Technical sciences

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DESIGNING MICROGRIDS WITH RENEWABLE ENERGY SOURCES AND ENERGY STORAGE SYSTEMS

Summary. *The article discusses the design of microgrids that use renewable energy sources and energy storage systems as a controlled local power system that operates in both grid-connected and island mode. The goal is to present an integrated approach that combines the choice of architectural design (AC/DC/hybrid), the selection of distributed energy resources (DER) and energy storage systems (ESS), and management requirements (power quality control, energy management system) within the framework of the IEEE 1547 and 2030 standards. Key methods for modeling and optimization, such as multicriteria and stochastic optimization, are described, as well as the main challenges to implementation, such as variability in generation, cyber resilience, and costs. Examples of successful projects demonstrate improvements in reliability, flexibility, and economic efficiency for local power systems.*

Key words: *microgrids, renewable energy, energy storage (ESS), DER, EMS, island mode, PCC, AC/DC architectures, optimization.*

The relevance of the study stems from global changes in the energy sector, specifically the increasing share of renewable energy sources and the need for decentralized power supply systems. As the modern energy industry moves towards integrating solar, wind, and other renewable energy installations into local systems, it is due to a combination of factors, including the decreasing cost of renewable technologies and the desire for increased environmental sustainability and energy independence.

However, one key challenge lies in the variability of renewable energy generation. Solar and wind power plants have unpredictable output, which directly depends on weather patterns, making it challenging to balance supply and demand on the grid.. In these circumstances, microgrids equipped with energy storage systems represent an effective solution. They not only improve the reliability of electricity supply, but also ensure flexibility, stability, and cost-efficiency in the operation of local energy systems.

The relevance of the topic is further emphasized by the fact that microgrids are becoming an essential component of the "smart city" concept, the energy modernization of rural areas, and industrial and transportation facilities where uninterrupted power supply is of critical importance.

The purpose of this research is to develop an integrated approach to designing microgrids that incorporate renewable energy sources and storage systems. A microgrid, as defined by the IEEE, is a group of loads and distributed energy resources (DER) that are connected within well-defined electrical boundaries. These systems act as a single entity in relation to the external network, capable of operating in both networked and island modes. The IEEE 2030.7 standard defines the specifications for microgrid controllers, while the 2030.8 standard details the functions and testing requirements for these controllers. The IEEE 1547-2018 standard provides guidelines for connecting DER to the grid [5].

The key international and industry standards on which the design is based are summarized in table 1.

Table 1

Key international and industry standards

Standard	Subject	What sets
IEEE 1547-2018	Connecting DER to electrical systems	Criteria and requirements for DER interfaces and Network Interoperability (EPS)

IEEE 2030.7-2017	Specification of Microgrid controllers	Mandatory microgrid management functions as a single entity, including island/network operation
IEEE 2030.8-2018	Testing of microgrid controllers	Procedures and metrics for verifying compliance with IEEE 203.0.7 functions
IEEE 2030.9-2019	The practice of planning and designing microgrids	Approaches to DER configuration, protection, compatibility, monitoring, measurements

Source: author's development

The architecture of renewable energy microgrids consists of a combination of distributed energy resources (DERs), storage devices, converter equipment, and loads within well-defined electrical boundaries, with a point of common grid connection (PCC). These microgrids can operate both synchronously with the grid and autonomously.

IEEE 1547-2018 sets the basic requirements for connecting DERs, and the functional specifications and testing of microgrid controllers follow IEEE 2030.7/2030.8 standards (connection and disconnection management, quality maintenance, and coordination of DERs and energy storage systems). Engineering reviews and manuals identify AC, DC, and hybrid AC/DC topologies, as well as hierarchical management (primary, secondary, and tertiary levels) to ensure the reliability and quality of electricity supply.

A simple diagram of a typical AC microgrid is shown in Figure 1.

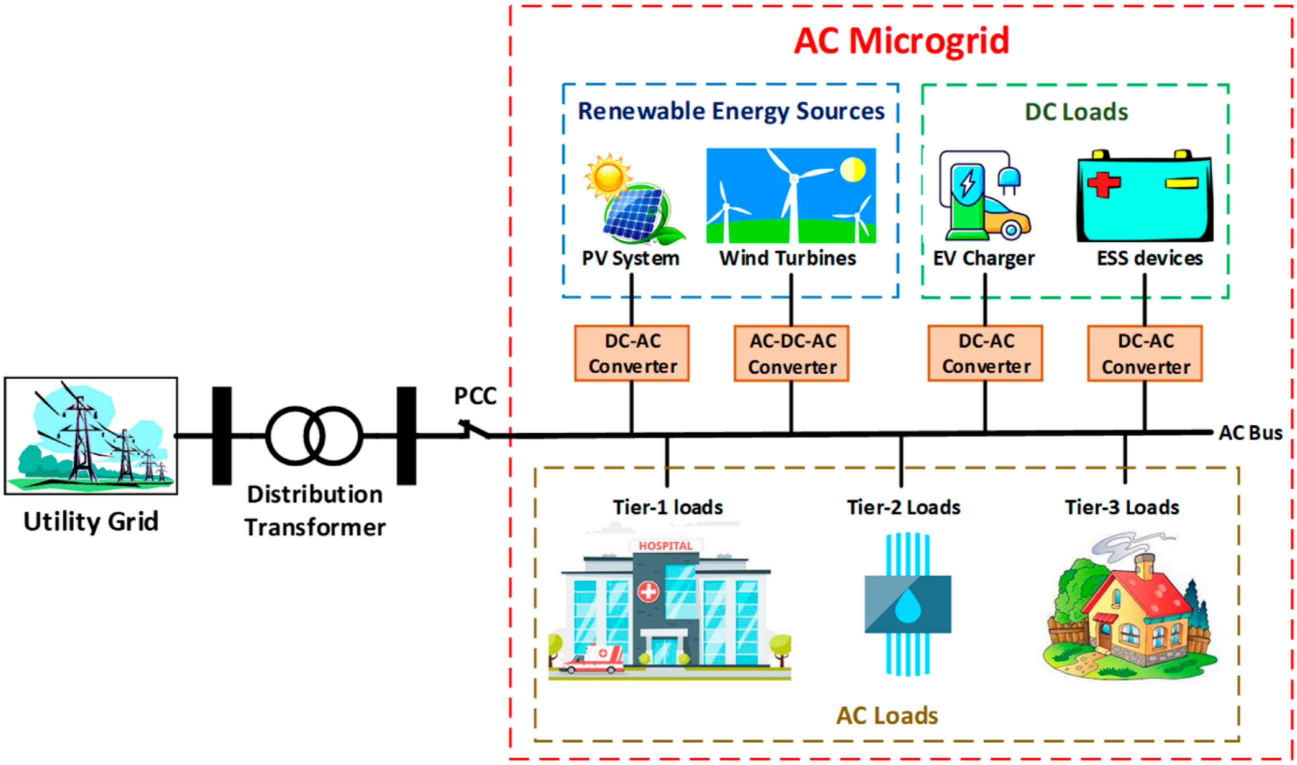

Fig. 1. A simple diagram of a typical AC microgrid [8]

Methods and approaches to designing microgrids involve sequential stages of composition and sizing planning, modeling of power flow and modes, and optimization of dispatch/energy management. These processes take into account uncertainties in renewable energy generation and demand.

Review papers highlight the use of mathematical programming techniques such as linear programming (LP), mixed-integer linear programming (MILP), and nonlinear programming (NLP), as well as metaheuristic algorithms like genetic algorithms and particle swarm optimization. Hybrid schemes that combine multiple criteria, such as cost, emissions, and reliability, are also used. Stochastic programming is employed to account for uncertainties in weather and prices, as shown in Figure 2.

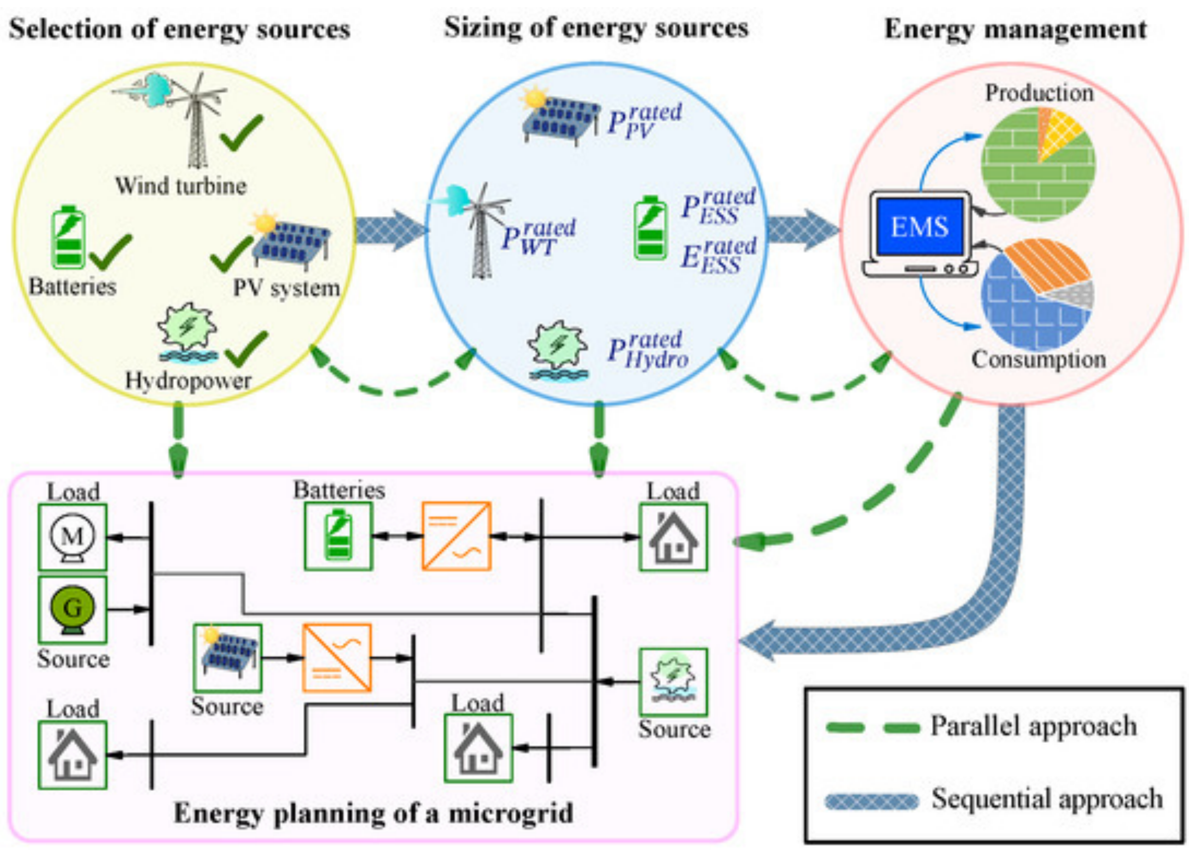

Fig. 2. The main stages of energy planning of a microgrid [1]

The practical implementation is based on specialized software and model complexes. The tools and tasks of designing/modeling microgrids are described in Table 2.

Table 2

Microgrid design/modeling tools and tasks

The tool	Issue type	Representative features / data
HOMER Pro	Layout and economic optimization of hybrid microgrids	Chronological simulation with a step time of 1 min – 60 min; iteration / optimization of configurations; sensitivity analysis
GridLAB-D	Dynamics of distribution networks, integration of DER	Open agent-based PNNL/DOE environment; support for DER impact analysis and distribution network planning
OpenDSS	Calculation of modes of distribution networks, scenarios of microgrids	Open EPRI simulator for distribution networks; support for various analyses, co-simulation

Pandapower	Power flows, AC/DC OPF, Research automatio	OPF documentation; library based on pandas / PYPOWER; used by operators / research institutes

Source: author's development

The challenges and difficulties in implementing microgrids powered by renewable energy sources include technical, economic, regulatory, and cyber aspects. One of the main technical challenges is ensuring the stability of renewable energy supply and maintaining the quality of electricity during transients. This includes addressing voltage and frequency fluctuations, as well as harmonics. Additionally, there is a need for sustainable management strategies, including the use of predictive methods and virtual synchronous generators (VSG) (Figure 3).

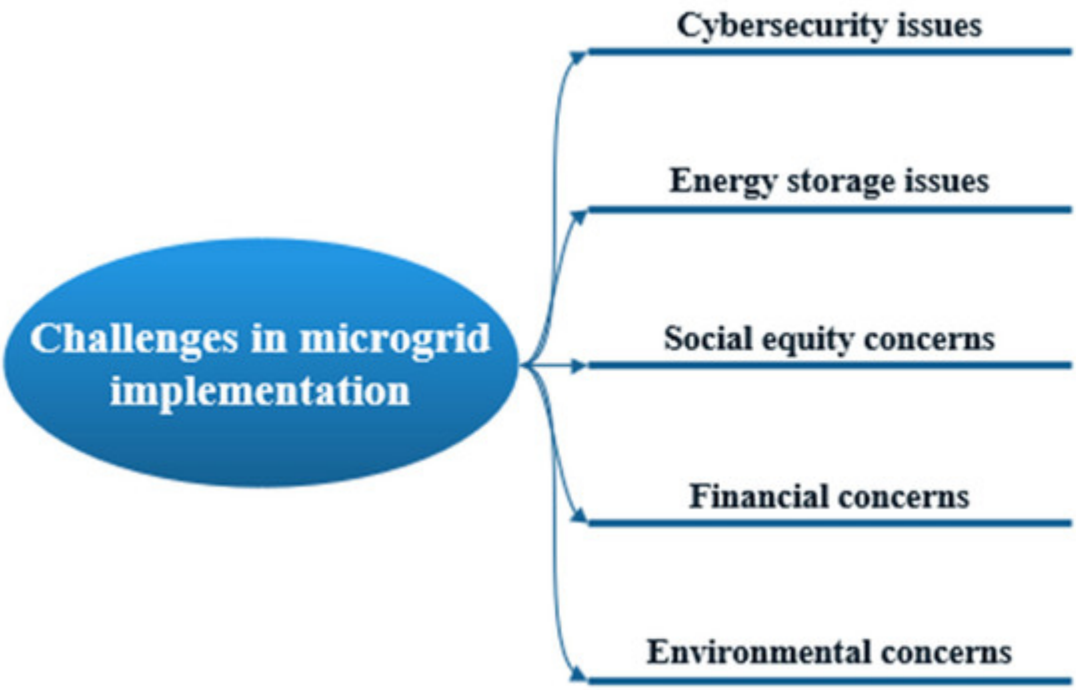

Fig. 3. Problems of microgrid development [6]

At the same time, the significance of digitalization and cybersecurity is increasing. NREL and other organizations emphasize the need for thorough testing of the "cyber-physical" interactions of microgrids, as the proliferation of communication and remote control expands the potential for attacks. On the economic front, barriers include capital and operational expenses, as well as fluctuations in the prices of equipment and components.

The prospects for the growth of microgrids powered by renewable energy sources are increasing as projects with greater autonomy are rapidly growing and advancing in market mechanisms. For instance, in the United States, the opening up of markets for distributed energy resources facilitates the implementation of microgrids. FERC 2222 enables the aggregation of distributed energy resources (DER) to participate in electricity and system operator markets, and regulators and market operators for each region have already established the timetable for implementation. This expands business models for microgrids and renewable energy storage devices, enhancing their commercial viability [4].

In Europe, the "energy communities" and the updated EU Renewable Energy Directive (RED III) have become a significant driver, increasing the target for the share of renewable energy by 2030 and streamlining the process of obtaining permits, which makes it easier to implement local projects and microgrids at the municipal and residential levels. The 2023 set of regulations directly encourages the development of communities and cooperatives that generate and store energy locally [3].

In practice, the dynamics and effects of microgrids can be seen through the implementation of various types of projects, from campuses and airports to isolated islands. One example of a "multi-client" microgrid is the Redwood Coast Airport Microgrid (RCAM) project in California, which has 2.2 megawatts of solar generation and a battery system with a capacity of about 2.3 megawatts/8.9 megawatt-hours (according to CPUC documents, it is also 2.2 megawatts/8.8 megawatt-hours). This microgrid manages energy and participates in the CAISO wholesale market. The project was completed in 2021-2022 and serves as a reference for communities with critical infrastructure [7].

In isolation conditions, the island of Tau (American Samoa) has an integrated solar battery microgrid from SolarCity/Tesla, with a capacity of 1.4

megawatts (MW) of photovoltaic (PV) and 6 megawatt-hours (MWh) of storage (60 Powerpacks), providing close to 100% of renewable energy and replacing diesel generation [9].

At the local community level in California, the Blue Lake Rancheria microgrid combines solar generation and battery storage. According to the developers, the energy savings reach approximately $150,000 per year. The configuration includes 420 kilowatts (kW) of PV (photovoltaic) solar panels and 500 kilowatt-hours (kWh) of battery storage, which was made possible through CEC (California Energy Commission) EPIC (Energy Performance Incentive Contract) grants [2].

A separate area is that of hybrid microgrids using hydrogen fuel cells for long-term redundancy. In California, a project has been approved and launched at the Calistoga substation. The capacity is 8.5 megawatts, with an energy intensity of approximately 293 megawatt-hours and a duration of 48 hours. The system replaces diesel generators during fire safety shutdowns.

These cases demonstrate the trajectory of development in this area: from isolated and "public" solutions to multi-client nodes with market integration, and to hybrid long-term storage systems. These developments, combined with regulatory changes and LDES (Low-Density Energy Storage) demonstration programs, set a practical agenda for scaling microgrids as part of a sustainable and flexible electricity industry.

Thus, microgrids powered by renewable energy sources and energy storage devices are transitioning from being experimental solutions to becoming a mature local energy infrastructure. The value of these systems is not only determined by the "green" energy they generate, but also by their manageability, sustainability, and ability to integrate with market mechanisms. The key to successfully designing these systems lies in linking configuration and size choices, management models, and economic considerations into a single decision-making process that works both online and offline. This process must be verified using real-world data and tested in practice.

Practice has shown that the best results are achieved in projects where all the components - sources, storage devices, and a digital control system - are considered as an integrated asset. This approach allows for ensuring critical loads, reducing electricity costs during peak hours, and earning from flexible services. However, implementation of such projects faces challenges such as connection bottlenecks, supply chain volatility, and cybersecurity risks. Therefore, technical solutions must be accompanied by well-planned protection, monitoring, and equipment lifecycle management.

For further scaling, there are three areas that are prioritized: increasing the use of long-term storage and hybrid backup systems, fault-tolerant management that takes into account the uncertainty of demand, generation, and prices, as well as the interoperability and standardization of data exchange between DERS (Distributed Energy Resource Systems), storage devices, and network operators.

At the methodological level, it would be advisable to combine stochastic planning, multi-criteria optimization, and real-time testing. At the policy level, we should rely on regimes that allow distributed assets to participate in service markets and encourage local energy communities.

An economically and technically viable microgrid is a system that integrates renewable energy sources with long-term energy storage, has robust cyber-physical resilience, and uses tools that shorten the time from modeling to operation. This system must be able to withstand disturbances and provide a measurable set of services. The goal is to create a system that pays off within a specified period.

For the research agenda, it is important to focus on these aspects of microgrids: integrating renewable energy and long-term storage, ensuring cyber-physical resilience, and developing tools that help move from modeling to actual operation more quickly.

References

1. A Comprehensive Review of Sizing and Energy Management Strategies for Optimal Planning of Microgrids with PV and Other Renewable Integration. URL: https://www.mdpi.com/2076-3417/14/22/10479.

2. Blue Lake Rancheria microgrid – Schatz Energy Research Center. URL: https://schatzcenter.org/blrmicrogrid/.

3. Energy communities. URL: https://energy.ec.europa.eu/topics/markets-and-consumers/energy-consumers-and-prosumers/energy-communities_en.

4. FERC Order No. 2222 Explainer: Facilitating Participation in Electricity Markets by Distributed Energy Resources[i] | Federal Energy Regulatory Commission. URL: https://www.ferc.gov/ferc-order-no-2222-explainer-facilitating-participation-electricity-markets-distributed-energy.

5. IEEE SA – IEEE 2030.7-2017. URL: https://standards.ieee.org/ieee/2030.7/5941/.

6. Possibilities, Challenges, and Future Opportunities of Microgrids: A Review. URL: https://www.mdpi.com/2071-1050/15/8/6366.

7. Redwood Coast Airport Microgrid – Redwood Coast Energy Authority. URL: https://redwoodenergy.org/about/community-impact/rcam/.

8. Review on the Microgrid Concept, Structures, Components, Communication Systems, and Control Methods. URL: https://www.researchgate.net/publication/366795944_Review_on_the_Microgrid_Concept_Structures_Components_Communication_Systems_and_Control_Methods

9. The Ta'u Island is powered entirely by solar panels | WIRED. URL: https://www.wired.com/story/island-tau-solar-energy-solarcity/.