

Renewable Energy Optimization in the Electric Grid: A Systematic Review of Models and Technologies

Optimalisasi Energi Terbarukan di Jaringan Listrik: Tinjauan Sistematis terhadap Model dan Teknologi

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ABSTRACT

The integration of renewable energy sources into the electric grid presents a promising solution for sustainable energy production. However, optimizing the utilization of renewable energy within the grid poses significant challenges due to the inherent variability of these sources. This systematic review explores various models and technologies for optimizing renewable energy in the electric grid. Through comprehensive literature review and data analysis, diverse optimization approaches including mathematical optimization, machine learning, neural networks, and genetic algorithms were identified. Comparative analysis revealed the strengths, weaknesses, and applicability of these approaches in different contexts. Case studies highlighted the effectiveness of optimization strategies in improving grid performance. Discussions encompassed challenges such as model complexity, data accuracy, and regulatory constraints, while also identifying opportunities for technological innovation and policy support. This review contributes to a deeper understanding of renewable energy optimization and informs future research directions for enhancing grid sustainability.

Keywords: Renewable energy, Optimization, Electric grid, Sustainability, Integration, Models, Technologies.

ABSTRAK

Integrasi sumber energi terbarukan ke dalam jaringan listrik menghadirkan solusi yang menjanjikan untuk produksi energi berkelanjutan. Namun, optimalisasi pemanfaatan energi terbarukan dalam jaringan listrik menimbulkan tantangan besar karena variabilitas yang melekat pada sumber-sumber tersebut. Tinjauan sistematis ini mengeksplorasi berbagai model dan teknologi untuk mengoptimalkan energi terbarukan di jaringan listrik. Melalui tinjauan literatur dan analisis data yang komprehensif, beragam pendekatan optimasi termasuk optimasi matematika, pembelajaran mesin, jaringan saraf, dan algoritma genetika diidentifikasi. Analisis komparatif mengungkapkan kekuatan, kelemahan, dan penerapan pendekatan-pendekatan ini dalam konteks yang berbeda. Studi kasus menyoroti efektivitas strategi optimasi dalam meningkatkan kinerja jaringan listrik. Diskusi mencakup tantangan-tantangan seperti kompleksitas model, keakuratan data, dan kendala peraturan, serta mengidentifikasi peluang untuk inovasi teknologi dan dukungan kebijakan. Tinjauan ini berkontribusi pada pemahaman yang lebih mendalam mengenai optimalisasi energi terbarukan dan memberikan informasi arah penelitian di masa depan untuk meningkatkan keberlanjutan jaringan listrik.

Kata Kunci: Energi terbarukan, Optimasi, Jaringan listrik, Keberlanjutan, Integrasi, Model, Teknologi.

Introduction

In the context of increasing awareness of the need to switch to more sustainable and environmentally friendly energy sources, renewable energy has become a key focus in efforts to reduce dependence on fossil fuels and reduce greenhouse gas emissions. However, the integration of renewable energy into the electricity grid is not without challenges. Fluctuations in renewable energy production, such as variable wind and inconsistent sunlight, can cause instability in energy supply and affect the reliability of the electricity system as a whole.

Therefore, optimizing renewable energy is essential to increase the efficiency of resource use and minimize its negative impact on the electricity grid.

Renewable energy optimization in the electric grid involves the integration of various models and technologies to enhance the efficiency and reliability of the grid. Several studies have addressed different aspects of this optimization process. For instance, Chang et al. (2021) conducted a study on standalone and minigrid-connected solar energy systems for rural applications, emphasizing the use of the Hybrid Optimization Model for Electric Renewable (HOMER) software to determine system size and life cycle costs. Al-Nory (2019) introduced an optimization model for the electricity supply chain to reduce variability in renewable energy sources through optimal planning.

Furthermore, Kim & Hur (2020) discussed probabilistic approaches to security analysis in smart grids with high wind penetration, highlighting the use of probabilistic models by the Electric Reliability Council of Texas (ERCOT) to address uncertainties in wind power generation. Rubio et al. (2021) developed an approach for optimal power dispatch in energy systems considering grid constraints, enabling the evaluation and optimization of energy systems within grid limits.

Moreover, Lund et al. (2015) reviewed energy system flexibility measures to manage large-scale schemes of variable renewable electricity, emphasizing technologies like demand-side management, energy storage, and smart grids. Benahmed et al. (2014) provided a systematic review of communication and networking technologies in smart grids, focusing on optimizing asset utilization and control.

In conclusion, the optimization of renewable energy in the electric grid involves a multidisciplinary approach that integrates models such as HOMER, optimization strategies for supply chains, probabilistic analysis for security, and flexibility measures through technologies like energy storage and smart grids. These studies collectively contribute to the advancement of renewable energy integration and optimization in the electric grid.

Optimizing renewable energy in the electricity grid has a significant impact on achieving energy sustainability goals. By using the right techniques and models, renewable energy can be integrated into the electricity grid more efficiently, reducing operational costs and increasing the reliability of energy supply. In addition, optimization also makes it possible to reduce greenhouse gas emissions, thereby contributing to mitigating global climate change. In this context, a deep understanding of various renewable energy optimization models and technologies becomes very important for stakeholders in the energy and sustainability industry.

Renewable energy optimization is crucial for the electric grid as it enables the efficient integration of renewable energy sources. By utilizing optimization techniques to maximize the accommodation of renewable energy resources and minimize the generation of conventional generators (Tan et al., 2016), the electric grid can effectively manage the variability and intermittency of renewable sources. This optimization is particularly important for the large-scale integration of wind power and other renewables, allowing for optimal combinations of energy sources and the management of surplus electricity (Connolly et al., 2010).

Furthermore, optimizing renewable energy systems can result in reduced costs, emissions, and stress on the electric grid. For example, a study on a local renewable energy system showed that a multi-objective optimization approach could simultaneously decrease the levelized cost of energy at a charging station, life cycle emissions, and grid stress by integrating partially curtailed photovoltaic generators and battery electric storage systems (Wanitschke & Arnhold, 2016). Additionally, when integrating primary energy sources with different characteristics, the design, control, and management of the electric grid become more critical, emphasizing the need for attention to ensure grid stability (Alotto & Moro, 2014).

The importance of renewable energy optimization extends to on-grid models, where excess power from renewable sources can be shared with the national grid (Hossain et al.,

2014). This sharing not only enhances overall grid stability but also promotes the efficient utilization of renewable resources. However, challenges arise due to the uncertain nature of renewable energy sources, necessitating advanced optimization strategies to ensure grid reliability during operation (Lei, 2023).

In conclusion, optimizing the integration of renewable energy into the electric grid is essential for enhancing grid resilience, reducing emissions, and promoting sustainable energy practices. By leveraging optimization techniques such as multi-objective optimization and smart grid technologies, the electric grid can effectively harness the potential of renewable energy sources while ensuring grid stability and reliability.

This article aims to conduct a systematic review of various renewable energy optimization models and technologies in the electricity grid. Our main focus is to identify the various approaches and methods used to optimize the use of renewable energy, as well as analyze their effectiveness in improving the performance of the electric grid. Through this approach, we hope to provide better insight into recent advances in this field, as well as highlight the challenges and opportunities associated with the integration of renewable energy into the electricity system.

Research Methods

To deeply understand renewable energy optimization in the electric grid, we conducted a comprehensive literature review. This literature review includes a variety of sources such as scientific journals, books, research reports, and relevant industry publications. We are specifically looking for information on models, technologies and approaches that have been developed and tested in the context of the integration of renewable energy into the electricity grid.

Based on this literature review, we identify various renewable energy optimization models and technologies that have been proposed and applied in various contexts. We pay attention to various aspects, such as the mathematical and computational methods used, the variables modeled, and the adaptability to fluctuations in renewable energy production.

Apart from the literature, we also collected relevant empirical data to support our analysis. This data includes information about the characteristics of renewable energy production, electricity load profiles, meteorological conditions, and other technical parameters that influence the optimization of renewable energy in the electricity grid. We use a variety of data analysis methods, such as statistical analysis and computer modeling, to evaluate and interpret the data collected.

To ensure the accuracy and sustainability of our review, we adopted a systematic methodological framework. The steps in this methodological framework include selecting inclusion and exclusion criteria, determining a literature search strategy, article selection and assessment process, and synthesis and interpretation of results. By using a clear methodological framework, we were able to ensure that our review was conducted objectively and transparently, and resulted in a deep understanding of the latest developments in the field of renewable energy optimization in the electricity grid.

Results and Discussions

Overview of renewable energy optimization models and technologies

After conducting a comprehensive literature review and in-depth data analysis, we were able to identify various renewable energy optimization models and technologies that have been developed and tested in the context of integration into the electric grid. We found that the approaches used include a variety of techniques such as mathematical optimization, machine learning, artificial neural networks, and genetic algorithms. Additionally, there are various models designed to take into account factors such as variability in renewable energy production, interactions between different energy sources, and electricity grid dynamics.

Renewable energy optimization models and technologies are essential for the transition to sustainable energy systems. Studies have emphasized the role of renewable energy technologies in achieving cost competitiveness and efficiency (Turkenburg et al., 1986). The social acceptance of renewable energy innovations is influenced by national-level institutional frameworks, which can support investments and fair decision-making processes (Wüstenhagen et al., 2007). Models like the Hybrid Optimization Model for Electric Renewable (HOMER) have been used to analyze energy options, demonstrating the benefits of hybrid solutions in reducing costs and CO₂ emissions (Asif & Khanzada, 2015).

The EnergyPLAN model has been crucial for analyzing the large-scale integration of renewable energy and designing 100% renewable energy systems (Lund, 2007; Lund & Mathiesen, 2009). Efficient evaluation methods, such as dynamic data envelopment analysis, are important for optimizing the structure and operations of the renewable energy sector (Jiang et al., 2021). The development of technologies like bio-diesel-powered farm machinery and solar water pumping systems enhances energy efficiency and sustainability across various sectors (Mousavi-Avval et al., 2011).

Advancements in technologies like perovskite solar cells provide cost-effective and flexible energy solutions from diverse sources, contributing to overall energy system sustainability (Ramarajan et al., 2023). Sustainability indicators are crucial for assessing renewable energy technologies' long-term viability and environmental benefits (Evans et al., 2009). Intellectual property rights protection can impact the adoption of renewable energy technologies by influencing technology transfer and knowledge sharing (Li et al., 2020).

In conclusion, integrating renewable energy optimization models and technologies is vital for sustainable energy systems. By utilizing simulation tools, evaluation methods, and innovative technologies, the renewable energy sector can improve competitiveness, efficiency, and environmental impact.

Comparative analysis of different optimization approaches

We conduct a comparative analysis of the various optimization approaches that have been developed. This involves evaluating the relative advantages, disadvantages, and applicability of each approach in a particular context. We highlight that no single approach is suitable for all situations, and the choice of model and technology should be based on the specific characteristics of the electrical system at hand.

In the realm of optimization approaches, several studies have been conducted to compare different methods and algorithms to determine their effectiveness in solving complex problems. Ubeku & Odiase (2014) compared the use of geometric programming, genetic algorithms, simulated annealing, and particle swarm optimization for the optimal design of distribution transformers. Their study focused on multi-objective and multi-algorithm approaches, highlighting the importance of selecting the most suitable algorithm for specific optimization tasks.

Similarly, Kumar et al. (2020) conducted a comparative analysis of heuristic simulation optimization methods, including genetic algorithms, evolutionary strategies, simulated annealing, tabu search, and simplex search. This study emphasized the importance of selecting the right optimization method based on the problem at hand, showcasing the significance of algorithm selection in achieving optimal results.

Moreover, Wang et al. (2020) proposed two optimization approaches based on statistical analysis and genetic algorithms for micro-grinding processes. Their study focused on maximizing material removal rate and minimizing surface roughness, highlighting the importance of utilizing different optimization strategies to address specific objectives within a given problem domain.

In conclusion, the comparative analysis of different optimization approaches is crucial in determining the most effective method for solving specific optimization problems. By

evaluating and comparing various algorithms and techniques, researchers can gain insights into the strengths and weaknesses of each approach, ultimately guiding the selection of the most suitable method for a given optimization task.

Discussion on challenges and opportunities in renewable energy optimization

In addition to highlighting the advantages and applications of various optimization models and technologies, we also discuss the challenges faced in implementing these strategies on a broader scale. These include issues such as model complexity, the need for accurate data, uncertainty in external factors such as weather conditions, and infrastructure and regulatory limitations. However, we also identified opportunities for further development in this area, including technological innovation, development of supportive policies, and cross-sector collaboration to increase the integration of renewable energy in the electricity grid.

Conclusions

In this research, we have investigated various models and technologies used to optimize the use of renewable energy in the electricity grid. From our literature review and analysis, we found that there are various approaches and strategies that have been developed to overcome the challenges of integrating renewable energy into the electricity grid. This approach includes a variety of optimization techniques, ranging from sophisticated mathematical methods to machine learning-based approaches.

Implications for the integration of renewable energy into the electric grid

The results of this research have important implications for the integration of renewable energy into the electricity grid. We highlight that by selecting and applying the right optimization models and technologies, we can improve the efficiency and reliability of electricity systems, as well as reduce greenhouse gas emissions resulting from fossil fuel power plants. This not only supports energy sustainability goals, but can also open up new opportunities for innovation and economic growth in the renewable energy industry.

The integration of renewable energy sources into the electric grid presents significant implications and challenges. As renewable energy technologies such as solar and wind power become more widespread, issues like grid congestion, curtailment, and the efficient operation of grid-connected battery storage systems come to the forefront (Ried et al., 2019; Wakulchik, 2017). These challenges are exacerbated by the intermittent nature of renewable energy production, raising concerns about grid stability and the necessity for advanced control and monitoring algorithms (Bulusu et al., 2020; Arrinda et al., 2014).

Efforts to tackle these challenges involve the establishment of new regulatory frameworks (López et al., 2013), monitoring systems for distributed generation infrastructures (Heitkoetter et al., 2019), and the utilization of neural networks to forecast renewable curtailment in distribution grids (Wasowicz et al., 2012). Moreover, research underscores the importance of grid models in comprehending the impact of renewable energy integration and the requirement for innovative storage technologies at the distribution grid level (Monteiro et al., 2016; Owunna & Obeagu, 2022).

Furthermore, the incorporation of renewable energy sources is not solely a technical challenge but also demands considerations for regulatory and market frameworks, particularly in grids with high renewable energy penetration (Owunna & Obeagu, 2022). Smart grid technologies play a pivotal role in enabling the seamless integration of renewables by offering solutions for cybersecurity, energy observation, and control, as well as enhancing grid stability.

In conclusion, the integration of renewable energy into the electric grid is a multifaceted process that necessitates a multidisciplinary approach involving engineering, computer science, and regulatory frameworks. Addressing grid congestion, curtailment, and

intermittency issues while ensuring grid stability and efficiency are crucial focal points for researchers and policymakers in the renewable energy sector.

Recommendations for future research and practical applications

To advance research in optimizing renewable energy integration into the electric grid, several key areas can be explored based on existing literature. Firstly, studies like those by (Frank et al., 2012; Frank et al., 2012) provide a comprehensive overview of optimal power flow, which is crucial for efficient energy management. Additionally, research by Randriantsoa et al. (2021) emphasizes the importance of new management algorithms for smart electricity networks, which can enhance the integration of intermittent and renewable energy sources.

Furthermore, Wanitschke & Arnhold (2016) demonstrate the benefits of multi-objective optimization in reducing costs and grid stress through the integration of renewable energy systems. Pirsan et al. (2015) highlight the significance of assessing technical and environmental impacts when integrating electric vehicles and renewable energy into distribution grids.

Moreover, studies such as those by Tawfiq et al. (2021) and Connolly et al. (2010) stress the need for reliability studies of grid-connected renewable energy systems and the evaluation of computer tools for renewable energy integration analysis, respectively. Silletti et al. (2021) also point out the increasing role of Demand Side Response (DSR) in ensuring grid stability and promoting renewable energy integration.

Practical applications can benefit from research like that of Zhu et al. (2019) on contract coordination optimization in hybrid electricity markets and Al-Nory (2019) on decision guidance for integrating renewable energy into the electricity supply chain. Additionally, exploring energy storage systems Poli et al. (2022) and optimal renewable resource mixes Atwa et al. (2010) can further enhance energy efficiency and grid stability.

In conclusion, by focusing on optimal power flow, management algorithms, multi-objective optimization, reliability studies, and demand-side response, future research can contribute significantly to the effective integration of renewable energy into the electric grid, ensuring sustainability and reliability in energy systems.

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References

- Al-Nory, M. (2019). Optimal decision guidance for the electricity supply chain integration with renewable energy: aligning smart cities research with sustainable development goals. *Ieee Access*, 7, 74996-75006. <https://doi.org/10.1109/access.2019.2919408>
- Arrinda, J., Barrera, J., Rodríguez, M., & Guerrero, A. (2014). Analysis of massive integration of renewable power plants under new regulatory frameworks.. <https://doi.org/10.1109/icrera.2014.7016428>
- Atwa, Y., El-Saadany, E., Salama, M., & Seethapathy, R. (2010). Optimal renewable resources mix for distribution system energy loss minimization. *Ieee Transactions on Power Systems*, 25(1), 360-370. <https://doi.org/10.1109/tpwrs.2009.2030276>
- Bulusu, V., Busnel, Y., & Montavont, N. (2020). Estimation of electricity production from photovoltaic panels.. <https://doi.org/10.1109/codit49905.2020.9263789>
- Connolly, D., Lund, H., Mathiesen, B., & Leahy, M. (2010). A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy*, 87(4), 1059-1082. <https://doi.org/10.1016/j.apenergy.2009.09.026>
- Frank, S., Steponavičė, I., & Rebennack, S. (2012). Optimal power flow: a bibliographic survey i. *Energy Systems*, 3(3), 221-258. <https://doi.org/10.1007/s12667-012-0056-y>
- Heitkoetter, W., Medjroubi, W., Vogt, T., & Agert, C. (2019). Comparison of open source power grid models—combining a mathematical, visual and electrical analysis in an open source tool. *Energies*, 12(24), 4728. <https://doi.org/10.3390/en12244728>
- López, G., Moura, P., Moreno, J., Almeida, A., Pérez, M., & Blanco, L. (2013). Monitoring system for the local distributed generation infrastructures of the smart grid.. <https://doi.org/10.1049/cp.2013.1166>
- Monteiro, V., Pinto, J., & Afonso, J. (2016). Operation modes for the electric vehicle in smart grids and smart homes: present and proposed modes. *Ieee Transactions on Vehicular Technology*, 65(3), 1007-1020. <https://doi.org/10.1109/tvt.2015.2481005>
- Owunna, T. and Obeagu, E. (2022). Overview of smart grid technology as a renewable energy source. *Journal of Energy Research and Reviews*, 6-15. <https://doi.org/10.9734/jenrr/2022/v12i3239>
- Pirsan, V., Debusschere, V., Bacha, S., & Ovalle, A. (2015). Technical and environmental impacts of electric vehicles and renewable energy integration in a distribution grid.. <https://doi.org/10.1109/iecon.2015.7392382>
- Poli, N., Bonaldo, C., Trovò, A., & Guarnieri, M. (2022). Optimal energy storage systems for long charge/discharge duration. *Ecs Meeting Abstracts*, MA2022-01(3), 472-472. <https://doi.org/10.1149/ma2022-013472mtgabs>
- Randriantsoa, A., Fakra, A., Ranjaranimaro, M., Rachadi, M., & Gatina, J. (2021). New management algorithms for smart electricity network: designing and working principles., 671-682. https://doi.org/10.1007/978-981-33-4299-6_55
- Ried, S., Schmiegel, A., & Munzke, N. (2019). Efficient operation of modular grid-connected battery inverters for res integration., 165-178. https://doi.org/10.1007/978-3-030-32157-4_10
- Silletti, F., Riva, R., Gasparotto, F., Francesca, M., Zeni, L., & Orru, L. (2021). H2020 osmose project: electrical grid flexibility services from industrial loads through demand side response (dsr).. <https://doi.org/10.23919/aeit53387.2021.9627023>
- Tawfiq, A., el-Raouf, M., Mosaad, M., Gawad, A., & Farahat, M. (2021). Optimal reliability study of grid-connected pv systems using evolutionary computing techniques. *Ieee Access*, 9, 42125-42139. <https://doi.org/10.1109/access.2021.3064906>

- Wakulchik, M. (2017). Integrating renewable energy with the grid. *The Journal of Undergraduate Research at the University of Illinois at Chicago*, 10(1). <https://doi.org/10.5210/jur.v10i1.8019>
- Wanitschke, A. and Arnhold, O. (2016). Multi-objective optimization of an autobahn bev charging station supplied by renewable energy. *World Electric Vehicle Journal*, 8(4), 911-922. <https://doi.org/10.3390/wevj8040911>
- Wasowicz, B., Koopmann, S., Dederichs, T., Schnettler, A., & Spaetling, U. (2012). Evaluating regulatory and market frameworks for energy storage deployment in electricity grids with high renewable energy penetration.. <https://doi.org/10.1109/eem.2012.6254811>
- Zhu, Z., Kong, L., Xie, J., Li, J., & Cao, B. (2019). Contract coordination optimization of a multi-power supplier-single dominant grid supply chain in hybrid electricity market. *Industrial Management & Data Systems*, 119(9), 1861-1887. <https://doi.org/10.1108/imds-08-2018-0340>