findings presented can serve as a valuable resource for researchers, engineers, policymakers, and industry stakeholders in advancing the deployment and widespread adoption of these integrated renewable energy solutions.

As the global energy landscape continues to evolve, the importance of hybrid solar-wind-storage systems will only grow, contributing to the transition towards a more sustainable, resilient, and decarbonized energy future. The continued research, innovation, and collaboration in this field will be instrumental in unlocking the full potential of hybrid renewable energy systems and driving the clean energy transformation.

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