Optimal Sizing and Operation of Standalone Power Systems for Remote Industrial Applications

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Abstract. This paper reviews the work in the areas of optimal sizing and operation of standalone power systems for remote industrial applications. The first study delves into an innovative approach applied to sizing in a hybrid power system, focusing on meeting the demands of a residential area in south-east Iran. This system integrates fuel cells, wind units, electrolysers, a reformer, an anaerobic reactor, and hydrogen tanks, utilizing biomass as an energy resource. The system's design ensures that power produced from wind turbines and fuel cells meets the demand, with excess power directed to the electrolyser and shortages supplemented by stored hydrogen. The primary objective is cost minimization using the PSO algorithm. The subsequent studies emphasize the accelerated development of eco-friendly technologies shaping the future of electric power generation. They present a methodology for capacity optimization of a residential standalone microgrid, incorporating renewable energy sources, diesel generators, and battery storage systems. The microgrid caters to both typical residential loads and electric vehicle charging demands. Through intricate optimization, the studies aim to minimize costs, reduce greenhouse gas emissions, and limit dump energy. The research also explores the impact of load shifting on distributed generators and storage systems, offering valuable insights for decision-makers and policy developers.

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1 Introduction

The evolution of standalone power systems has been driven by the necessity to provide electricity to remote areas where conventional utility lines are impractical or uneconomical. Such regions, often characterized by challenging terrains, environmental concerns, or right-of-way difficulties, have been historically underserved. The World Bank estimates that over 2 billion people reside in such disconnected villages, making them a prime market for hybrid standalone systems, particularly those integrating fuel cells with wind energy [4]. These systems not only address the immediate energy needs but also pave the way for sustainable and eco-friendly solutions.

Historically, the focus of research in this domain has been on the optimal sizing of hybrid systems, with studies exploring combinations of wind, solar, and fuel cells. The introduction of biomass as a means to produce the required hydrogen for these systems has added another layer of complexity and potential to the mix. The Particle Swarm Optimization (PSO) algorithm has emerged as a popular tool for such optimization tasks, ensuring that the hybrid systems are not only efficient but also reliable, especially with the inclusion of reformers for hydrogen generation.

In recent times, the global emphasis on eco-friendly technologies has intensified, driven by concerns such as depleting fossil fuel reserves, environmental policies, global warming effects, and the unpredictable nature of renewable energy sources. This has led to the rise of the microgrid (MG) concept, which promises a more controlled, coordinated, and efficient operation of power systems. MGs, being closer to the load centres, promise reduced power losses, better power quality, and a greener energy supply. Especially in remote areas, where connecting to the national grid is not feasible, standalone MGs leveraging local renewable energy sources present a compelling solution. However, the inherent unpredictability of renewable sources like solar and wind necessitates the integration of energy storage systems, such as batteries, to ensure reliability.

The challenges associated with renewable energy sources, from load mismatches to reliability concerns, can be mitigated by employing a judicious mix of renewable technologies and energy storage systems. While battery energy storage systems offer a solution, their high initial costs and limited life cycles present challenges. This has led to the exploration of other sources, such as diesel generators, which, despite their predictability, come with environmental and operational concerns. Furthermore, the transportation sector's shift towards electric vehicles (EVs) introduces another layer of complexity to the power demand landscape. The integration of EVs into the power system, coupled with advancements in power electronics and communication systems, is transforming MGs into future-ready smart grids. These grids, with their two-way communication channels, promise enhanced reliability, efficiency, and flexibility, especially with the potential of load shifting through controllable loads.

In this review, we delve into the intricate interplay of these various components, exploring methodologies for capacity optimization in standalone MGs, the challenges and solutions in integrating renewable sources, storage systems, and conventional generators, and the potential of next-generation power systems in shaping a sustainable energy future.

2 Review and discussion

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In a study by Hakimi et al. (2009), the researchers presented an innovative approach to sizing a hybrid power system, specifically for the Kahnouj area in south-east Iran [1]. This region, like many others globally, has unique energy demands and resources. The proposed system comprises fuel cells, wind units, electrolysers, a reformer, an anaerobic reactor, and hydrogen tanks. The system operates independently and utilizes biomass as a primary energy resource. The hydrogen produced by the reformer is directly supplied to the fuel cell. When the combined power from the wind turbine and the fuel cell exceeds the demand, the surplus is directed to the electrolyser. Conversely, when the generated power is insufficient, additional fuel cells powered by stored hydrogen are employed. The primary objective of this study was to minimize the overall system costs while ensuring the energy demand is met. The Particle Swarm Optimization (PSO) algorithm was employed for optimal sizing of the system's components [5-9].

Table 1. Hybrid Power System Components & Sizing

Component	Description	Specifications/Details
Wind Turbine	Converts wind energy to electricity.	Uses Bergey Wind Power's BWC Excel-R/48 with a rated capacity of 7.5 kw. Costs $19.4k/unit with a 20-year lifespan.
Fuel Cell	Combines hydrogen fuel with oxygen to produce electricity.	Uses Ballard fuel cell. Efficiency is 50%. Costs $3k for a 1-kw system with a 5-year lifespan.
Electrolyser	Dissociates water into hydrogen and oxygen.	Uses Avalence electrolyser. Efficiency is 90%. Costs $2k for a 1-kw system.
Anaerobic Reactor	Processes waste in the absence of oxygen to produce methane.	Produces a constant volume of methane each hour.
Reformer	Produces hydrogen from methane using high temperature steam.	Uses MAHLER reformer. Converts waste to hydrogen at a constant rate daily.
Hydrogen Tank	Stores hydrogen.	Uses CH2 based on application size. Costs $1.3k for a tank with 1 kg capacity with a 20-year lifespan.
Power Converter	Converts DC to AC.	Costs $800 for a 1-kw system with a 15-year lifespan and 90% efficiency.
Optimization Method	Particle Swarm Optimization (PSO) was used to determine the optimal sizing of the system components.	PSO algorithm is faster and less complicated than other methods.
Objective	Minimize the total costs of the system while ensuring the energy demand is met.	The study considered three situations: generation meets demand, over generation, and over demand.

The research by Hakimi et al. (2009) provides valuable insights into the optimal sizing of hybrid power systems, especially for regions with specific energy demands and resources.

Their innovative approach, utilizing the PSO algorithm, offers a promising solution for regions similar to Kahnouj. The comprehensive design, which integrates various energy components, emphasizes the importance of renewable energy sources and the potential for their efficient utilization. As we delve deeper into the realm of renewable energy in our review, this study serves as a testament to the advancements in the field and the potential for sustainable energy solutions in the future.

Another study by Akram et al. (2018) delves into the future of autonomous residential smart power systems. The key findings from the study are summarized as follows [2,10-14]:

- **Objective and Scope**: The paper presents a methodology for optimizing the capacity of a residential standalone microgrid (MG) that employs renewable energy (RE) sources such as solar photovoltaic (PV), wind turbines (WTs), diesel generators (DGs), and battery energy storage system (BESS). This MG is designed to supply a residential community load, which includes typical residential demands and electric vehicle (EV) charging loads.
- **Significance of the Study**: With the rapid development of eco-friendly technologies like renewable energy, smart grids, and electric transportation, the future of electric power generation and supply is evolving. Modern power systems are becoming more flexible and controllable, which impacts the sizing of power generation systems.
- **Challenges with Renewable Energy**: While renewable energy sources like solar and wind are gaining attention due to reduced costs and advancements in power electronics, they are inherently intermittent and dependent on weather conditions. This intermittency can lead to mismatches between energy supply and demand, affecting the reliability of the power system.
- **Role of Energy Storage**: To address the challenges posed by renewable energy sources, the study suggests using a combination of different RE technologies along with energy storage systems like BESS. However, solely relying on RE sources and BESS can be costly. Thus, incorporating a dispatchable source like a diesel generator is recommended for effective and economical power supply.
- **Electric Vehicles (EVs)**: The transportation sector is a significant contributor to greenhouse gas emissions. Electric vehicles, which have been gaining traction as a solution to reduce emissions, will play a crucial role in future power system planning. The study emphasizes the need to consider a substantial number of EVs in future power system designs.
- **Smart Grids**: The study envisions microgrids evolving into smart grids in the future, thanks to innovations in power electronics and advanced communication systems. Smart grids can provide two-way communication between power generation stations and end-users, allowing for more efficient load management.
- **Optimization Methodology**: The paper introduces a capacity optimization methodology for a standalone MG that employs distributed generators, BESS, and considers EV charging loads. The methodology aims to minimize costs, reduce greenhouse gas emissions, and curtail excess energy.
- **Case Study**: The methodology is validated using real-world data from Dammam, located in the eastern region of Saudi Arabia. The results highlight the effectiveness of the proposed idea.

In relation to our review article, Akram et al.'s study provides valuable insights into the future of autonomous residential power systems. Their comprehensive approach to integrating renewable energy sources, energy storage systems, and electric vehicles offers a blueprint for sustainable and efficient power generation and supply. The emphasis on smart

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grids and the potential for load management further underscores the importance of technological advancements in shaping the future of energy.

Another study by Khezri et al. (2020) delves into the optimal sizing of standalone hybrid electricity systems with a focus on time-of-use (ToU) incentive demand response [3]. The research introduces a two-stage optimization technique for determining the size of various components in these systems. Here are the key findings from the study [16-21]:

- **Objective**: The study aimed to optimize the sizing of various components in standalone hybrid electricity systems, incorporating a time-of-use (ToU) incentive demand response program. The optimization was carried out in two stages: the first stage determined the minimum levelized cost of electricity (LCOE) without using demand response, while the second stage used the result from the first stage to develop a ToU demand response for incentive payment.
- **Hybrid Standalone Power Systems**: The research considered various combinations of diesel generators (DG), wind turbines (WT), solar photovoltaics (PV), battery storages (BS), and flywheels (FW) to develop five different standalone system configurations.
- **Case Study**: The study was based on a remote area residential community in Nundaroo, South Australia. The data used for the study included real yearly data of electricity consumption, solar radiation, wind speed, and air temperature.
- **Optimization Model**: The study employed a two-stage optimization model. The first stage focused on minimizing the LCOE of the power system configurations without demand response. The second stage introduced the incentive demand response, adjusting the consumption pattern based on ToU rates.
- **Results**: The results from the first stage of optimization, without demand response, revealed that the hybrid standalone system consisting of diesel, solar, wind, and battery had the minimum overall cost of electricity. The second stage introduced ToU rates for incentive demand response based on three periods of a day: off-peak, shoulder, and peak.
- **Conclusion**: Incorporating demand response programs can significantly reduce the total costs of standalone hybrid power systems. The application of such programs can alter consumption patterns, potentially eliminating nonessential loads in the power system.

In the context of our review article, Khezri et al.'s research underscores the potential of hybrid electricity systems in remote areas, especially when combined with demand response programs. Their two-stage optimization approach offers a comprehensive method to determine the most cost-effective configurations for standalone systems. This study further emphasizes the importance of integrating renewable energy sources and demand response programs to achieve sustainable and economical electricity supply in remote regions.

3 Future Scope of Research

The rapid evolution of standalone power systems for remote industrial applications has paved the way for numerous advancements. However, as with any burgeoning field, there are myriad avenues yet to be explored. Here are some potential directions for future research:

- **Advanced Energy Storage Solutions**: While current research has touched upon battery storage systems, there's potential to delve deeper into next-generation

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energy storage solutions, such as supercapacitors, flow batteries, and thermal storage.

- **Integration of Multiple Renewable Sources**: Exploring the synergies between various renewable energy sources, such as geothermal, tidal, and biomass, in conjunction with the more common solar and wind sources, could lead to more robust and resilient systems.
- **Demand Response Algorithms**: With the advent of smart grids and IoT, developing sophisticated algorithms that can predict and adjust to demand in real-time could be a game-changer.
- **Decentralised Energy Systems**: Investigating the feasibility and efficiency of decentralised energy systems, where multiple small-scale standalone systems work in tandem, could offer more flexibility and resilience.
- **Environmental Impact Assessments**: As the push for green energy continues, comprehensive studies on the environmental footprint of these standalone systems, including their lifecycle impact, would be invaluable.

4 Knowledge Gaps

The journey towards optimal standalone power systems for remote applications has been enlightening, yet there remain certain areas where our understanding is still nascent. These gaps in our knowledge present both challenges and opportunities.

- **Economic Viability**: While the technological aspects are often discussed, comprehensive economic analyses, especially long-term return on investment and total cost of ownership for these systems, are sparse.
- **System Longevity and Maintenance**: There's limited data on the long-term performance, degradation rates, and maintenance needs of hybrid standalone systems, especially in harsh or variable climates.
- **Interplay between Components**: While individual components like solar panels, wind turbines, and batteries are well-researched, the intricate dynamics when they're integrated into a single system need more attention.
- **Cultural and Social Acceptance**: The human element is often overlooked. How do remote communities perceive these technologies? What's their level of trust and acceptance?
- **Regulatory and Policy Frameworks**: As these systems become more prevalent, there's a pressing need to understand and shape the regulatory landscapes that can either facilitate or hinder their adoption.

In the grand tapestry of standalone power systems for remote applications, these future research avenues and knowledge gaps represent the threads yet to be woven. Addressing them will not only enrich the fabric but also ensure that the solutions developed are holistic, sustainable, and truly beneficial for all stakeholders involved.

5 Conclusion

The exploration into the optimal sizing and operation of standalone power systems for remote industrial applications has been both enlightening and promising. As we reflect upon the insights gathered from the three pivotal studies reviewed, several key findings emerge that shape our understanding and vision for the future:

- **Holistic Approach to System Design**: Standalone power systems, especially in remote areas, benefit immensely from a comprehensive approach that integrates various energy sources, storage solutions, and demand response mechanisms. This ensures not only energy sufficiency but also system resilience.

- **Significance of Hybrid Systems**: The combination of renewable energy sources, such as solar and wind, with traditional power generation methods, like diesel generators, offers a balanced solution that addresses both reliability and sustainability concerns.
- **Role of Advanced Algorithms**: Techniques like Particle Swarm Optimization (PSO) have proven instrumental in achieving optimal sizing of system components, ensuring that the demand is met efficiently and economically.
- **Demand Response and Smart Grids**: The future of standalone power systems is intertwined with the evolution of smart grids. The ability to adjust to demand in real-time, especially with the integration of electric vehicles, will be pivotal in ensuring system efficiency.
- **Economic and Environmental Balance**: While the drive towards green energy is commendable, it's equally crucial to ensure the economic viability of these systems. Striking the right balance between initial investments, operational costs, and environmental benefits is key.
- **Global Relevance and Scalability**: The studies, though focused on specific regions like south-east Iran or Dammam in Saudi Arabia, underscore the global relevance of the findings. Many regions worldwide share similar energy challenges, making the insights universally applicable.

In the context of our review article, it's evident that the realm of standalone power systems for remote applications is at an exciting juncture. The authors' studies that we have reviewed in this paper provide a foundation, but the true potential lies in the amalgamation of these insights, leading to solutions that are not only technologically advanced but also socially impactful and environmentally conscious. The journey ahead, while challenging, holds immense promise for a sustainable energy future.

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