

Energy Interconnection and Multi - Energy Coupling Strategies in the Context of Power Market Reforms

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Abstract: In the context of the global pursuit of carbon peaking and carbon neutrality, the effective integration of new energy sources and their synergistic optimization with energy storage systems have become key to achieving dual carbon goals. This study aims to develop optimization models that facilitate the efficient integration of new energy while ensuring the stability of the power grid. By employing mathematical modeling and simulation techniques, this research analyzes the interaction between new energy sources and energy storage systems and explores how to maximize the utilization of new energy and minimize environmental impact through source-storage synergy. The main research question focuses on designing effective operation strategies to achieve optimal synergy between new energy and energy storage systems.

Keywords: New Energy Integration, Source - Storage Synergy, Optimization Models, Dual Carbon Goals, Energy Transition

1. Introduction

The global commitment to achieving carbon peaking and carbon neutrality has set a new agenda for the energy sector, emphasizing the need for the integration of new energy sources such as wind and solar power into the existing power grid. This integration is crucial for meeting the dual carbon goals. However, the intermittent and unpredictable nature of these energy sources poses significant challenges to the stability and reliability of the power grid. Energy storage systems are instrumental in addressing these challenges by providing flexibility and balancing supply and demand. This study focuses on analysing optimization models that guide the integration of new energy sources and the operation of energy storage systems in a synergistic manner, ensuring the efficient and sustainable use of energy resources. The research employs mathematical modeling and simulation techniques to analyze the interaction between new energy sources and energy storage systems. The main research questions explore how to design optimal operation strategies for source-storage synergy that can maximize the utilization of new energy and minimize environmental impact. The findings indicate that optimization models can significantly enhance the efficiency of new energy integration, providing valuable insights for policymakers and industry practitioners [1]. The significance of this study lies in its potential to provide policymakers and industry practitioners with valuable insights into the energy transition field, contributing to the development of strategies that align with environmental sustainability and economic viability.

2. The Path towards Dual Carbon Goals: Challenges and Solutions for Renewable Energy Integration

2.1. Dual Carbon Goals and Energy Transition

The global community has reached a consensus on the urgency of addressing climate change, leading to the widespread adoption of carbon peaking and carbon neutrality as key targets. Governments and industries around the world are actively seeking ways to transition from traditional fossil-fuel-based energy systems to more sustainable and low-carbon alternatives. This section reviews the international and domestic policies related to dual carbon goals, as well as the current progress and future trends of energy transition. For example, the European Union's Green Deal is a comprehensive plan to accelerate the transition to clean energy and achieve carbon neutrality by 2050. It includes a series of measures such as increasing the share of renewable energy, improving energy efficiency, and promoting the decarbonization of various sectors [1].

2.2. Challenges in New Energy Integration

The integration of new energy sources, especially wind and solar power, into the power grid faces several challenges. Firstly, the intermittent and variable output of these energy sources makes it difficult to ensure a stable power supply. Secondly, the geographical distribution of new energy resources may not match the location of energy demand, leading to the need for long - distance transmission and related losses. In addition, the existing power grid infrastructure may not be fully adapted to the large - scale integration of new energy, requiring significant upgrades and investments. According to a review by Li et al., the challenges of new energy integration include technical, economic, and policy - related aspects [2].

2.3. The Role of Energy Storage Systems in Power Grids

Energy storage systems play a crucial role in addressing the challenges of new energy integration. They can store excess energy during periods of high generation and release it during peak demand or when generation is insufficient. This helps to balance the supply and demand of electricity, improve the stability and reliability of the power grid, and reduce the need for backup power generation capacity. There are various types of energy storage technologies, such as batteries, pumped-hydro storage, and compressed air energy storage, each with its own advantages and limitations. Zhang and Li provided a comprehensive review of energy storage systems for renewable energy integration, highlighting their importance in the energy transition [3].

2.4. Current Research on Optimization Models for RE Integration

Numerous studies have been conducted on optimization models for renewable energy integration. These models aim to optimize the operation and management of power systems with a high penetration of renewable energy, taking into account various factors such as generation forecasting, load demand, and energy storage. Some models focus on the economic dispatch of power systems, while others consider the environmental impact and technical constraints. Wang and Liu discussed mathematical modeling and simulation for renewable energy systems, which can provide a basis for the development of optimization models.

3. Optimization Models and Simulation Analysis for Renewable Energy Integration with a Focus on Source - Storage Synergy and Policy Integration

3.1. Mathematical Modeling of New Energy Integration

This study developed mathematical models to represent the integration of new energy sources into the power grid. The models considered the generation characteristics of wind and solar power, such as their intermittent and variable output, as well as the load demand patterns. We used time-series data to simulate the generation and load profiles, and incorporated the uncertainties associated with new energy generation through probabilistic methods. For example, the generation of wind power can be modeled using a Weibull distribution, while solar power generation can be represented by a beta distribution.

3.2. Optimization Techniques for Source - Storage Synergy

To achieve optimal synergy between new energy sources and energy storage systems, this study employed various optimization techniques. These included linear programming, mixed-integer programming, and stochastic optimization methods. The optimization models aimed to minimize the total cost of the power system, including the cost of new energy generation, energy storage investment and operation, and the cost of grid reinforcement, while maximizing the utilization of new energy and ensuring the stability and reliability of the power supply. The constraints of the models included the power balance, energy storage capacity and power limits, and the technical and policy-related requirements.

3.3. Simulation and Analysis Framework

This paper established a simulation and analysis framework to evaluate the performance of the optimization models. The framework included the generation of input data, such as new energy generation forecasts, load demand forecasts, and energy storage parameters, as well as the implementation of the optimization models and the analysis of the results. We used software tools such as MATLAB and GAMS to perform the simulations and analyze the data. The results were presented in terms of the new energy utilization rate, the cost savings, and the impact on grid stability and reliability.

3.4. Incorporation of Policy Requirements into Model Constraints

Policy requirements related to dual carbon goals were incorporated into the optimization models as constraints. These requirements included the targets for the share of renewable energy in the total energy mix, the reduction of carbon emissions, and the incentives for energy storage investment and operation. By including these constraints, the models could provide solutions that were not only technically and economically feasible but also aligned with the policy objectives. For example, the EU Green Deal sets specific targets for the share of renewable energy and the reduction of carbon emissions, which can be used as constraints in the optimization models [4].

4. Case studies

4.1. Case Study 1: Wind Energy Integration and Storage

This case focused on the integration of wind energy into the power grid and the role of energy storage systems. We selected a region with a high potential for wind energy generation and analyzed the data on wind speed, power generation, and load demand. The optimization model was applied to determine

the optimal capacity and operation strategy of the energy storage system to maximize the utilization of wind energy and minimize the cost of the power system. The results showed that the energy storage system could significantly improve the wind energy utilization rate and reduce the fluctuation of the power output, thereby enhancing the stability of the power grid, as shown in Figure 1.

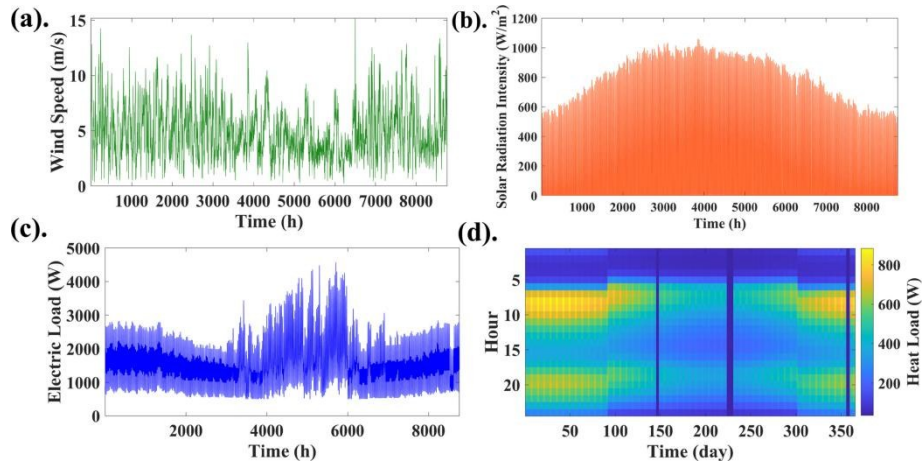


Figure 1: Wind power generation and load demand profile [5]

4.2. Case Study 2: Solar Energy Integration and Storage

This case study examined the integration of solar energy and the application of energy storage systems. It considered a region with abundant solar resources and analyzed the solar irradiance, power generation, and load demand data. The optimization model was used to optimize the operation of the solar power plant and the energy storage system, taking into account the diurnal variation of solar generation and the load demand patterns. The findings indicated that the energy storage system could effectively balance the supply and demand of electricity, increase the solar energy utilization rate, and reduce the need for backup power generation (see Figure 2).

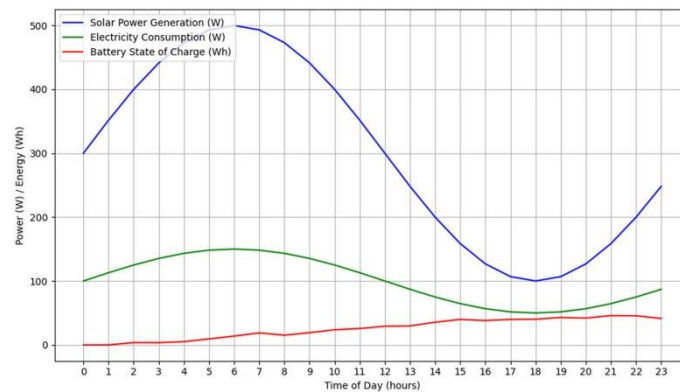


Figure 2: Solar power generation and load demand profile [6]

4.3. Case Study 3: Hybrid Renewable Energy Systems

This case investigated the integration of hybrid renewable energy systems, including wind and solar power, with energy storage. We analyzed the data from a region where both wind and solar resources were available and developed an optimization model to coordinate the operation of the different energy sources and the energy storage system. The results in Figure 3 demonstrated that the hybrid

renewable energy system, combined with energy storage, could provide a more stable and reliable power supply, with a higher utilization rate of renewable energy and lower environmental impact.

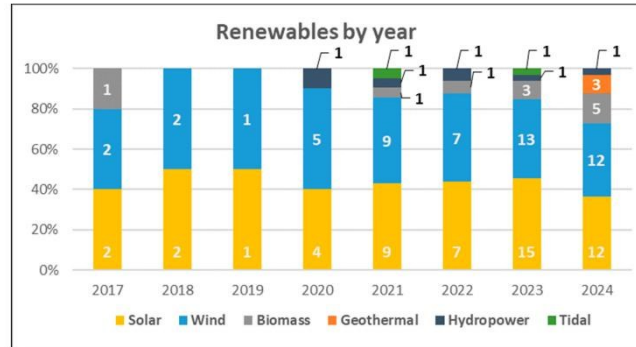


Figure 3: Hybrid renewable energy system configuration [7]

4.4. Analysis of Energy Storage Technologies and Demand Side Response

This section analyzed the impact of different energy storage technologies and demand side response measures on the integration of new energy sources. The study compared the performance of various energy storage technologies, such as lithiumion batteries, pumped-hydro storage, and compressed air energy storage, in terms of their energy density, cycle life, and cost (Table 1). This study also examined the role of demand-side response in shifting the load demand to match the generation of new energy sources, thereby reducing the need for energy storage capacity and improving the overall efficiency of the power system (Figure 4).

Table 1: Comparison of energy storage technologies

Technology	Energy Density (Wh/kg)	Cycle Life	Cost (\$/kWh)
Lithium - ion battery	150 - 250	3000 - 5000	150 - 200
Pumped - hydro storage	5 - 10	20000 - 30000	50 - 100
Compressed air energy storage	20 - 50	10000 - 15000	100 - 150

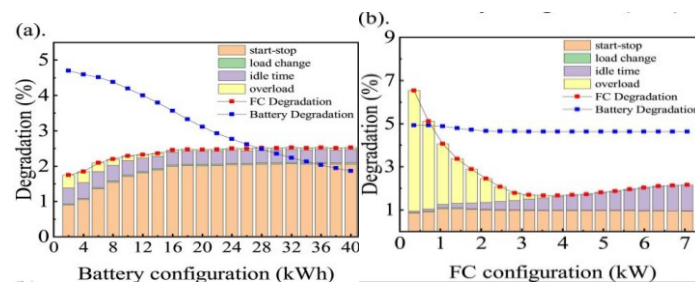


Figure 4: Comparison of different energy storage technologies [5]

5. Assessment of Optimization Models and Their Impact on Renewable Energy Integration for Dual Carbon Goals

5.1. Effectiveness of Optimization Models in RE Integration

The results of the case studies showed that the optimization models developed in this study were effective in improving the integration of new energy sources into the power grid. The models could provide optimal operation strategies for the energy storage systems, maximizing the utilization of new energy and minimizing the cost and environmental impact. The effectiveness of the models was demonstrated by the significant improvement in the new energy utilization rate and the reduction in the fluctuation of power output, as well as the cost savings achieved through the optimization of the power system operation.

5.2. Impact of Source-Storage Synergy on Grid Stability

The source-storage synergy achieved through the optimization models had a positive impact on the stability and reliability of the power grid. The energy storage systems could effectively balance the supply and demand of electricity, reducing the need for backup power generation capacity and improving the grid's ability to cope with the intermittency and variability of new energy sources. The case studies showed that the integration of energy storage systems could significantly reduce the voltage fluctuations and frequency deviations in the power grid, enhancing its overall stability.

5.3. Environmental and Economic Benefits Analysis

The optimization models not only improved the efficiency of new energy integration but also brought significant environmental and economic benefits. From an environmental perspective, the increased utilization of new energy sources led to a reduction in carbon emissions and other pollutants, contributing to the achievement of dual carbon goals. Economically, the optimization of the power system operation and the reduction in the cost of energy storage investment and operation resulted in cost savings for both power producers and consumers. The case studies provided evidence of the environmental and economic benefits of the optimization models, highlighting their potential for wide-scale application.

5.4. Policy Implications and Challenges in Dual Carbon Goals Context

The findings of this study have important policy implications for the achievement of dual carbon goals. The optimization models can provide policymakers with a scientific basis for formulating policies and regulations related to new energy integration and energy storage development. However, there are still some challenges in the context of dual carbon goals. These include the need for further improvement of the optimization models to better reflect the complexities of real-world energy systems, the integration of emerging technologies and market structures, and the scaling-up of the models for practical implementation in policy-making and industry practices (Table 2).

Table 2: Policy implications of optimization models

Policy Area	Implications
Renewable energy integration	Provide incentives for new energy generation and grid connection
Energy storage development	Support the research and development of energy storage technologies
Power system operation	Promote the use of optimization models in power system operation and management

6. Conclusion

This study has provided a comprehensive analysis of optimization models for integrating new energy sources and enhancing source-storage synergy to achieve dual carbon goals. The developed models significantly improve the efficiency of new energy integration and contribute to grid stability and reliability. By optimizing the interaction between new energy sources and energy storage systems, the study identifies strategies that maximize energy utilization and minimize environmental impact.

The findings demonstrate that optimization models can effectively manage source-storage synergy, addressing the intermittency and unpredictability of new energy sources. Despite these achievements, the study acknowledges its limitations, including assumptions that may not fully capture the complexities of real-world energy systems. Future research should focus on refining the models to incorporate dynamic and stochastic elements, enhancing their predictive capabilities. Additionally, future work should explore the social and environmental impacts of new energy integration and source-storage synergy, ensuring a holistic approach to sustainable energy transition. In summary, this study lays a foundation for further research and development of more sophisticated models, guiding the energy sector towards achieving dual carbon goals and ensuring a sustainable energy future. The results highlight the potential of optimization models to support policy-makers and industry practitioners in developing effective strategies for energy transition. The study also emphasizes the importance of considering both economic and environmental factors in the pursuit of sustainable energy solutions. Furthermore, the research suggests that continued advancements in optimization techniques and energy storage technologies will play a crucial role in overcoming the challenges associated with new energy integration.

In summary, this study lays a foundation for further research and development of more sophisticated models, guiding the energy sector towards achieving dual carbon goals and ensuring a sustainable energy future.

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