Optimization of Nanogrids for Remote Off-Grid Communities

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Abstract. This review article delves into the advancements in the realm of nanogrids and their potential in addressing energy challenges, particularly in regions with limited access to centralized power grids. The paper reviews the work in the areas of nanogrids as solutions for regions like sub-Saharan Africa, where a significant population lacks access to main grid electricity. The integration of multiple nanogrids within a community, coupled with an investor energy bank, is explored as a means to alleviate the economic burden of energy storage and to harness the full potential of solar energy. The article also examines the challenges faced by centralized power grids and the shift towards distributed generation (DG) as a remedy. The concept of nanogrids is further elaborated, discussing their control topologies, techniques, and the potential of interconnecting multiple nanogrids to form a microgrid. Lastly, the co-design of solar generation-based nano-grids and water treatment in remote areas is studied, emphasizing the importance of providing essential drinking water and electricity to underdeveloped regions. The integration of solar-powered electricity with water treatment processes offers a unique solution to address both electricity and water needs in such areas.

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1 Introduction

The concept of nanogrids is emerging as a beacon of hope in the realm of sustainable energy solutions. These systems, smaller than the more commonly discussed microgrids, offer the potential for localized power generation and consumption, especially in remote and underserved communities. The modular nature of nanogrids allows for the interconnection of multiple units, creating a network that can efficiently balance supply and demand.

In this review, we aim to shed light on these pivotal areas of research, exploring the intricacies of nanogrids and their transformative potential in the energy landscape.

Distributed generation (DG), which produces power closer to its consumption point, is also gaining traction. By reducing transmission losses and enhancing efficiency, DG presents a promising solution to the challenges of traditional power grids. However, the intermittent nature of renewable energy and the initial financial outlay required for its setup pose challenges to its widespread adoption.

Furthermore, the pressing challenge of ensuring access to clean water in underserved communities cannot be overlooked. The interdependence of water treatment and electricity supply further complicates the issue. For instance, communities like the Texas Colonias, located along the Texas-Mexico border, face both water and electricity scarcity. Addressing these dual challenges requires innovative solutions that can optimize the use of available resources. This review delves into the advancements in nanogrids and their potential in addressing these intertwined challenges, focusing on the integration of solar-powered electricity with water treatment processes to offer holistic solutions to underserved communities.

2 Review and discussion

In a study by Giraneza et al. (2020), the dynamics of power production and consumption in a system of interconnected nanogrids were explored. The study simulated the system over a duration of 24 seconds, representing a day's cycle, and examined the energy production, consumption, and export patterns of three nanogrids. The findings from this study provide insights into the potential of nanogrids in optimizing energy usage and ensuring a sustainable energy trading system [1].

Table 1. Dynamics of Power Production and Consumption in Interconnected Nanogrids

Parameter	Nanogrid 1	Nanogrid 2	Nanogrid 3	Overall/Remarks
Simulation Duration	24 seconds	24 seconds	24 seconds	Representing a day's cycle
Initial Assumption	6 seconds	6 seconds	6 seconds	Represents 6 hours of clear sky day
Load Variation	Decreased by 50% for commercial users	Decreased by 50% for commercial users	Decreased by 50% for commercial users	Increased by 50% for domestic users at t=8 seconds

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	at t=8 seconds	at t=8 seconds	at t=8 seconds	
Total Power Produced	8 kW	10 kW	6 kW	-
Energy Export (1 hour)	6 kW	8 kWh	5 kWh	Combined Power Export: 20 kW
Total Energy Export (6 hours)	-	-	-	120 kWh with an irradiance of 1000 W/m^2
Energy Bank Role	Takes over after t=6.5 seconds	Takes over after t=6.5 seconds	Takes over after t=6.5 seconds	Represents sunset; supplies power to all clients and nanogrids
Load Management	Essential	Essential	Essential	Maintains supply-demand balance; local loads and cell tower as critical loads
Factors for Economic Viability	Capacity	Size of energy bank	Number of clients	Especially commercial users
Energy Bank Sizing	In line with capacity	In line with capacity	In line with capacity	Prevents energy wastage
Energy Pricing	Governed by supply vs. demand	Governed by supply vs. demand	Governed by supply vs. demand	Optimal sizing ensures affordable prices while covering costs

The study seamlessly aligns with the overarching theme of our review article, emphasizing the pivotal role of nanogrids in the broader landscape of sustainable energy solutions. By underscoring the importance of optimizing the energy trading system, it sheds light on the intricacies of efficient energy production, consumption, and trading. The findings, as detailed in the table, not only provide a granular understanding of interconnected nanogrid dynamics but also accentuate the imperative of strategic planning. This encompasses judicious energy bank sizing and astute pricing strategies, both of which are paramount for the economic viability and sustainability of the system. As we delve deeper into the advancements in solid oxide fuel cells and electrolysers for green hydrogen production, such insights offer a foundational understanding, bridging the gap between micro-level nanogrid operations and macro-level sustainable energy goals [4].

Another study by Burmester et al. (2017) delves into the intricacies of nanogrid networks and their potential advantages in the realm of power systems [2]. The research emphasizes the modular nature of nanogrids and their capability to form larger, interconnected power systems. Here are the summarized key findings of the study [5-9]:

- **Modularity and Interconnectivity**:
  - Nanogrids offer a bottom-up approach, allowing for the creation of larger power systems by interconnecting multiple nanogrids.
  - This leads to a hierarchical power distribution system, transitioning from nanogrids to microgrids and eventually to the national grid.
- **Bidirectional Power Sharing**:
  - The main function of a nanogrid network is to facilitate bidirectional power sharing.
  - The diversity in power consumption and production patterns among houses and small buildings can be leveraged for sharing excess power, leading to financial savings.
- **Communication in Nanogrid Networks**:
  - Communication is central to the nanogrid network, enabling intelligent information sharing.
  - Multiple layers of communication exist, from internal nanogrid communication to microgrid and national grid communication.
- **Financial Benefits**:
  - The interconnection of multiple nanogrids offers financial benefits.
  - Power can be sold within the network at negotiated prices, benefiting both the buyer and seller.
- **Resilience to Power Outages**:
  - Nanogrid networks can operate independently during national grid blackouts, ensuring continuous power supply.
- **Gradual Introduction**:
  - The nanogrid network paradigm allows for a phased introduction, negating the need for large-scale investments upfront.
- **Grid Stability**:
  - Nanogrid networks can respond quickly to utility grid commands, potentially aiding in grid stabilization and real-time pricing.
- **Nanogrid Network Testbed Installation**:
  - The study provides a detailed discussion on a nanogrid network testbed installation.
  - The system operates on DC power and focuses on power sharing exclusively within the network.
  - The design and setup of the system were tested and replicated, with ongoing installations in inhabited houses.

In essence, the study by Burmester et al. underscores the potential of nanogrid networks in revolutionizing power distribution, offering a blend of modularity, resilience, and financial benefits.

Nanogrids, with their modular design, are becoming pivotal in reshaping future power systems. These tailored power systems for individual homes or small buildings offer a solution to the challenges of renewable energy intermittency. By using nanogrid controllers, it's possible to synchronise energy supply and demand, and even trade energy with other entities, enhancing the return on renewable investments.

On a larger scale, interconnected nanogrids can form expansive microgrid systems, ensuring efficient energy distribution and economic benefits. The choice between DC and AC nanogrids depends on specific needs, but the right control mechanisms are crucial for their success. In essence, nanogrids present a promising avenue for a sustainable and economically viable energy future.

Within the scope of our review article on power distribution dynamics, the study underscores the transformative role of nanogrids. These modular systems are more than just technological advancements; they symbolise a new era in energy solutions. By championing sustainable, efficient, and economically sound energy practices, nanogrids emerge as pivotal for stakeholders and policymakers. Their significance in our review is a clear indicator of their potential in shaping a sustainable energy future.

In another study, Modarresi et al. (2020) embarked on an intricate exploration of the co-design of energy and water filtration systems, particularly focusing on the application of solar-powered nano-grids [3]. Their research was driven by the need to provide sustainable solutions for remote areas, with the Texas Colonias serving as a representative community. The study meticulously addressed various components of the system, from filtration design to energy requirements, and even delved into the economic implications of their findings. The table below encapsulates the pivotal outcomes of their research:

Table 2. Key findings from the study on Co-Design of Energy and Water Filtration Systems [10-18]

Aspect	Detail	Observation/Outcome	Implication/Significance
Filtration Component Design	NF270 Membrane	Identified as optimal	Energy-efficient and maintains water quality standards.
Simulation Results	NF270-4040 Membranes	Three membranes used	Effectively filtered water to maintain a TDS level below 500 mg/L without requiring pretreatment.
System Performance & Fouling	Surface vs Groundwater	Surface water more prone to fouling	Highlights the need for different treatment considerations based on water source.
Energy Requirements for Filtration	NF270 Membranes	Required less energy	Especially beneficial during periods of minimal solar energy availability.
Nano-grid Co-design	Filtration Modes	Variable pressure filtration modes used	Required fewer solar panels, thus reducing costs.
Battery Capacity Optimization	Filtration Modes	Variable mode showed significant reduction	Reduced battery capacity compared to the constant mode.
Cost Estimations	System Design	Variable pressure operation design	Could result in a 20% reduction in costs. Mobilising the NF unit and sharing between two locations provided economic benefits.

The study concluded that the co-design approach could significantly lower overall costs compared to traditional designs. While the methodology was applied to the Texas Colonias as a representative community, it is broadly applicable to any under-developed community aiming to meet water and energy needs sustainably. Future research will focus on larger-scale cases and robustness analysis under varying conditions.

The study by Modarresi et al. (2020) holds significant relevance to our review article as it exemplifies a practical application of integrating energy and water systems, a theme central to our discourse. Their focus on solar-powered nano-grids aligns with our emphasis on sustainable and renewable energy sources. Furthermore, the detailed exploration of filtration components, energy requirements, and cost implications provides invaluable insights into the challenges and solutions associated with such integrations. The application to the Texas Colonias, in particular, underscores the potential of these systems in addressing the needs of remote or under-developed communities, a topic of keen interest in our review. The methodologies and findings from this study enrich our understanding and offer a tangible case study that complements the broader themes we are exploring.

3 Future Scope of Research

The evolution of nano-grids presents a myriad of opportunities for future exploration. As the energy landscape shifts towards decentralisation and sustainability, it's imperative to delve deeper into the potential avenues that can further enhance the efficiency and applicability of nano-grids. From integrating diverse renewable energy sources to harnessing the power of cutting-edge technologies for smarter control systems, the horizon is vast. Moreover, understanding the broader socio-economic and environmental implications of these systems can pave the way for more holistic and community-centric energy solutions.

- **Integration of Multiple Renewable Sources:** While solar energy has been a primary focus, the integration of other renewable sources like wind, hydro, and geothermal with nano-grids can be explored further.
- **Advanced Control Systems:** With the advent of artificial intelligence and machine learning, there's potential to develop smarter control systems for nano-grids that can predict and adapt to changing energy needs and environmental conditions.
- **Scalability:** Research on how nano-grid systems can be scaled up or interconnected to form larger, more resilient energy networks, especially in urban settings.
- **Energy Storage Innovations:** As energy storage is a critical component of nano-grids, future research could delve into more efficient and sustainable battery technologies or alternative storage solutions.
- **Socio-economic Impacts:** A deeper understanding of how nano-grids can impact local economies, job creation, and community development, especially in remote or under-developed regions.
- **Environmental Considerations:** While nano-grids promote sustainability, it's essential to study their long-term environmental impact, especially concerning the materials used in energy storage and production.

4 Knowledge Gaps

While the promise of nano-grids is undeniable, there remain several areas where our understanding is still nascent. The long-term reliability of these systems, especially in diverse environmental and logistical contexts, is yet to be fully grasped. Additionally, the challenges of interconnecting multiple nano-grids, both technical and logistical, warrant deeper investigation. Economic viability, especially in regions with existing robust infrastructure, remains a question. Furthermore, the cultural, regulatory, and holistic environmental impacts of nano-grids are areas where more comprehensive research is essential to ensure their sustainable and widespread adoption.

- **Long-term Reliability:** While the benefits of nano-grids are evident, there's limited data on their long-term reliability and maintenance needs.
- **Interconnection Challenges:** While the idea of interconnecting multiple nano-grids is promising, the technical and logistical challenges of doing so are not fully understood.
- **Economic Viability:** The cost-benefit analysis of implementing nano-grids, especially in regions with existing infrastructure, needs more comprehensive research.
- **Cultural and Social Acceptance:** The acceptance and adoption of nano-grid technologies in various cultural and social contexts are not well-documented.
- **Regulatory and Policy Implications:** As nano-grids become more prevalent, there's a gap in understanding the regulatory challenges and policy implications they might introduce.
- **Holistic Environmental Impact:** While nano-grids are sustainable, a comprehensive study on the entire lifecycle environmental impact, from production to disposal, is lacking.

5 Conclusion

The exploration into the realm of nano-grids and their potential in future power systems has unveiled several pivotal insights:

- **Modularity and Diversity:** Nano-grids, with their modular nature, offer a bottom-up approach to power system design, making them ideal for diverse applications ranging from single households to interconnected community systems.

- **Economic Viability:** Through smart controllers and gateways, nano-grids can address the economic challenges associated with small-scale renewable energy sources, notably by balancing supply and demand curves and facilitating power trade with larger grids or other nano-grids.

- **Efficiency and Design:** The debate between AC and DC nano-grids highlights the importance of efficiency, with DC nano-grids offering fewer power conversions, especially beneficial for new constructions. However, the current prevalence of AC loads in households poses challenges for retrofitting.

- **Control Topologies:** The centralised, decentralised, and hybrid control topologies for nano-grids underscore the importance of resilience and adaptability in managing power distribution and demand-supply balance.

- **Water-Energy Nexus:** The co-design of energy and water filtration systems, as explored by Modarresi et al. (2020), emphasises the potential of nano-grids in addressing broader sustainability challenges, especially in remote areas like the Texas Colonias.

- **Operational Risks:** The scenario-based approach to understanding the risks associated with PV panel design showcases the importance of modelling uncertainties and their correlation to investment sizes in nano-grid systems.

In reflection, our journey through these articles resonates with the essence captured in our abstract. The transformative potential of nano-grids in reshaping the energy landscape is evident. Their ability to offer sustainable, efficient, and economically viable energy solutions, especially in remote and underserved regions, positions them as a cornerstone for the future of decentralised power systems. As we venture further into this era of sustainable energy, the insights from these studies will undoubtedly serve as foundational pillars, guiding our path forward.

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