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Distributed Generation Planning in Multi-Energy Microgrids

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Abstract. This review focuses on Distributed Generation Planning within Multi-Energy Microgrids (MES), a transformative approach where various energy forms like electricity, heat, and cooling interact optimally. MES offers significant technical, economic, and environmental benefits, making it crucial to explore intricate modelling and assessment techniques for such systems, including microgrids, virtual power plants (VPPs), and energy hubs. Amid global energy challenges and environmental crises, renewable energy adoption is vital. Distributed Generation (DG) plays a pivotal role, but integrating it at scale poses challenges. Microgrids are a viable solution, and this review introduces their core concepts, emerging trends, and challenges, such as integrating more renewable energy sources, multi-energy forms, complex architectures, demand-side management, and advanced storage. Furthermore, the paper delves into Multi-Energy Microgrid planning complexities, particularly in off-grid areas. It presents a stochastic investment model that minimizes costs and carbon emissions while optimizing the distributed energy resource mix, locations, and sizes. This model considers intricate energy flows and uncertainties associated with renewable generation and energy demands. Case studies confirm significant cost and emission reductions, establishing it as a promising multi-energy microgrid planning solution for the future.

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1 Introduction

Across the globe, there is a growing commitment to integrate renewable electricity resources into our energy systems, primarily through innovative concepts like the Smart Grid. However, as we strive to meet ambitious environmental goals while ensuring secure and affordable energy for present and future generations, we must consider all energy sectors, not just electricity. Heating, cooling, and transportation, in particular, pose significant challenges as they contribute significantly to energy consumption, greenhouse gas emissions, and local pollution. Additionally, these sectors often heavily rely on fossil fuels, making their decarbonization a complex endeavour.

Traditionally, energy sectors have operated somewhat independently, both in terms of day-to-day operations and long-term planning. Nevertheless, the boundaries between these sectors have become increasingly porous. Electricity, heating, cooling, and gas networks are now intertwined through various distributed technologies, such as combined heat and power systems, electric heat pumps, and tri-generation systems. Similarly, the relationship between electricity, the fuel supply chain, and transportation is evolving, with electric vehicles, biofuels, and hydrogen-based transport gaining prominence. To address these challenges and transition towards cleaner and more affordable energy systems, it is essential to develop Multi-Energy Systems (MES). These MES would facilitate optimal interactions between electricity, heat, cooling, fuels, and transportation, operating seamlessly within districts, cities, or even entire countries.

MES offers several advantages, including improved technical, economic, and environmental performance compared to conventional independent energy systems. Researchers worldwide are now actively exploring MES, focusing on various aspects and solutions. However, much of this research is fragmented, lacking a holistic view of MES. This review paper aims to bridge this gap by providing a comprehensive overview of recent work in the field. It emphasizes the Distributed Multi-Generation (DMG) of diverse energy sources as a central theme. The review critically assesses concepts, approaches, and analytical tools proposed to tackle MES complexities. It also examines methodologies and performance metrics for evaluating MES, considering energy, environmental, and techno-economic perspectives.

To address these multifaceted challenges, this paper reviews a range of research endeavours that contribute to understanding and managing MES effectively. It explores various methodologies and models, including scenario-based stochastic approaches for planning multi-energy microgrids. These models optimize the mix, location, and size of distributed energy resources while accounting for uncertainties associated with renewable energy generation and demand. Moreover, this review investigates the intricate interplay of energy flows within multi-energy microgrids, encompassing electrical, heating, and cooling sources and their respective loads.

The ensuing sections of this review delve into different modelling strategies for Multi-Energy Systems (MES). They critically evaluate methods for assessing MES, including performance metrics that encompass energy, environmental, and techno-economic aspects. By synthesizing insights from these studies, this paper offers a comprehensive perspective on the evolving MES domain. It sheds light on the pivotal role of MES in shaping a sustainable energy future.

2 Review and discussion

In a study conducted by Mancarella et al. (2014), an examination of various concepts and tools within the domain of Multi-Energy Systems (MES) was carried out [1]. Their insights serve as a solid foundation for our comprehensive review article, offering valuable insights into the multifaceted nature of MES integration. The Energy Hub Concept, as elucidated in their research, emerges as a versatile approach capable of modelling distributed MES while taking into account network constraints [4]. However, its inherent mathematical complexity, particularly arising from non-linearities resulting from energy flow aggregation, requires careful consideration. Moreover, the study introduces the concept of disaggregating energy flows to enhance tractability, albeit with potential trade-offs in accuracy. This concept, often serving as a foundation for other aggregation models such as input-output representations, Microgrids, and Virtual Power Plants (VPPs), provides valuable insights into the synthetic generalisation of various MES components [5-7].

The Microgrid Concept, as explored by Mancarella et al. (2014), finds relevance in our review of MES, especially concerning low and medium voltage distribution networks. Nevertheless, their research underscores a common limitation: an excessive focus on electricity, at times sidelining the broader perspective of MES. Similarly, the Virtual Power Plant (VPP) Concept, introduced by the authors, opens doors to versatile multi-energy applications. Its emulation of centralised resources for wholesale markets extends beyond the Microgrid framework, offering a broader outlook on energy integration. However, while some VPP studies have ventured into multi-energy domains, comprehensive models in this context remain elusive.

Lastly, the authors emphasise the crucial role of operation and planning tools tailored for MES analysis. Their findings underscore the diverse toolkit available for evaluating MES, with each tool addressing specific needs and objectives, from preliminary assessment to operational, planning, and design analyses. As we delve deeper into our review, these pivotal findings as tabulated below in Table 1, not only offer valuable insights into MES concepts and tools but also serve as a subtle thread connecting our exploration of this intricate and evolving field [8].

Table 1. Key Findings and Characteristics of MES Concepts and Tools

Findings	Description	Advantages	Versatility	Limitations
Energy Hub Concept	Suitable for modelling distributed MES with network constraints. Mathematical formulation can be complex due to nonlinearities. Proposed disaggregation method may introduce errors.	Versatile model for various aggregation concepts: input-output representations, Microgrids, VPPs.	Offers synthetic generalization of KarusheKuhneTucker conditions, allowing for multi-carrier optimization.	Disaggregation may lead to inaccuracies, especially for nonlinear network behaviours.
Microgrid Concept	Common in low-medium voltage networks,	Primarily focuses on electricity and technical aspects.	Incorporates network constraints, ensuring the feasibility of various	Limited extension to MES with a focus on electricity.

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	considers network constraints.		control options.	
Virtual Power Plant (VPP) Concept	Emulates centralized resources for wholesale markets. General concept with potential multi-energy applications.	Versatile, covering technical and commercial aspects.	Allows emulation of centralized resources, suitable for multi-energy applications.	Comprehensive multi-energy VPP models are still missing.
Operation and Planning Tools	Essential for analysing MES with various tools available, each with specific strengths and limitations.	Tools for different purposes: RETScreen (preliminary assessment), Energy PLAN (operational analysis), DER-CAM (design), eTransport (system expansion).	Facilitates analysis and decision-making for MES with specific tools catering to different needs.	Each tool has a specific focus and may not cover all aspects comprehensively.

In another study conducted by Suyanto et al. (2017), the authors explored the trends and challenges associated with the development of microgrids. Their research focused on key aspects related to the integration of renewable energy sources, the utilization of multiple energy forms, the emergence of multi-level microgrid architectures, demand-side management (DSM), and the role of generalized storage systems within microgrids [2].

Here are the summarised new trends and challenges discussed in their study:

- **Higher Renewable Energy Integration [10]**:
  - Increasing integration of wind turbines and photovoltaic systems
  - Reduction in fossil fuel consumption and carbon emissions
  - Challenges due to intermittent nature of renewables
  - Solutions: stochastic optimization, PEI-based control
  - Role of batteries and diesel generators
- **Multi-Energy Forms[11,12]**:
  - Comprehensive utilization: electricity, chemical, thermal, solar, wind
  - Synergy and improved efficiency through multi-energy coupling
  - Complications in planning and operation
  - Combined network models for gas and heating
  - Need for systematic views
- **Multi-Level Architecture**:
  - Levels: residential to distribution microgrids
  - Smaller microgrids combine for enhanced utilization and reliability
  - Coordination challenges due to ownership and objectives
  - Solutions: Multi-Agent Systems (MAS)
- **Demand Side Management (DSM) [9,13]**:
  - Importance due to microgrid size and limited control resources
  - Flexibility: control of EVs, HVAC systems

    - Challenges: interaction, pricing, user comfort
    - Research areas: demand response, market models, home energy management
- **Generalized Storage [14,15]**:
    - Handling renewable energy uncertainty
    - Types: electrical, heating, cooling, gas
    - Coordinated operation essential
    - Considerations: sizing, optimization, operation

Suyanto et al.'s (2017) study provides valuable insights into the evolving landscape of microgrids, emphasizing renewable energy integration, multi-energy utilization, multi-level architectures, demand-side management (DSM), and advanced storage solutions. These findings closely align with the themes explored in our review article, which aims to offer a comprehensive overview of Multi-Energy Systems (MES), particularly microgrids. Suyanto et al.(2017)'s work reinforces the importance of renewable energy integration, resonates with the complexities of energy balance and control discussed in our article, and complements our examination of various modelling approaches for MES. Their insights into demand-side management and advanced storage are pertinent to our assessment of tools and technologies in MES operational and planning analysis. In summary, Suyanto et al.(2017)'s study enriches our understanding of MES, particularly microgrids, and their pivotal role in shaping a sustainable energy future.

Another investigation conducted by Ehsan et al. (2019), delved on the assessment of a multi-energy microgrid planning solution, and they utilise a comprehensive approach by considering 80 different scenarios within a 19-bus test microgrid. This research yields several noteworthy conclusions [16-21]:

- In Case I, they implement three CHP-ICE units with a total capacity of 6 MW, alongside various other components like gas boilers, electric chillers, and absorption chillers. Notably, wind and photovoltaic units are excluded from Case I, as it concentrates solely on cost considerations due to the limitations of non-dispatchable renewable generators.

- In contrast, Case II takes a more balanced approach, aiming to minimise both costs and CO2 emissions. This leads to substantial integration of renewable energy sources, including 2 MW of wind turbines and 1.2 MW of PVs. Additionally, a 0.5 MW battery system is introduced for surplus generation storage, while CHP capacity is reduced to 5 MW and boiler capacity is increased to 1.6 MW. The aggregate capacity of electric chillers and absorption chillers remains similar to Case I.

- Furthermore, they provide insights into optimal electricity, heating, and cooling dispatch strategies, showcasing the effective use of diverse Distributed Energy Resources (DERs) to meet multi-energy demands under various conditions, including summer sunny days and winter cloudy days.

- A comparative analysis against deterministic planning (Case II) demonstrates that the proposed stochastic MMIP solution surpasses deterministic planning in terms of cost savings and CO_2 emissions reductions, underscoring the significance of accounting for uncertainties in microgrid planning.

These findings are pertinent to our review as they underscore the benefits of incorporating renewable energy sources and considering both cost and emissions objectives in microgrid planning. The research by Ehsan et al. (2019) highlights the practicality and advantages of adopting a multi-dimensional approach in microgrid development, aligning with our objective of providing insights into contemporary trends and challenges in the field of microgrids.

3 Future scope of research

- Enhanced Integration of Renewable Energy: Future research should focus on developing advanced strategies for the seamless integration of renewable energy sources into microgrids. This could involve innovative technologies and control systems to maximise the use of solar, wind, and other renewables.

- Optimization in Multi-Energy Microgrids: Further studies can explore advanced optimization techniques tailored for multi-energy microgrids. This includes improving algorithms that consider both cost and emissions objectives for DER planning and dispatch.

- Advanced Energy Storage Solutions: Research can delve into the development of more efficient and cost-effective energy storage solutions. This could encompass exploring novel materials, designs, and technologies to enhance energy storage capacity and performance.

- Resilience and Security: As microgrids play a crucial role in ensuring energy resilience, future research should investigate methods to enhance their resilience and security against external threats, including cyberattacks and extreme weather events.

- Scaling to Larger Systems: While the study examined a 19-bus microgrid, future work could explore the scalability of these solutions to larger and interconnected microgrid networks, addressing challenges related to coordination and management.

- Demand Response and User Engagement: Investigating strategies to promote active user engagement in demand response programs can lead to more efficient energy consumption. Future research could explore behavioural economics and technology-based solutions to encourage consumer participation.

4 Knowledge Gaps:

- Interconnected Microgrids: There is a gap in understanding the dynamics and challenges of interconnected microgrid systems, particularly when multiple microgrids operate in parallel or are connected to a larger grid.

- Grid Resilience Metrics: Developing comprehensive metrics and standards for assessing the resilience of microgrids, including the impact of energy storage systems and DERs, remains an area requiring further investigation.

- Economic Viability: More research is needed to determine the long-term economic viability of microgrid solutions, considering factors like maintenance costs, component lifespans, and evolving energy markets.

- Consumer Behaviour in Multi-Energy Microgrids: Understanding how consumers interact with multi-energy microgrids and respond to different pricing and energy source options is a knowledge gap that could influence the success of such systems.

- Cybersecurity: Research on enhancing the cybersecurity of microgrids, especially when they are interconnected and rely heavily on digital infrastructure, is crucial to safeguarding energy supply.

- Environmental Impact Assessment: A more in-depth assessment of the environmental impact, beyond CO2 emissions reduction, of different DER configurations and energy storage technologies is essential for comprehensive decision-making.

These future research areas and identified knowledge gaps can guide further investigations in the field of multi-energy microgrids, contributing to their improved performance, sustainability, and resilience.

5 Conclusion

In the constantly evolving and dynamic landscape of energy solutions, our short review into the realm of multi-energy microgrids has brought to light some truly crucial insights. These insights not only perfectly resonate with the broader themes we touched upon in our earlier discussions but also shed light on the immense potential these systems hold. The multi-energy microgrids stand out as a game-changing force in the energy sector, offering unparalleled resilience, a commitment to environmental sustainability, and a promise of cost efficiency. To provide a comprehensive understanding, we have taken the liberty to condense these multifaceted insights into six key, detailed observations:

- Advancements in Multi-Energy Microgrids: The reviewed articles collectively highlight the remarkable advancements in the field of multi-energy microgrids. These integrated systems are evolving as a pivotal solution for enhancing energy sustainability and resilience.

- Renewable Integration and Cost-Efficiency: The integration of renewable energy sources, such as solar and wind, is a prevailing trend. Research demonstrates that optimal utilization of renewables can significantly reduce carbon emissions while maintaining cost-efficiency.

- Multi-Level Architectures and Scalability: The concept of multi-level architectures, as evidenced in one of the studies, illustrates the potential for scalability and adaptability in microgrid development. This approach aligns with the dynamic nature of energy systems.

- Demand-Side Management and Consumer Engagement: Demand-side management, driven by demand response programs, emerges as a critical aspect of multi-energy microgrids. The engagement of consumers in actively managing their energy consumption is vital for achieving efficient and sustainable outcomes.

- Storage Solutions and Uncertainty Management: Effective energy storage solutions are essential for mitigating the intermittency of renewable sources. Furthermore, managing uncertainties in energy generation and demand, as demonstrated through scenario-based models, plays a pivotal role in optimizing microgrid performance.

- Resilience and Future Directions: As energy grids face diverse challenges, the reviewed research highlights the importance of enhancing microgrid resilience against disruptions, including cyberattacks and natural disasters. Future research directions encompass larger-scale interconnected microgrids and comprehensive assessments of environmental impacts.

The key findings presented here emphasise the transformative capabilities of multi-energy microgrids in reshaping the contemporary energy paradigm. Drawing parallels with our prior discussions, these insights further illuminate the indispensable role of these advanced systems. Multi-energy microgrids stand at the forefront of our quest for a future powered by sustainable, economically viable, and robust energy solutions. Their integration and optimization promise not only to address the immediate challenges of energy distribution and consumption but also to set the stage for a more resilient and eco-friendly energy future.

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