UNIVERSITY OF SPLIT
FACULTY OF ELECTRICAL ENGINEERING, MECHANICAL ENGINEERING AND NAVAL ARCHITECTURE

DOCTORAL STUDY IN MECHANICAL ENGINEERING

DOCTORAL QUALIFYING EXAM

REVIEW OF PEM FUEL CELL POWERED SYSTEMS FOR STATIONARY APPLICATIONS USING RENEWABLE ENERGY SOURCES

Motalleb Miri

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1. INTRODUCTION

Renewable energy sources, particularly solar and wind power, have emerged as key enablers in the global transition toward sustainable energy systems. These technologies offer clean, abundant, and increasingly cost-effective means of electricity generation, making them ideal candidates for powering hydrogen production through water electrolysis. In particular, when coupled with electrolyzers, solar and wind energy can be converted into green hydrogen, a versatile energy carrier that supports energy storage, decarbonization of transportation, and grid balancing. The intermittent nature of renewable resources can be effectively mitigated through hydrogen production, which serves as a long-term storage medium, enabling continuous operation of PEM fuel cells even during periods of low solar irradiance or wind availability. This synergy between renewable electricity generation and hydrogen technology represents a crucial step toward achieving a resilient, low-carbon energy infrastructure.

In 2024, global renewable electricity capacity grew 22% to reach nearly 685 GW. Despite increasing policy uncertainty and ongoing regulatory challenges, 2025 is expected to be another record year, with capacity additions reaching over 750 GW in the main case and 840 GW in the accelerated case. [Fig. 1.1]

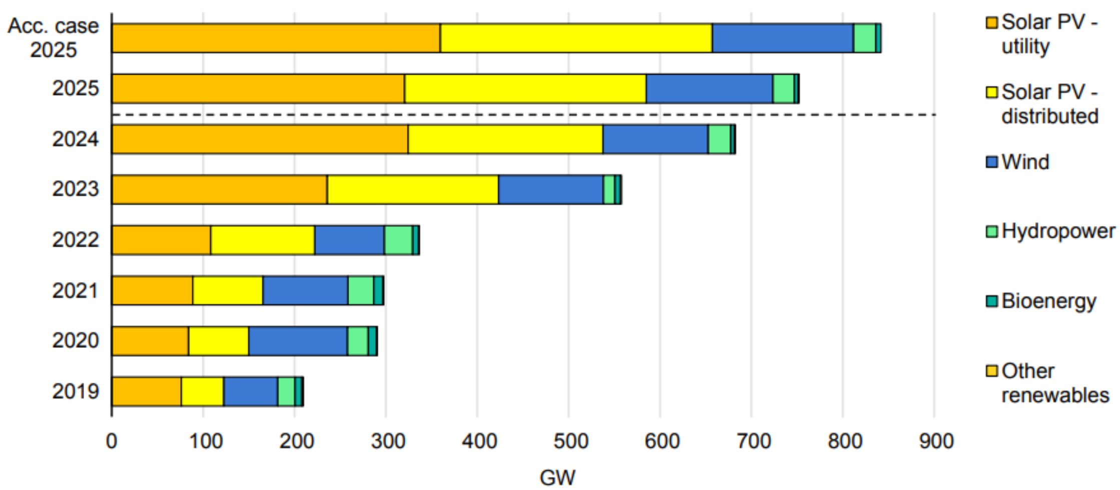


Figure 1.1. Renewable electricity capacity additions by technology, 2019-2025 [Ref:IEA[1]]

In the main case, global annual renewable capacity additions rise from 683 GW in 2024 to almost 890 GW in 2030. Solar PV and wind account for 96% of all renewable capacity additions through 2030 because they are the most affordable options to add new capacity in almost every country in the world, and policies in more than 130 countries continue to support them. Renewables will become the largest global energy source, used for almost 45% of electricity generation by 2030.

[1] IEA – International Energy Agency

Low-emissions hydrogen production grew by 10% in 2024 and is on track to reach 1 Mt in 2025, but it still accounts for less than 1% of global production. While the uptake of low-emissions hydrogen is not yet meeting the ambitions set in recent years – held back by high costs, uncertain demand and regulatory environments, and slow infrastructure development – there are still notable signs of growth. A recent wave of project delays and cancellations has reduced expectations for the deployment of low-emissions hydrogen this decade. [[Fig. 1.2]

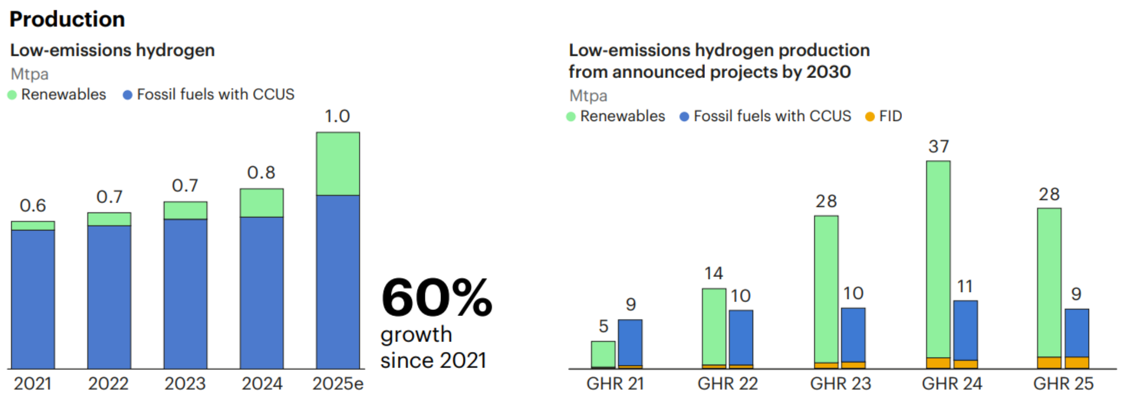


Figure 1.2. Hydrogen production and announced projects by 2030[Ref:IEA[2]]

Despite the recalibration of industry plans, low-emissions hydrogen production is expected to grow strongly by 2030. Low-emissions hydrogen production from projects that are today operational or have reached FID is set to reach 4.2 Mtpa by 2030, a fivefold increase compared with 2024 production. While this is much lower than government and industry ambitions at the start of this decade, it represents growth from less than 1% of total hydrogen production today to around 4% in 2030. This low-emissions hydrogen growth to 2030 would resemble the fast expansions of other clean energy technologies seen in recent years, such as solar PV.

The fuel cell market is experiencing significant growth, projected to expand from around $9-10 billion in 2023-2024 to over $100 billion by 2032 in some estimates. This growth is driven by the demand for clean energy, supportive government policies, and increasing applications in transportation (especially for commercial vehicles), stationary power, and industrial uses. Asia-Pacific currently holds the largest market share, driven by government support and the adoption of fuel cells in the region.

Solar and wind power present viable options for generating the necessary electricity to produce hydrogen for PEM fuel cells. Due to the intermittent nature of renewable energy, there are spatial and temporal gaps between energy availability and consumption. Solar energy and wind turbines can be used to produce hydrogen via electrolysis, which can then be stored and utilized by PEM fuel cells to generate power on demand. To address these issues, it is necessary to develop suitable energy storage and conversion systems for the power grid [1]. Integrating these technologies into a cohesive microgrid system offers a sustainable and resilient solution for powering telecommunication infrastructure. Proton Exchange Membrane (PEM) fuel cells have

[2] IEA, Global Hydrogen Review 2025

emerged as a promising technology to meet these needs. PEM fuel cells generate electricity through an electrochemical reaction between hydrogen and oxygen, producing only water and heat as by-products. This clean energy technology offers several advantages over conventional power sources, including higher efficiency, lower emissions, and the potential for integration with renewable energy systems.
PEM fuel cell systems, combined with solar and wind energy, offer a sustainable and reliable solution for powering stationary telecom infrastructure. While challenges remain, ongoing advancements and increasing adoption of renewable energy sources are covering the way for broader implementation. This hybrid approach not only enhances energy security but also contributes to the reduction of greenhouse gas emissions, aligning with global sustainability goals.

Several projects and studies have demonstrated the feasibility and benefits of integrating PEM fuel cells with solar and wind energy for telecom applications. For instance, a solar-hydrogen system for telecom applications involves using photovoltaic (PV) panels to generate electricity from sunlight.

The following sections will delve into the literature on microgrid systems, dissecting their architecture and critically analyzing their constituent components, with a particular emphasis on energy management and storage systems. Subsequently, the text will explore optimization methods to enhance system performance and address the challenges and potential of energy storage solutions.

Research has demonstrated the potential of this system in powering remote telecom towers, especially in regions with unreliable grid access or where diesel fuel costs for backup generators are high [2].

Building upon existing research on microgrid systems [3], the role of Energy Management Systems (EMS) in optimizing power flow and ensuring system stability within the hybrid framework will be explored. Additionally, an analysis of different energy storage options will be conducted, with a specific focus on comparing hydrogen storage to other methods such as batteries [4].

Through a comprehensive review of research and advancements in technology, the aim is to assess the potential of this hybrid system to revolutionize the way we power our homes, businesses, and critical infrastructure like telecommunication towers. Existing challenges and future considerations for this promising technology, paving the way for a clean and reliable energy future are discussed.

This work was conducted across major scientific databases, using keywords such as PEM fuel cells, stationary application, renewable energy, microgrid, energy management system, hydrogen storage, and optimization methods. These terms were applied individually and in combination to ensure broad coverage of publications relevant to hybrid microgrid systems. The final selection of sources was based on their relevance to PEMFC-based stationary systems, the integration of renewable technologies, the implementation of hydrogen storage solutions, and the use of advanced control or optimization approaches.

Once the literature was compiled, an analytical framework was created to organize the review around the essential components of PEM fuel cell–based microgrids. The studies were then grouped into thematic categories aligned with the main sections of this work, allowing for a clear and consistent evaluation of system architecture, energy management strategies, storage technologies, and optimization methods.

Insights derived from this structured process informed the critical findings and future recommendations presented in the work. These findings highlight key technological challenges, current research gaps, and emerging opportunities within the field. They also provide a foundation for defining future research pathways, design objectives, and operational considerations that can support the continued development and improvement of hybrid microgrids incorporating PEM fuel cell technology.

2. MICROGRID SYSTEM AND ARCHITECTURE

Microgrid systems, which integrate various distributed energy resources, have emerged as a viable solution for powering telecom infrastructure. Previous surveys have highlighted the effectiveness of micro-grids in enhancing energy reliability and sustainability. This section delves into the architecture of microgrids, focusing on energy management and storage systems.

A typical microgrid classification is shown in Fig. 2.1. while integrating the distributed energy sources into microgrid optimal sizing, efficient control, and scheduling of distributed energy sources play a vital role. Moreover, to deal with the uncertainties associated with renewable energy resources, Microgrid demands an energy management system (EMS) to maintain its optimal and efficient operation.

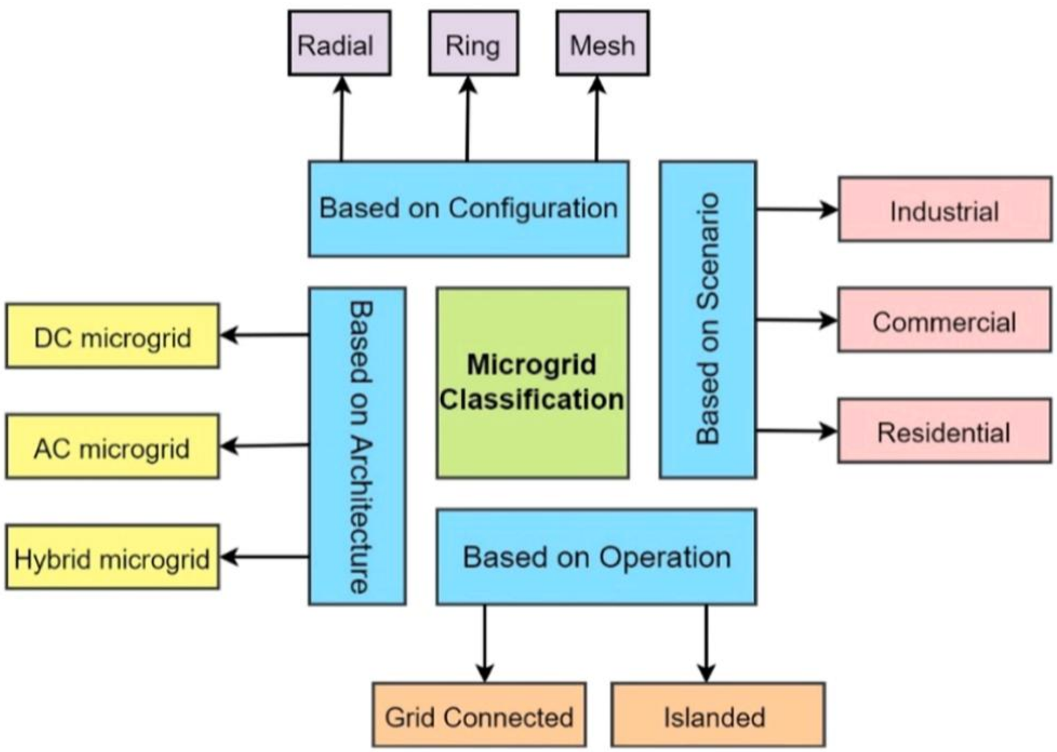


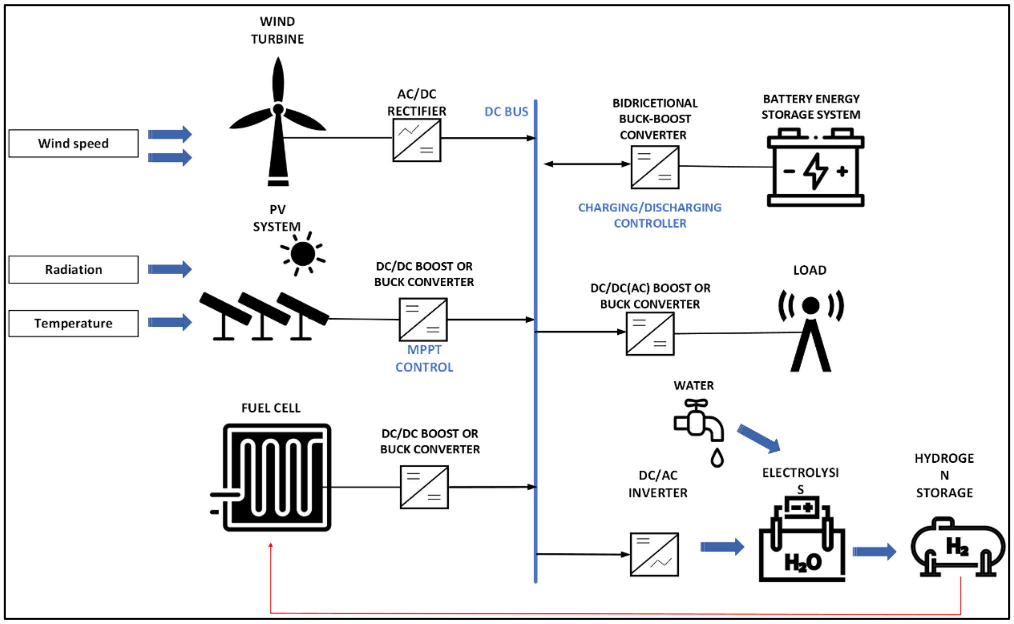
Figure 2.1. Typical microgrid classification

Microgrid systems have gained significant attention in recent years to enhance the reliability and sustainability of power supply for various applications, including telecommunication infrastructure. This chapter provides a comprehensive review of the existing literature on microgrid systems, focusing on their design, components, and integration with renewable energy sources.

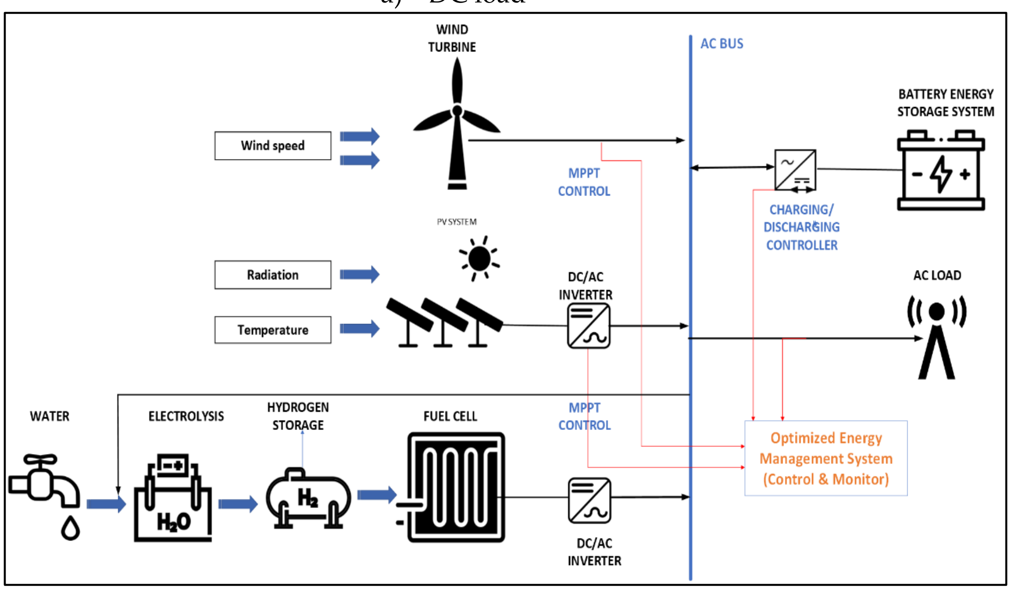
A solar hydrogen microgrid represents a cutting-edge approach to achieving sustainable and reliable energy solutions by integrating solar power with hydrogen energy storage. This hybrid system capitalizes on the strengths of photovoltaic (PV) solar panels and the flexibility of hydrogen storage, offering a resilient and environmentally friendly energy infrastructure.

Microgrids are localized energy systems that can operate independently or in conjunction with the main power grid. They consist of various distributed energy resources (DERs) such as solar panels, wind turbines, and fuel cells, along with energy storage systems [Figure.2.2]. The primary goal of a microgrid is to ensure a reliable and efficient power supply, particularly in remote or off-grid locations. Several studies have explored the potential of microgrid systems in different contexts.

Figure 2.2 illustrates the structure of the autonomous microgrid backup power system for stationary applications, detailing its principle scheme for both DC and AC bus configurations in stand-alone mode. To ensure optimal and efficient operation of the autonomous microgrid, the system's dimensioning and structure were designed using HOMER Pro (Hybrid Optimization of Multiple Energy Resource) software. This system includes photovoltaic (PV) and wind turbine (WT) production, a battery storage system, consumers, and a hydrogen subsystem comprising fuel cells (FC), an electrolyzer, and a hydrogen tank.



a) DC load



b) AC load

Figure 2.2. Microgrid architecture. (a) Off-grid configuration of the microgrid. (b) AC load distribution within the microgrid

All renewable energy sources (RES) and consumers, along with their associated energy converters, are connected in parallel to the AC(DC) bus. The energy management system (EMS) is linked to each unit through communication networks to establish proper control and management. The EMS is proposed to enhance the economy and robustness of the entire system, adding value to the developed concept. Integrating a photovoltaic energy source and wind turbines with hydrogen as an energy storage system result in a reliable energy source that is environmentally friendly and reduces overall maintenance costs.

In this hybrid system, hydrogen is produced by an electrolyzer powered by excess electricity from renewable energy sources. Hydrogen is then used to generate electricity in fuel cells, acting as a secondary energy source during periods of high demand. Simultaneously, the battery storage system is used to maintain power balance and system stability. This configuration not only ensures a consistent power supply but also contributes to a sustainable and cost-effective energy solution.

PEM fuel cells play a crucial role in this solar-hydrogen stand-alone system. Their integration into solar hydrogen microgrids represents a significant advancement in future energy systems and the ongoing energy transition, providing a sustainable and efficient solution for energy generation and storage. In solar hydrogen microgrids, the primary energy source is solar power, which is harnessed through photovoltaic (PV) panels. However, solar energy is intermittent, varying with weather conditions and time of day. To address this variability, solar hydrogen microgrids incorporate energy storage systems that can store excess solar power generated during periods of high irradiance and supply power during periods of low or no solar output. PEM fuel cells play a crucial role in this context by providing a reliable and efficient means of energy storage and conversion. One of the primary functions of PEM fuel cells in solar hydrogen microgrids is to provide a stable and continuous power supply. By converting stored hydrogen into electricity, PEM fuel cells can effectively balance the intermittent nature of solar power, ensuring that the microgrid can meet energy demands even when solar irradiance is low.

This capability is particularly valuable in remote or off-grid locations where a consistent and reliable power supply is critical. As the demand for clean and reliable energy solutions continues to grow, the role of PEM fuel cells in solar hydrogen microgrids will become increasingly important, contributing to the advancement of sustainable energy technologies and the transition to a low-carbon future. Continued research and development in PEM fuel cell technology and its integration with solar hydrogen microgrids are essential to fully realize their potential and maximize their benefits.
PEM fuel cells operate through an electrochemical reaction in which hydrogen (H_2) and oxygen (O_2) combine to produce electricity, water (H_2O), and heat. The key reactions occurring in a PEM fuel cell are as follows:

Anode (Oxidation): $\mathrm{H_2 \rightarrow 2H^+ + 2e^-}$ (1)

Cathode (Reduction): $\mathrm{1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O}$ (2)

Overall Cell Reaction: $\mathrm{H_2 + 1/2O_2 \rightarrow H_2O}$ (3)

Both electrodes are generally comprised of a gas diffusion layer (GDL) with a thin catalyst layer (CL) coating at the electrode-electrolyte interfaces where the reactions take place [5], as illustrated in Fig. 2.3. The GDLs are porous materials, typically made of carbon fiber, located adjacent to the catalyst layers. The GDL provides structural support to the CL and contributes to removing water produced as a by-product from the catalyst layer.

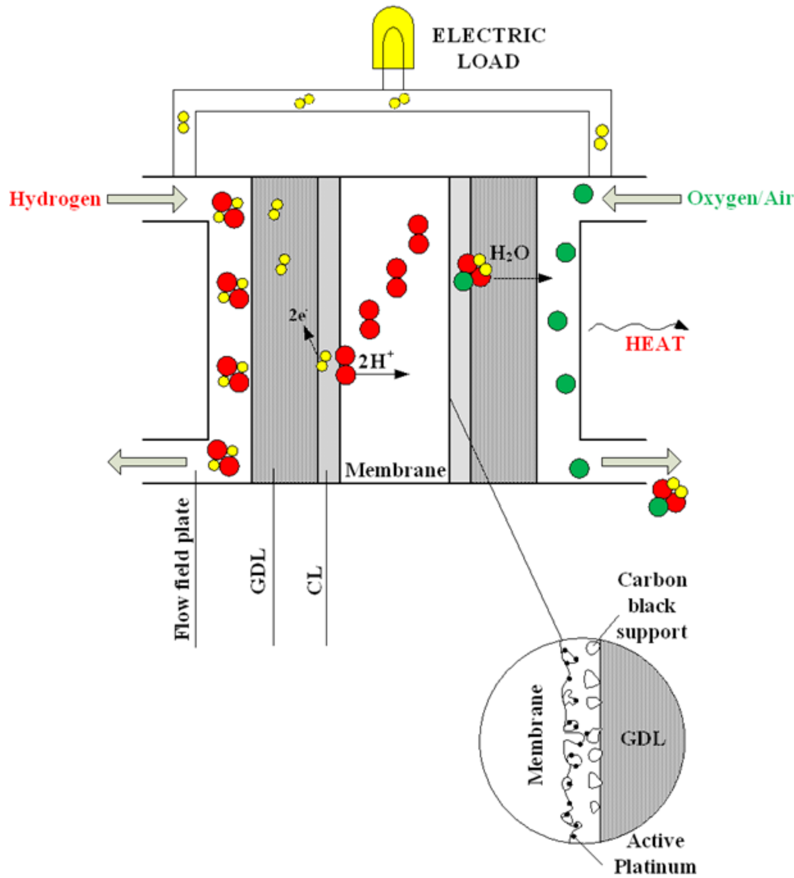


Figure 2.3. The basic schematic view of a PEMFC [adopted from Doctoral thesis, I. Tolj, Temperature field se-lection in order to improve membrane fuel cell performance, University of Split, FESB, Split, 2012]

Sunay Turkdogan [5] provides a detailed and well-researched examination of a renewable-based hybrid energy system for residential and transportation applications. The system is optimized using HOMER software, which simulates various configurations to find the most cost-effective and efficient setup. Manuel Castañeda, et.al. [6] have conducted an extensive study on the architecture, optimization, and management of a hybrid energy system. The system combines photovoltaic (PV), hydrogen storage, and battery storage to create a reliable and efficient standalone energy solution that harnesses renewable energy sources.

Numerous case studies demonstrate the successful implementation of microgrid systems in various applications. For instance, a study conducted by National Renewable Energy Laboratory [7] (NREL) analyzed a micro-grid system for a remote telecom tower that included solar panels, a wind turbine, a PEM fuel cell, and battery storage. The study found that the hybrid system reduced fuel consumption by 70% compared to a diesel-only system and significantly lowered operational costs. The literature review indicates that microgrid systems offer a viable and sustainable solution for powering telecommunication infrastructure, especially in remote and off-grid locations.
Future research should focus on optimizing the design and operation of microgrid systems, addressing challenges related to energy storage, and exploring innovative approaches to

integrating diverse energy sources. By doing so, microgrids can play a crucial role in advancing the sustainability and resilience of the telecommunication industry.

2.1. ENERGY MANAGEMENT SYSTEM(EMS) IN MICROGRIDS

EMS plays a pivotal role in ensuring the efficient and reliable operation of hybrid systems integrating solar, wind, hydrogen, and fuel cell technologies. Arshad Nawaz et al. [8], published in Applied Energy, provides an in-depth examination of the multi-microgrids (MMGs) concept, emphasizing its potential to enhance the integration of renewable energy sources (RES) and improve power system efficiency, reliability, and stability. The study addresses the significant role of energy management systems (EMS) and demand response programs within MMGs, highlighting their economic benefits and operational challenges.

The EMS in a microgrid performs several key functions such as Load Balancing, Peak Shaving, Renewable Integration, Battery Management, Grid Interaction.

Several technologies and approaches are employed in the development and implementation of EMS in microgrids are shown in table 2.1.

Table 2.1. EMS technologies and approaches

SN	References	Highlights
1	Guan, X. et.al [9], 2010	Algorithms such as Model Predictive Control (MPC), Genetic Algorithms (GA), and Particle Swarm Optimization (PSO) are used to optimize energy distribution and resource allocation within the microgrid.
2	Zhou, Y. et. al [10],2014	Real-time sensors and smart meter data are analyzed to inform energy management decisions, predict demand and supply fluctuations, and optimize energy resource operations.
3	Palensky, P., et.al [11], 2011	Demand response adjusts power demand rather than supply, using strategies like load shedding and shifting to align consumption with available supply.

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Table 2.1. continued

4	Dongfang Chen et al. [12], 2022	A novel approach for predicting the performance degradation of Proton Exchange Membrane (PEM) fuel cells utilizes a bidirectional Long Short-Term Memory (Bi-LSTM) neural network, optimized by a Bayesian algorithm, to enhance voltage prediction accuracy in PEM fuel cells.
5	Pavitra Sharma et al. [13], 2022	Classifies Energy Management Systems (EMS) by supervisory control, operating time platform, and decision-making strategies. Examine optimization techniques, including conventional programming (linear, non-linear, mixed-integer), meta-heuristic (Particle Swarm Optimization, Genetic Algorithm), and AI-based methods (fuzzy logic, neural networks).
6	Mahmudul Hasan et al. [14], 2023	The article reviews microgrid control mechanisms, focusing on centralized, decentralized, and distributed strategies. It highlights the importance of effective monitoring for real-time management and discusses using IoT and advanced communication technologies to enhance microgrid monitoring and control.
7	Gugulothu et al. [15], 2023	Presents a study on the configuration and control of a DC microgrid with photovoltaic (PV) systems, fuel cells, and battery energy storage systems (BESS). Fuel cell output is controlled based on BESS's state of charge (SOC) to optimize hydrogen usage under varying loads. Adjusting hydrogen and oxygen pressures in the fuel cell enhances power output, efficiently meeting additional load demands.
8	Atul S. Dahane et al. [16], 2024	Focuses on Demand Side Management (DSM) and its importance in modern energy systems, highlighting the integration of intelligent energy systems and smart loads to improve energy efficiency and grid stability.
9	Peng Wu et al. [17], 2024	The article explores the integration of Internet of Things (IoT) and digital twin technology in the management of hybrid microgrids (HMG) with a focus on achieving net-zero energy.

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Table 2.1. continued

10	Reagan Jean Jacques Molu et.al.[18], 2023	The article presents an optimization-based energy management system (EMS) designed for grid-connected photovoltaic (PV)/battery microgrids, addressing the challenges of uncertainty in energy generation and demand. Utilizes linear programming (LP) and mixed-integer linear programming (MILP) for optimization, aiming to minimize operating costs.
11	Ali Reza Abbasi et al. [19], 2023	This review provides a comprehensive analysis of energy management strategies in MGs, focusing on advancements from 2009 to 2022. It systematically classifies various methods based on techniques, control strategies, and structures, highlighting the integration of renewable energy resources and energy storage systems. Enhancing real-time monitoring, predictive maintenance, and system optimization using IoT-enabled sensors and digital twin simulations.
12	Long Phan Van et al. [20], 2023	Analyzed different optimization methods used in EMS, such as fuzzy logic control, model predictive control, heuristic and meta-heuristic algorithms, stochastic and robust programming, and hybrid approaches. Detailed the objectives (technical, economic, environmental) and constraints (energy storage, power capacity, transmission) considered in designing EMS for hydrogen-based microgrids.

Energy management systems may have numerous objective functions, some of which are suitable for specific cases. Tajjour and Chandel [21] categorize objective functions for microgrid planning into four primary areas: social, economic, environmental, and technical. These categories encompass a wide range of factors, including but not limited to human development indicators, financial costs, environmental impact metrics, and system performance indicators. To effectively balance these often-conflicting objectives, suitable optimization algorithms are required.

The reviewed studies illustrate the dynamic and multifaceted nature of EMS in microgrids, encompassing a wide range of optimization techniques, real-time data analysis, demand response strategies, and advanced control mechanisms. The table provides a comparative overview of various energy management systems (EMS) for microgrids, highlighting key methodologies and their respective focuses.

The comparative analysis of EMS in microgrids demonstrates a diverse range of methodologies and technologies aimed at enhancing energy distribution, resource allocation, and system reliability. Future developments in AI, IoT, and digital twin technologies are crucial for improving real-time monitoring, predictive maintenance, and overall efficiency of microgrid operations.

Table 2.2. List of selected publications with their goals, aims, methods and results

Publication	Goals and aims	Methods and conditions	Some results
Nguyen et al. [22], 2024	- Microgrid planning - scheduling the operation of the microgrid - minimizing the overall operating costs of microgrid and operational cost of the tank system	- Two-layer optimization model -connected to main grid, bidirectional energy exchange possible	The proposed model reduced the overall operating costs by 42.75 % compared to single level model
Phan-Van et al. [23], 2023	-Finding optimal size of a hydrogen storage-based microgrid - minimization of the microgrid cost - contains battery and tank	- Comparison 8 metaheuristic optimization algorithms (artificial bee colony, biogeography-based optimization, genetic algorithm, harmony search, invasive weed optimization, particle swarm optimization, shuffled complex evolution, and teaching–learning based optimization)	The particle swarm optimization algorithm was best, 25.3% lower annual system cost than the worst one energy management strategy for algorithm testing
Ammara et al. [24], 2024	- A mathematical model for DC microgrids - Ensuring and maximizing power production	- Artificial neural network	The simulations showed that load demands were met efficiently along with the global asymptotic stability of the system

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Table 2.2. continued

Rezaei et al. [25], 2024	- Energy management for isolated multi-energy microgrids which were used for hydrogen refueling stations.	- A two-layer framework for islanding operation of a multi-energy microgrid, a mixed-integer linear programming	The simulations showed that the model decreased expected operational cost
Kilic [26], 2024	- Energy management system - Improving power quality -Reducing operational costs - Optimization of hydrogen production	- A modified version of the Symbiotic Differential Whale Optimization Algorithm	The solution maintains DC-Link voltage stability despite varying renewable energy production and providing substantial cost reduction
Yousri et al [27], 2023	- Minimize the electricity and battery degradation costs, customers' discomfort, and peak-to-average ratio - In four scenario testing: good, bad, average weather scenarios, and a forecasted weather profile	- A model for energy management and demand response for hybrid energy storage system consisting of batteries and hydrogen tanks - A multi-objective artificial hummingbird optimizer	The model increased customer's savings and decreased greenhouse gas emissions in all four scenarios.
Shi et al. [28], 2023	- Self-consistent microgrid with hydrogen storage for transportation	-Particle swarm optimization	The storage stabilizes varying energy production from the wind and provides adjustability.

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Table 2.2. continued

Abdelghany et al. [29], 2024	- Predictive control of islanded and grid-connected modes - Considering daily as well as real-time markets (which have different time-scale).	- Advanced model predictive control strategy	- Tested on lab scale The solution minimizes bidirectional exchange with grid and operational costs. It is also capable of managing four modes: islanded, grid-connected, and exchange of energy modes
Zhang et al. [30], 2022	- Electric-hydrogen hybrid refueling stations and DC-microgrids - Voltage stability and reliable operation	- Fuzzy logic controller	Fuzzy controller provided optimal power allocation, and its use improved the lithium battery service life and hydrogen safety
Chamout et al. [31],2024	- Requirements of hydrogen purification - Off-grid household with availability of solar and wind electricity - Component costs and capacities	- A decision algorithm	The purification unit uses small amounts of energy but its operations affect sizing of the components.
Lyu et al. [32], 2024	- Global optimality for both sizing and scheduling of microgrid	- Combined solution methodology (Rolling Horizon Optimization and Particle Swarm Optimization)	The method converges within 30 generations and reaches a global satisfactory solution. Time-of-day tariff strategy is important.

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Table 2.2. continued

Sun et al. [33], 2024	- Operation planning for a microgrid	- A multistage stochastic mixed-integer program - A nested decomposition algorithm based on stochastic dual dynamic integer programming	The planning strategy was shown to have economic benefits and was successful for the seasonal and intra-day dynamics of the system.
Zhu et al. [34], 2024	- Optimal control framework containing energy management, economic optimization, and power regulation	-Distributed economic model predictive control scheme - A mixed integer nonlinear programming algorithm u	Simulations under varying irradiance and load condition showed the model to be suitable for Photovoltaic-Hydrogen DC microgrid
Fang et al. [35],2022	- Supply electricity, hydrogen and heating loads - Minimizing operational costs	- Day-ahead energy scheduling and model predictive control	- A multiple time-scale energy management was shown to be suitable for multi-energy microgrid.
Dong et al. [36], 2023	- Hydrogen-based microgrids fuel-cell electric buses - Economic feasibility	- A two-stage robust optimization formulation with integer corrective decisions	The proposed energy management solution demonstrates significant improvements over a benchmark method. Notably, it reduces mean daily operational costs by 37.08%.
Shen et al. [37], 2022	- A zero-carbon microgrid	- Capacity planning and operation strategies	Operational reliability and economic feasibility are verified in a village

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Table 2.2. continued

K/bidi et al. [38], 2022	- Solving a unit commitment problem arising from different system component constraints, together with a multistage power and energy management strategy	- distributed explicit model predictive control -a mixed-integer quadratic programming	The proposed method is shown to avoid inadequate start-up of fuel cells and electrolyzers.
Fang et al. [39],2024	-The electricity-heat-hydrogen supply-demand balance and demand uncertainties	- The day-ahead scheduling stage, model predictive control (intraday rolling stage) and intraday real-time adjustment stage (markets)	Proposed methodology effectively addresses the challenges of balancing electricity, heat, and hydrogen supply and demand, especially in the face of uncertain conditions.
Huangfu et al. [40], 2023	- A global optimal power distribution scheme and a rule-based judgment approach for reducing control complexity	- A subsection bi-objective optimization dynamic programming strategy and a multi-objective genetic algorithm strategy.	The solution improved photovoltaic utilization and fuel economy

Several case studies highlight the effectiveness of EMS in microgrids. In urban settings, EMS has been employed to enhance energy efficiency and reliability. A study by Navigant Research (2020) demonstrated that urban microgrids equipped with advanced EMS could reduce energy costs and emissions significantly. EMS has been crucial in the operation of microgrids powering remote telecom towers. For example, a study by NREL (2018) on a hybrid renewable energy system for a telecom tower showed that the EMS optimized the use of solar and wind energy, along with battery storage, resulting in a 70% reduction in diesel consumption. Community-based microgrids utilize EMS to manage the collective energy resources of multiple households and businesses. This enhances the resilience and sustainability of the local energy supply [41]. Future research should focus on developing more robust and scalable EMS solutions, enhancing interoperability through standardization, and improving cybersecurity measures. By addressing these challenges, EMS can further enhance the efficiency, reliability, and sustainability of microgrids.

Control system algorithms play a fundamental role in ensuring the stable, efficient, and intelligent operation of microgrids. These algorithms govern how distributed energy resources (DERs), energy storage systems, and loads interact within the network, maintaining reliable power supply under both grid-connected and islanded operating conditions. As microgrids increasingly integrate renewable energy sources, such as solar photovoltaic (PV) and wind systems—alongside energy storage and hydrogen technologies, advanced control algorithms become essential for balancing generation, storage, and consumption in real time. Microgrid control systems are typically designed using hierarchical control architecture. To meet the challenges of modern microgrids, advanced control algorithms are increasingly implemented.

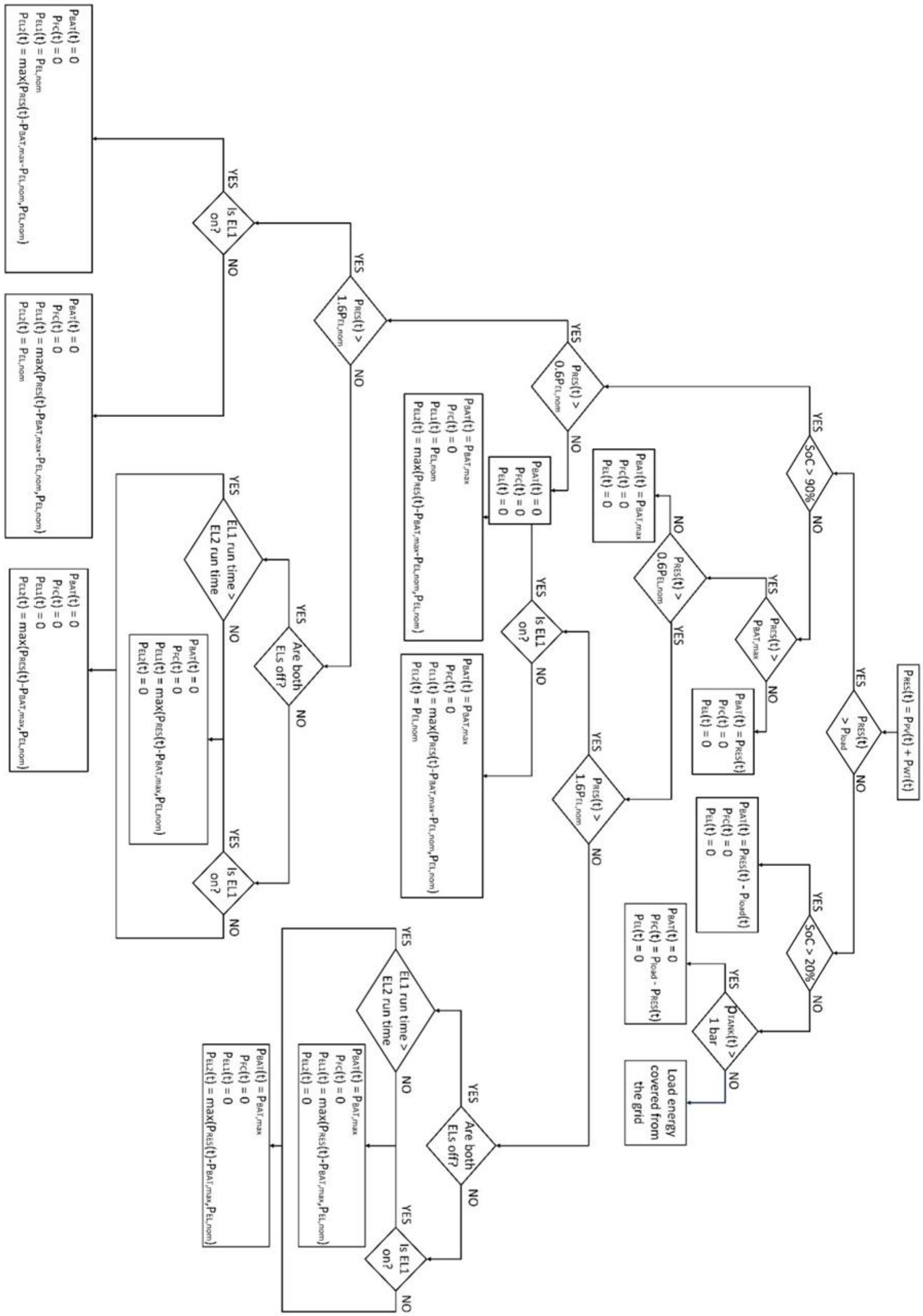

Figure 2.4. Flow chart of the control algorithm

Figure 2.4 presents the flowchart of the control algorithm implemented within the energy management system. This algorithm regulates and balances energy flows among the system components, namely the PV array, battery storage, electrolyzer, compressor, hydrogen storage, and fuel cell to ensure that the total energy supply meets the load demand while minimizing losses and maintaining safe and reliable operation.

2.2. ENERGY STORAGE SYSTEM IN MICROGRIDS (LOW AND HIGH PRESSURE HYDROGEN STORAGE)

Hydrogen storage is one of the most critical aspects of developing a sustainable hydrogen economy. Since hydrogen has a low volumetric energy density under ambient conditions, efficient and safe storage solutions are essential for its widespread adoption in transportation, stationery, and industrial applications. The choice of storage technology directly influences the performance, cost, and safety of hydrogen systems, including those integrated with fuel cells and renewable energy sources.

Hydrogen can be stored using three primary approaches: compressed gas, liquefied hydrogen, and solid-state storage. Each method presents unique advantages and challenges in terms of energy density, operating conditions, and technological maturity.

The various storage methods and their categorizations are shown in Figure 2.5. The most popular strategies are pressurized gas and liquid hydrogen preservation. The solid-state storage technology is in progress and anticipates increased application in the next decades. Hydrogen can be compressed to 700 bars in appropriate buildings and kept as a gas in cylinders, containers, and subterranean cavities.

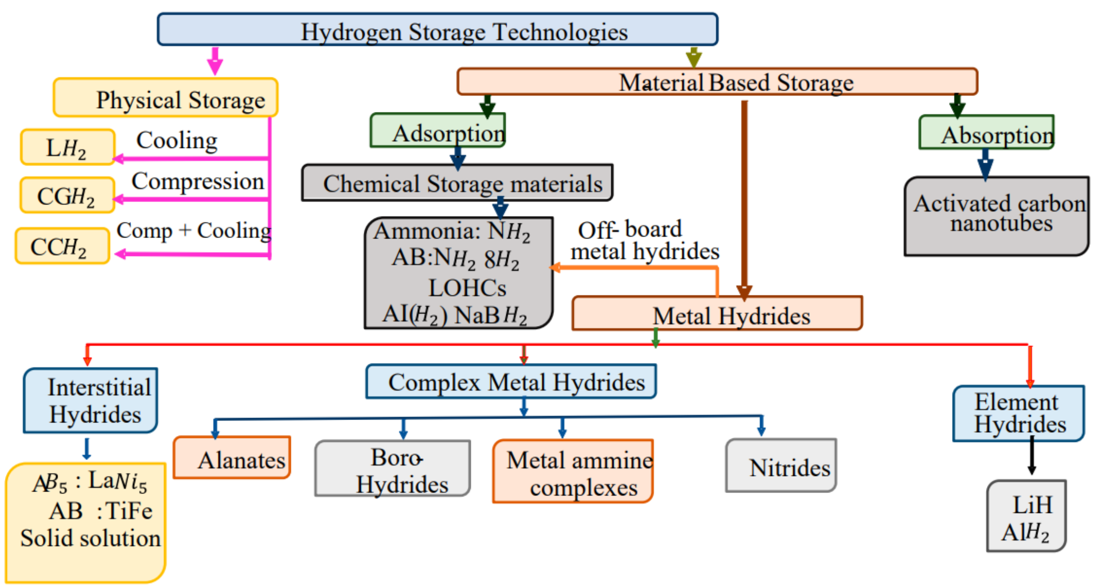

Figure 2.5. Types of hydrogen storage technologies

Microgrid systems may contain both battery and hydrogen storage to provide adequate supply without electric grid. This has been demonstrated by many researchers (e.g. Chamout et al. [42]).

Different phases of hydrogen used in storage can be naturally utilized with a battery. Jahanbin et al. [43] utilizes hydrogen gas and metal hydride battery with battery storage for a building using solar energy. Both storage solutions increased the annual renewable energy ratio which was increased further by adding battery storage.

There are already many reviews on issues related to hydrogen (e.g. Tajjour & Chandel [21], Ge et al. [44] and Khare et al. [45] studied advantages and disadvantages of hydrogen energy and storage for a power system. This review provides detailed technical aspects of hydrogen production and storage.

Table 2.3. Review of selected publications of hydrogen storage systems

Publication	Goals and aims	Methods and conditions	Some results
Van et al. [46], 2023	- Energy management strategy for renewable energy microgrid with hydrogen storage system	-A state machine-based strategy combined with a hysteresis band control strategy -connected to main grid, bidirectional energy exchange possible	- Balanced supply and demand within the microgrid. - Extended lifespan of electrolyzer and fuel cell. - Maintained appropriate storage levels for battery and hydrogen
Bouaouda & Sayouti [47], 2024	-A framework for microgrid size optimization and performance assessment	- Quantum-based Beluga Whale Optimization	- Simulated microgrid with renewable sources and hydrogen storage. - Demonstrated capability to supply energy to a remote off-grid site.
Karimi [48], 2024	- Sustainable scheduling of hybrid hydrogen-power systems - Minimize the total costs, carbon emission, and peak load	A stochastic three-objective optimization mode and min-max approach	- Hydrogen tank enhanced system flexibility. Excess renewable energy converted to hydrogen. - Min-max approach increased load factor from 77.22% to 83.48%.

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Table 2.3. continued

Abdelghany et al. [49], 2024	- Energy management strategy for a microgrid with wind-hydrogen strategy - Short-term and long-term operations (load demand, maximize the revenue, minimizing operation costs)	- A hierarchical model predictive control, mixed-logic dynamic framework, a mixed-integer linear program	- Wind energy surplus converted to hydrogen. - Hydrogen stored for later use. - Hydrogen utilized in grid-islanded and connected operations.
Wu et al. [50], 2024	- Energy management for a residential microgrid -Combatting long-term and short-term uncertainty introduced by renewable sources	- Proposed a hierarchical on-line energy management for a Hybrid hydrogen–electricity Storage - Operating time: battery storage for every minute and hydrogen storage hourly. The hydrogen energy storage was for long-term, seasonal energy variation.	- Reduced overall energy cost by 21% compared to battery-only system

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Table 2.3. continued

Giovanniello & Wu [51], 2023	- Sizing components for a microgrid with 100 % wind energy (Canada) -Long and short-term storages	- A mixed integer linear programming model - Lithium-ion batteries and hydrogen to solve issues in short- and long-term	- Hybrid storage reduced costs significantly. - Hybrid storage is more cost-effective than single storage. - Lithium-ion battery costs dominated by energy storage capacity. - Hydrogen system impacted overall microgrid costs. - Lower electrolyzer efficiency significantly increased total microgrid cost. - Improved fuel efficiency primarily reduced total system costs. - Hydrogen system provided less energy than batteries but was crucial during peak demand periods.
Yousri et al. [52], 2023	- Minimize the electricity and battery degradation costs, customers' discomfort, and peak-to-average ratio - In four scenario testing: good, bad, average weather scenarios, and a forecasted weather profile	- A model for energy management and demand response for hybrid energy storage system consisting of batteries and hydrogen tanks - A multi-objective artificial hummingbird optimizer	- Model increased customer savings and reduced greenhouse gas emissions across all scenarios.

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Table 2.3. continued

Abdelghany et al. [53], 2024	- Renewal electricity was utilized in hydrogen production -Several hydrogen tanks - Autonomous operation without utility grid - Economic and operational costs, degradation aspects, physical constraints, demands as well as smoothing variations of renewable energy production	- Model predictive control (also known as hierarchical rolling horizon control) for managing a hydrogen-energy storage system in an islanded wind/solar microgrid	- Microgrid capable of independent operation. - Multiple hydrogen tanks enable long-term storage. - System complexity increased with hydrogen storage. - Hydrogen storage might not suffice for extended periods. - System performance validated through laboratory testing.
Li et al. [54], 2024	- Increasing safety and stability of large power grids because of uncertainty in energy production using wind and solar - Different storage solutions - Economic costs -Multigrid system	-Distributional robust approximation solving - A combination of the Bonferroni test and Conditional Value at Risk	- Optimal solution: independent hydrogen storage, shared battery storage. - Power transmission between microgrids favored simultaneous storage configuration. - Hydrogen storage investment cost significantly impacted overall costs.

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Table 2.3. continued

Deng et al. [55], 2023	- A multi-microgrid system which has a shared electric-hydrogen storage - Combination of cooling, heating and power systems	- bi-layer optimization configuration model. The upper layer is energy storage capacity issues, lower level for multi-microgrid optimization	- Shared storage outperformed individual storage. - Reduced battery capacity by 75.94%. - Decreased daily operating costs by 11.53%. - Hybrid energy storage yielded further improvements. - Increased daily net income by 61.67%. - Reduced battery capacity by an additional 67.13%. - Decreased daily operating costs by 3.39%. - Achieved a payback period of 1.6 years
Shi et al. [56], 2023	- Self-consistent microgrid with hydrogen storage for transportation	-Particle swarm optimization	Storage balances fluctuating wind energy output and enables grid flexibility.
Qiu et al. [57], 2024	-Optimal scheduling of microgrids with coordinated long-term and short-term energy storage - Economic optimization	- Mixed Integer Linear Programming which solved using the Yalmip/Gurobi commercial solver	- Combined battery and hydrogen storage for effective cross-seasonal energy management in microgrids
Naseri et al. [58], 2022	- Controlling an islanded microgrid (stand-alone/off-grid microgrid) - Green hydrogen production, storage, and re-electrification	- Two-layer hierarchical control	Simulation results indicate that green hydrogen production is feasible using solar energy. Hydrogen is stored for later electricity generation when sufficient pressure is built up.

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Table 2.3. continued

Shao et al. [59],2023	- Multi-energy off-grid microgrids for hydrogen - Economics and resilience	- A two-stage risk-constrained stochastic programming. The first stage was about energy resource configuration optimization, second stage long term economics and on-emergency feasibility verification - risk constraints via sampling approximation strategy	Hydrogen storage provides both short-term and seasonal energy storage capabilities, contributing to overall cost reduction.
Er et al. [60], 2024	For sizing microgrid for a grid-vehicle-grid approach minimize life cycle costs and maximize the system reliability.	- Two-stage stochastic programming with a scenario-based approach	- Hybrid storage system most cost-effective with low power supply loss. - Increased power supply loss allowed for more economical solutions.
Xiang et al. [61], 2021	- Zero emission airport operation - techno-economic benefits	- A mixed integer linear programming optimization method, life cycle theory	- Hydrogen system reduced annual costs by over 40% and greenhouse gas emissions by over 65%

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Table 2.3. continued

Kumar et al. [62], 2022	- Stand-alone microgrids (off-grid energy providers) can get their energy 100 % from renewables - use of metal hydride-based hydrogen-energy storage system. -optimal sizing of components	- Optimization done via simulation software HOMER	Hybrid systems typically require smaller storage capacities compared to wind-only microgrid systems.
Zhang et al. [63], 2022	- Electric-hydrogen hybrid refueling stations and DC-microgrids - voltage stability and reliable operation	- Fuzzy logic controller	- Fuzzy control optimized power distribution, extending lithium battery life and enhancing hydrogen safety
Li et al. [64], 2023	- Analysis of hydrogen energy storage and battery based on the levelized cost of storage, carbon emissions and uncertainty assessments	-Monte Carlo method	- Hydrogen production using alkaline electrolyzers, pipeline delivery, and refueling demonstrated the lowest cost of 0.227 US$/kWh and CO2 emissions of 61.63 gCO2e/kWh. - Large-scale storage systems yielded comparable results.
Xu et al. [65], 2024	- A hydrogen storage for a pumping unit using renewable energy	-Simulations and control strategy	- Standalone operation for up to 72 hours. - Energy conversion efficiency of 35%. - Proven through real-world implementation

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Table 2.3. continued

Pignataro et al. [66], 2024	-Modelling a power-to-gas system (synthetic methane using wind energy)	- Management strategy incl. storage - Mathematical modelling	The larger size of storage leads to better performance.
Abdolmaleki & Berardi [67], 2024	- Solar and hydrogen energy for a single-house and a midrise apartment	- HOMER software	- Simulated systems: PV/battery, PV/hydrogen, PV/battery/hydrogen Best economical configuration: - 522 kW photovoltaic (PV) panels - 150 kW electrolyzers - 20 kW fuel cells - 200 kg hydrogen tank - 18.6 kW converter - 159 batteries.
Liu et al. [68], 2024	- Design of large-scale hydrogen storage pipeline networks - costs	- A mixed integer nonlinear optimization mode - hybrid genetic algorithm that combines the Modified Feasible Directions Method and Genetic Algorithm Theory	- investment of the pipeline network is affected by wellhead temperature more than ambient temperature
Dong et al. [69], 2023	- Hydrogen-based microgrids fuel-cell electric buses - Economic feasibility	- A two-stage robust optimization formulation with integer corrective decisions	- Hydrogen-based microgrids can serve as operation centers for fuel-cell electric buses. - This integration offers economic feasibility and contributes to decarbonization.

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Table 2.3. continued

K/bidi et al. [70], 2022	- Solving a unit commitment problem due to different constraints of system components - A multistage power and energy management strategy	- Distributed explicit model predictive control -A mixed-integer quadratic programming	- The proposed method effectively prevents premature and inefficient start-up of fuel cells and electrolyzers.

The comparative analysis of recent studies on hydrogen storage in microgrids reveals a diverse range of technical solutions and methodologies, each aimed at improving the efficiency, sustainability, and cost-effectiveness of energy management systems. The primary focus across these studies is on optimizing the use of renewable energy sources through innovative storage and control strategies, while addressing the inherent challenges of variability and uncertainty in renewable energy production. For instance, Van et al. [46] and Abdelghany et al. [49] aim to balance supply and demand within microgrids and convert surplus renewable energy into hydrogen. Karimi [48] and Yousri et al. [52] focus on sustainable scheduling and reducing costs and emissions, while Giovanniello & Wu [51] and Li et al. [54] explore the economic feasibility and stability of hydrogen storage systems. A variety of optimization techniques and control strategies are employed across these studies. Methods such as stochastic optimization, model predictive control, mixed integer linear programming, and quantum-based optimization are prominently featured. For example, Karimi [48] uses a stochastic three-objective optimization model, while Bouaouda & Sayouti [47] employ Quantum-based Beluga Whale Optimization. Wu et al. [50] and Giovanniello & Wu [51] leverage hierarchical and mixed integer linear programming models, respectively.

The results consistently demonstrate improvements in system performance, cost reduction, and energy efficiency. Van et al. [46] reports balanced supply and demand and extended component lifespans, while Wu et al. [50] shows a 21% reduction in overall energy costs with a hybrid storage system. Deng et al. [55] highlights significant reductions in battery capacity and daily operating costs with a rapid payback period. Furthermore, hybrid storage solutions, as examined by Giovanniello & Wu [51], prove to be more cost-effective than single storage options. While the technical solutions proposed are innovative and promising, several challenges remain for real-world application. The complexity and computational demands of advanced optimization methods, such as those used by Abdelghany et al. [49] and Shi et al. [56], can be significant barriers. Additionally, the high initial investment costs for hydrogen storage systems, as noted by Li et al. [54], may limit widespread adoption. There is also the challenge of ensuring system reliability and robustness in the face of renewable energy variability, which is crucial for practical deployment.

Future research should focus on simplifying these systems, reducing costs, and validating performance under real-world conditions to facilitate the practical integration of hydrogen storage in microgrids.

2.2.1. CRITICAL ANALYSIS OF HYDROGEN STORAGE SYSTEM- APPROACHES

Properties of an energy system management depend on components and processes of the system like power generation process. Hydrogen has been shown to good for power generation (e.g. Bai et al. (2024) [71]) which makes the storage necessary in many cases. In this subsection, some important aspects of the hydrogen storage systems are shortly evaluated.

Osman et al. [72]). explores recent advancements in hydrogen storage technologies, categorized into physical-based and material-based approaches. Physical storage methods, including compressed, liquefied, and cryo-compressed hydrogen, offer innovative solutions for enhancing hydrogen density and safety. Material-based storage methods focus on the utilization of metal hydrides, complex hydrides, and carbon-based materials like activated carbon, graphene, and carbon nanotubes, which employ absorption and adsorption techniques for hydrogen retention and release. The integration of computational chemistry, high-throughput screening, and machine learning has revolutionized the development of these storage materials, enabling the optimization of structural attributes, porosity, and stability. A more detailed description of storage methods can be found e.g. in Osman et al. [72]. The selected storing methods determine, for example, which kind of tank is needed. Sometimes the selection is limited by the environment, because underground storage is not available or cannot be utilized e.g. for environmental reasons.

Size parameters are very important for a storage tank. Since hydrogen can be stored in different phases (gas, liquid, and material-based hydrogen), different storage solutions are needed. For example, Ba-Alawi et al. [73] designed a storage system for reverse osmosis using a safety-oriented multi-criteria optimization with design parameters like storage size, pressure, flow rate, and temperature. The tank size is thus affected by the storing method selected.

Different phases of hydrogen are typically in different temperatures. For example, liquid hydrogen requires temperature no higher than -252.9 °C in. If a liquid hydrogen storage is used, then it needs to be insulated properly for safety and efficiency (Yin et al. [74]. Insulation is still under active development (e.g. Yin et al. (2024) [74]). Hydrogen storages have different pressures, which may some cases be selected. In these cases, the selected pressure can have economic impacts: According to Hu et al. (2024) [75], hydrogen utilization rate may effectively be improved by the nominal working pressure of the medium-pressure and high-pressure tanks for refueling station.

Storage requires often permission and must follow local regulations, codes and standards. For example, high pressure hydrogen cylinders have similar but not the same regulations, codes and standards in different countries (Li et al. [76]). Properties of hydrogen have to be taken into account on storage structure and material as well as safety issues. For example, Meda et al. (2023) [77] states that susceptibility to hydrogen embrittlement increases with strength and is thus higher for high-strength steels. Their suggestion to counter this embrittlement is multi-layered coatings.

2.2.2. EXISTING CHALLENGES AND FUTURE OF ENERGY STORAGE SYSTEM

Energy storage systems have still many challenges. A review of global trends and future scenarios can be found in Pleshivtseva et al. [78] and a bibliometric evaluation for grid-connected hydrogen storages is provided by Irham et al (2024) [79]. Table 4 lists challenges and future predictions found in publications. Tajjour & Chandel (2023) [21] identified following microgrid with a battery storage challenges like cyber security threat, optimal, stable power flow without any constrain violation, energy management for peak-shaving either via adding more power generation or load shedding\shifting, and optimal network configurations. Security may become a more important topic in the future including also the hydrogen storage systems.

Hassan et al. (2023) [79] discussed issues especially related to hydrogen storage systems. Main challenges of systems are related to large-scale hydrogen production and storage; costs, scaling-up and lack of infrastructure. Storing hydrogen has also many challenges in addition to its costs (storage material, tanks and other infrastructure, transportation). Storage materials are still under development as the current are not enough cheap or efficient. Hydrogen storage has still low energy density and requires specific environmental conditions like high pressure or low temperature. As hydrogen is a flammable and explosive substance, safety for a hydrogen system is a critical factor.

Schiaroli et al. [80] says that flammability is one of the issues using hydrogen for transportation sector. They present an alternative storage solution utilizing the Monte Carlo method. The highest security performance was cryogenic storage in the liquid phase at ambient pressure. Safety and cost issues are also considered by Sikiru et al. [81], Ghorbani et al. (2023) [82], and Ma et al. (2023) [83]. The lack of standardization and codes are hindering development of storage systems. The codes and standards were also discussed by Abdalla et al. (2018) [84] as well as weight, volume, cost, and efficiency of storage. Rasul et al. (2022) [85] considered hydrogen storage is main challenge for systems. Novel storage systems need to be therefore developed (e.g. Bosu et al. (2024) [86], Rasul et al. (2022) [85]).

The size of hydrogen storage affects costs, so bigger storage should be developed (Moran et al. (2024) [87]). There is also a need for better materials (Hassan et al. (2024) [88]). Hannan et al. (2022) [89] studied a hybrid system to response short and long time demands. They also found efficiency, costs and security to be important. Environmental issues related to hydrogen should be addressed carefully (e.g. Saadat et al. (2024) [90], Higgs et al. (2024) [91]) as well as operational challenges (Bosu et al. (2024) [86]).

Saberi Kamarposhti et al. (2024) [92] investigated use of AI for energy systems utilizing hydrogen while identifying several issues like data security. The use of AI can lead to decentralization of energy systems. Van et al. (2023) [93] discussed the need of better forecasting for renewable power production as well as load demand for energy system management. These are important factors for microgrid control.

Table 2.4. Challenges and future of energy storage systems

Publication	Challenges	Future
Tajjour & Chandel [21], 2023	Battery sizing, secure operation of microgrid	AI applications, technique development, Blockchains and Reinforcement Learning techniques
Hassan et al. [79], 2023	General challenges: scaling up hydrogen storage technologies, high cost of hydrogen production and storage, need for more extensive infrastructure, low production efficiency Storage specific challenges: Low energy density, High pressure or low temperature Requirement, Safety concerns, storage materials	Increasement in clean and sustainable energy, high-density, efficiency, and cost-effective hydrogen storage materials, reduced storage volume
Schiaroli et al. (2024) [80]	hydrogen flammability, safety	Better risk management, control and reduction of risks
Ghorbani et al. (2023) [82]	Safe and efficient storage, operating conditions, and application	Improvements in goals, energy safety and efficiency
Ma et al. (2023) [83]	Cost of large-scale hydrogen storage, high energy requirement for gas compression	Decrease in costs, a novel evaluation method of technical and economic feasibility, new infrastructure and storages
Abdalla et al. (2018) [84]	Weight, volume, cost, efficiency, codes, and standards safe, reliable and cost-effective	Advances in storage technologies and infrastructure
Rasul et al. (2022) [85]	development of hydrogen storage Storing conditions of hydrogen container material degradation	Novel storage systems increase in demand for hydrogen
Bosu et al. (2024) [86]	Operational challenges, cost effective storage, technical challenges, dehumidification of hydrogen, storage system volume problem	New storage materials, catalytic doping and structural modification, accurate lifecycle analysis, nanocomposites
Moran et al. (2024) [87]	storage size and cost	Increase in storage size reduces overall levelized cost

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Table 2.4. continued

Hannan et al. (2022)	A hybrid storage system (capacity, long-lifespan, low-cost, high-efficiency, and high-security)	Extended lifetime, lower cost, and higher security
Saadat et al. (2024) [90]	Hydrogen interactions with microorganisms in underground storage, in-situ reactions, leakages	Resilience, environmental safety
Higgs et al. (2024)[91]	potential contamination and/or changes to rock Properties, leakages for hydrogen storages in porous media	More research in hydrogen reactivity, mobility through seal, gas mixtures, storage site
Saberi Kamarposhti et al. (2024)[92]	Data security and privacy, interoperability, and the technical constraints of AI for hydrogen system	Decentralization, autonomous energy management system
Van et al. (2023) [93]	Forecasting power production and load demand	Multi-microgrid systems, environmental objectives, the utilization of other hydrogen roles, accurate microgrid modelling
Sikiru et al. [94], 2024	A safe, dependable, and cost-efficient large-scale storage system needed, reliability lack of appropriate standards and codes	The safe, dependable performance reduced cost in large scale hydrogen utilization improvement in durability and efficiency

The reviewed studies highlight various challenges in hydrogen storage, which can be broadly categorized into technical, economic, and safety concerns. Each study provides insights into current issues and proposes future directions to address these challenges.

Several studies focus on the technical complexities of hydrogen storage. Tajjour & Chandel [21] address the challenge of battery sizing for secure microgrid operations, suggesting advancements in AI and blockchain technologies. Hassan et al. [79] and Bosu et al. [86] discuss the low energy density and high-pressure requirements of hydrogen storage, proposing new materials and nanocomposites to improve efficiency.

High costs and low production efficiency are significant barriers identified by Hassan et al. [79] and Ma et al. [83]. Future research is directed towards reducing these costs through novel evaluation methods and the development of more efficient storage materials. Moran et al. [87] highlights the impact of storage size on reducing overall costs, advocating for increased storage capacities.

Safety is a major focus, with Schiaroli et al. [80] and Ghorbani et al. [82] emphasizing the risks associated with hydrogen flammability and safe operating conditions. Improvements in risk management and safety protocols are essential. Environmental concerns, such as hydrogen interactions with underground microorganisms, are addressed by Saadat et al. [90] and Higgs et al., who call for more research into hydrogen reactivity and mobility in storage sites.

Future research aims to overcome these challenges through technological innovations and infrastructure development. Abdalla et al. [84] and Rasul et al. [85] stress the importance of advancing storage technologies and infrastructure to ensure safe, reliable, and cost-effective hydrogen storage. Van et al. [93] and Sikiru et al. [94] highlight the need for accurate microgrid modelling and the establishment of comprehensive standards and codes.

3. OPTIMIZATION METHODS

Numerous studies propose various control algorithms to enhance the efficiency and stability of PEM fuel cell systems. These approaches not only reduce hydrogen consumption but also ensure more reliable power output, making them a promising solution for high-power applications.

Yurdagül Bentes Yakut [95] investigates the development of a new control algorithm designed to enhance the efficiency of Proton Exchange Membrane (PEM) fuel cells. This research is particularly relevant for applications where high efficiency and reliability are paramount, such as in the automotive industry and renewable energy systems. This system aims to optimize hydrogen fuel consumption and stabilize output voltage by employing a boost converter controlled by a Proportional-Integral (PI) controller fine-tuned using the Particle Swarm Optimization (PSO) method. The study concludes that the proposed control algorithm, combined with PSO-optimized PI controller parameters, offers a significant improvement in the efficiency and stability of PEM fuel cell systems.

H. Rezk et al. [96] presents an innovative optimization approach aimed at improving the efficiency of PEM fuel cells. The focus of their research is on the application of the Equilibrium Optimizer (EO), a recent metaheuristic algorithm inspired by physical processes, to optimize the control parameters of PEM fuel cells. The paper outlines a detailed methodology where the EO algorithm is used to fine-tune the parameters of a Fuzzy Logic Controller (FLC) integrated into the Maximum Power Point Tracking (MPPT) system of PEM fuel cells. The optimization process involves several phases, including initialization, equilibrium pool formation, and iterative concentration updates, to achieve a balance between exploration and exploitation in the search for optimal solutions. Jiankang Wang, et al. [97] explore innovative methods to enhance the performance of PEM fuel cells. The research introduces a Machine Learning-assisted Multiphysics Numerical model (MNM-ML) to optimize the parameters that mitigate NGC while maintaining high performance. The authors compare nine state-of-the-art machine learning algorithms to identify the best model for this task.

By integrating advanced optimization techniques, the study contributes to the development of sustainable and resilient energy solutions, promoting the broader adoption of hybrid renewable energy systems in remote and off-grid locations.

Abdeljelil Chammam et al. [98] explored the optimization of a novel multi-generation system designed to produce electricity, cooling, heat, and freshwater. The system utilizes a PEM fuel cell to generate electricity. To optimize this system, the study focuses on two primary objectives: exergy efficiency and the total cost rate (TCR). The optimization process employs a genetic algorithm (GA) to identify the optimal operating conditions. This method involves adjusting various design variables such as the operating temperature and pressure, and current density of the fuel cell.

Hegazy Rezk et al. [99] presents a robust methodology for the accurate parameter estimation of Proton Exchange Membrane (PEM) fuel cells using the Gradient-Based Optimizer (GBO). The optimization process treats the unknown parameters of PEM fuel cells as decision variables. The objective function, which needs to be minimized, is the sum of squared errors (SSE) between the measured and estimated data. This research focuses on a precise parameter estimation strategy for PEM fuel cells, which is crucial for ensuring accurate emulation of the fuel cell system characteristics. The proposed methodology leverages the Gradient-Based Optimizer (GBO) to identify optimal parameters for three types of PEM fuel cells: 250 W FC stack, BCS 500 W, and SR-12 500 W. The results highlight GBO's capability to deliver better accuracy and reliability in PEM fuel cell parameter estimation, making it a highly effective tool for optimizing PEM fuel cells' performance.

Chengjun Guoa et al. [100] delve into various optimization strategies for improving the performance of Proton Exchange Membrane (PEM) fuel cells. The focus is primarily on the application of advanced optimization algorithms to fine-tune critical parameters of PEM fuel cells, ensuring enhanced efficiency and operational reliability. The study evaluates several state-of-the-art optimization techniques, including Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Differential Evolution (DE), and Gradient-Based Optimizer (GBO). These methods are applied to a comprehensive model of the PEM fuel cell to identify the optimal parameter settings that minimize errors between experimental data and theoretical predictions. Key optimization variables considered in this study include the membrane thickness, electrode properties, and operational conditions such as temperature and pressure. The optimization process aims to achieve a balance between maximizing the fuel cell's power output and minimizing the total cost of operation, including maintenance and replacement of components. The Gradient-Based Optimizer, in particular, shows promise as a leading tool for achieving these optimization goals, paving the way for more efficient and sustainable energy solutions.

Wei Zhao et al. [101] highlights the critical role of effective water management in the performance and durability of proton exchange membrane fuel cells (PEMFCs). The paper provides a comprehensive review of common water management issues such as flooding and membrane dehydration, which significantly impact the efficiency and lifespan of PEMFCs. The paper concludes that while significant progress has been made, there are still challenges and opportunities for further development in water management for PEMFCs. Future research should focus on improving diagnostic accuracy, developing cross-scale and multi-physics simulation studies, and advancing data-driven diagnostic methods for efficient and stable PEMFC operation. These efforts are crucial for the commercialization and broader application of PEMFCs in achieving carbon neutrality and sustainable energy solutions.

Abdullah G. Alharbi et al. [102] presents a comprehensive approach to optimizing Proton Exchange Membrane (PEM) fuel cells using a variety of advanced algorithms, with the primary aim of enhancing efficiency and reducing energy losses. The optimization strategies discussed include Gradient-Based Optimizer (GBO), Genetic Algorithm (GA), hybrid optimization techniques, multi-objective optimization, and Particle Swarm Optimization (PSO).

The Gradient-Based Optimizer (GBO) is highlighted for its ability to quickly converge on optimal solutions by leveraging Newton's gradient-based principles. This method is particularly effective for complex engineering problems, showing superior performance in optimizing PEM fuel cell parameters compared to other algorithms. It asserts that these advanced optimization methods significantly improve the performance and efficiency of PEM fuel cells. The comprehensive comparison of different algorithms highlights the effectiveness of these strategies in achieving optimal system performance, making PEM fuel cells more viable for various applications, including off-grid and hybrid energy systems.

Dong fang Chen et al. [103] present a novel approach for predicting the performance degradation of Proton Exchange Membrane (PEM) fuel cells. The authors utilize a bidirectional Long Short-Term Memory (Bi-LSTM) neural network optimized by a Bayesian algorithm to enhance the accuracy of voltage prediction in PEM fuel cells. The study addresses the challenges of long-term operation of fuel cells, where performance degradation is a critical issue due to the aging of components such as the membrane electrode assembly. The study concludes that the proposed Bayesian-optimized Bi-LSTM neural network model offers a robust and accurate method for predicting the short-term performance degradation of PEM fuel cells, with potential applications in enhancing the reliability and efficiency of fuel cell systems in real-world scenarios.

4. CRITICAL FINDINGS

The findings and recommendations can be roughly divided into the following categories: regulatory and policies, economics, storage and its properties, environmental issues, applications as well as management system.

Hassan et al. [79] recommend policy and regulatory support which includes incentives and financial support from governments, changes in regulations, and international collaboration. Hannan et al. [89] found it necessary to change energy market. The financial and economic factors are critical as one of the issues in hydrogen usage in power production is price. The price of hydrogen may drop to economically suitable level of 1-2 $/kg within a couple of decades (Rasul et al. [85]). Capital costs should decrease so that hydrogen storage system would be an economic solution (de la Cruz-Soto et al. [104], Diaz et al. [105].). Kilic [26] noted that hydrogen production has intrinsically slow dynamics from electricity thus optimization of hydrogen production is needed from solar and wind.

Diaz et al. [105] found that hydrogen approach reduced the total annual cost of microgrid by 14.1 %. The selection of technologies was influenced by market factors (e.g. investment and tariff structure costs) and customer characteristics (the load profile and the availability of renewable energy sources). Aba et al. [106] recommends utilizing hydrogen in storage rather than as carriers. It is also suitable for regions where grid extensions are difficult as well as industry, which cannot otherwise reduce emissions (hard-to-abate).

Le et al. [107] describes critical future research objectives. Very important parameters are efficiency, sustainability, safety, and economic feasibility. Hydrogen has significant and numerous obstacles, one of them is storage. Yang et al. [108] studied critically battery and hydrogen energy systems. Important factors which are lacking: large storage capacity in limited space, frequent storage with rapid response, and continuous storage without loss. Batteries are good short time storage but have serious limits for longer use like a self-discharge rate (>1 %) and capacity loss (~20 %). Hydrogen is better for longer use, but the problem is with low efficiency. Yang et al. (2024) [108] recommends using a hybrid energy system using batteries and hydrogen storage.

Er et al. [109] used two-stage stochastic programming with a scenario-based approach for sizing microgrid (a grid-vehicle-grid approach). A hybrid storage system was found to be most cost-effective option with low loss of power supply probability. When more loss of power supply probability was allowed, it was more economical solution.

Ba-Alawi et al. [110] identified constraints of different phase storage systems: for gas storage systems, the long-term financials are concerns e.g. due to high investment cost. In liquid storage systems, constraints are liquefaction and boil-off operations, and necessary risk management. Hydrogen-material based systems require precise heat management and high investments.

Mehr et al. [111] highlights the critical role of hydrogen storage in the overall hydrogen value chain. Their research provides a comprehensive analysis of hydrogen storage technologies across various scales, considering technical maturity, and economic viability. Life cycle cost analysis, feasibility and safety are very important for systems. Giovanniello & Wu [112] also noted that high proportions of renewable sources increase supply-demand mismatches due to their variability. These mismatches can happen in multiple timescales thus indicating the importance of storage. Hren et al. [113] evaluates several aspects for hydrogen: greenhouse gas and energy footprints, acidification, eutrophication, human toxicity potential, and eco-cost. They utilize Life Cycle Assessment. One of their important findings was that storage and transport cause around 35.5 % of greenhouse gas emissions of the whole hydrogen chain.

Sikiru et al. [81] states that hydrogen has still adaptability constraints. Accidents related to hydrogen are causing negative public opinion which affects policies. Safety issues are thus one of the critical factors. Tariq et al. [114] provides an evaluation of fuel cells with a hydrogen tank for emergency or backup power scenario. This evaluation found many factors like the possibility to extra hydrogen tank influences on the system. Sadeq et al. [115] analyzed hydrogen energy system and found it suitable for transportation, industry, and residential heating to reduce greenhouse gas emission. To improve the economy of hydrogen systems, they recommend more research on improving hydrogen production as well as regulatory measures and incentives. It is also important to make rigorous safety regulations. Mohammad & Iqbal [116] developed a successful hybrid-energy system for housing complexes in Srinagar, India which indicates again the suitability of hydrogen systems for residential buildings. They recommended e.g. flexible energy policies and grid-extension for hydrogen-supported systems. The most cost-effective system produced, however, more greenhouse gas than the configuration with fuel cells.

Qiu et al. [117] identify high capital expenditure and low energy conversion efficiency as primary obstacles for power-to-gas technology. To address these challenges, they introduced green hydrogen-based Energy Storage as a Service model. By simulating this model using Shanghai's electricity market and weather data, the authors demonstrate a complete recovery of excess renewable energy and a substantial increase in renewable energy integration within microgrids, from 59% to 83%. To increase use of hydrogen, they recommend governmental subsidies and support policies as well as co-operation between microgrids.

Van et al. [93] provide a comprehensive overview of energy management techniques applicable to microgrids, including fuzzy logic, model predictive control, heuristic and metaheuristic algorithms, and stochastic and robust programming methods. While each approach offers distinct advantages, such as the flexibility of fuzzy logic, they also come with challenges like high implementation costs. The authors further emphasize the multifaceted nature of microgrid control by outlining a range of critical factors, encompassing technical, economic, and environmental objectives, as well as operational and system configuration considerations.
Many studies are simulations which are similar like values from real experiments Mohammad et al. [116]. This makes it possible to get significant observations. Simulations for hydrogen refueling stations made by Hu et al. [117] indicate that continuous filling is necessary to make simulated and experimental values close to each other.

In the future energy system, PEM fuel cells are recognized as a promising technology for microgrid applications due to their high efficiency, low emissions, and capability to provide reliable power. However, their widespread adoption is vulnerable by degradation issues that affect performance and lifespan. Xingwang Tang et al. [118] provides a comprehensive analysis of a degradation-adaptive energy management strategy for fuel cell hybrid electric vehicles (FCHEVs). This strategy focuses on understanding and managing the degradation processes of proton exchange membrane fuel cells (PEMFCs) to enhance their durability and performance over time. The authors conduct accelerated durability tests and temperature sensitivity tests to determine the temperature sensitivity characteristics of PEMFCs at different state-of-health (SOH) levels.

The utilization of PEM fuel cells in microgrid applications brings to light several critical issues concerning the raw and critical materials required for their production. PEM fuel cells rely on several key materials, including platinum for the catalysts, perfluorinated sulfonic acid (PFSA) for the membrane, and various carbon-based materials for the electrodes and gas diffusion layers. Platinum, in particular, is a crucial material due to its excellent catalytic properties, which facilitate the necessary electrochemical reactions. However, platinum is an expensive and scarce resource, making its cost a significant barrier to the widespread adoption of PEM fuel cells. Erik Eikeng et al. [119] provides an in-depth review of the critical and strategic raw materials (CRMs) essential for the development and implementation of hydrogen technologies. Critical raw materials (CRMs) such as platinum, palladium, rare earth elements, and others play a pivotal role in the hydrogen economy. Developing alternative materials or enhancing the efficiency of existing ones can significantly decrease the dependency on CRMs. For instance, advancements in nanotechnology and catalyst development might provide new pathways to achieve similar or better performance with less or no use of traditional CRMs. Critical raw materials are the backbone of the emerging hydrogen economy, enabling the technological advancements necessary for large-scale adoption. However, their strategic importance also brings challenges that need to be addressed through sustainable practices, innovation, and strategic policymaking. By understanding and mitigating these challenges, we can ensure the continued growth and sustainability of the hydrogen sector, paving the way for a cleaner energy future. Veeresh Patil [120] provides an in-depth review of the various degradation mechanisms (chemical, mechanical, catalyst, thermal and contamination) that affect Polymer Electrolyte Membrane (PEM) fuel cells, which are crucial for improving their durability and commercial viability. Understanding and mitigating this degradation mechanisms are essential for enhancing the performance and longevity of PEM fuel cells.

Another critical issue is water management in the operation of PEM fuel cells, particularly within the context of microgrid applications. Effective water management is essential for maintaining optimal performance, ensuring durability, and preventing operational issues such as flooding or drying of the fuel cell components. M. Ait Ziane et al. [121] presents a new diagnostic approach for water management in Polymer Electrolyte Membrane Fuel Cells (PEMFC). The focus is on addressing faults related to water management from a control perspective. The study emphasizes the importance of controlling operational conditions and early fault detection to enhance the durability and performance of PEM fuel cells. The study highlighted the significant impact of temperature sensor faults on PEMFC water management and the effectiveness of the proposed control and diagnostic strategies in enhancing fuel cell durability and performance.

The water content in PEMFCs significantly affects the transport of reactants and the conductivity of the membrane. Effective water management strategies can enhance performance and extend the lifespan of the fuel cell. Wenxin Wan et al. [122] outlines the development of an internal resistance-operating condition model that considers the coupling effect of temperature and humidity to determine the variation trend of total resistance and stack humidity with single-factor operating conditions. The proposed method includes optimizing operating conditions such as working temperature, anode gas pressure, cathode gas pressure, anode gas humidity, and cathode gas humidity to achieve the optimal water management state within the fuel cell stack.

M. Rahimi- Esbo et al. [123] investigates the effects of water accumulation in Polymer Electrolyte Membrane Fuel Cells (PEMFC) operated in dead-end mode. The study utilizes a transparent PEMFC stack to visualize water flow within the cells, providing direct insights into water management challenges. Water accumulation within the fuel cell channels leads to non-uniform distribution of reactant flow, causing voltage instability and degradation of the electrodes. Water tends to accumulate more in the lower half of the flow channels, necessitating a design adjustment to increase flow velocity and improve water removal. At higher current densities (e.g., 300 mA/cm^2), water accumulation can transition from droplet form to film and slug flow, significantly impacting performance by blocking the channels and reducing active area. The study emphasizes the importance of effective water management through proper purge timing and design optimization to prevent performance degradation and improve the efficiency and longevity of PEM fuel cells.

L. Vichard et al. [124] explores the long-term durability and degradation mechanisms of Proton Exchange Membrane Fuel Cells (PEMFC), focusing on their application in transportation and stationary systems. The study highlights the necessity of enhancing fuel cell durability to facilitate widespread adoption. The researchers developed a degradation model using an Echo State Neural Network (ESN) to predict performance over extended periods. The study concludes that the ESN-based model effectively predicts fuel cell degradation, with potential applications in real-time performance monitoring and prognostics for fuel cell systems. The findings underscore the impact of ambient temperature on fuel cell performance and suggest that improved humidification strategies could significantly enhance durability.

5. CONCLUSIONS AND FUTURE RECOMMENDATIONS INCLUDING OBJECTIVES AND CONSTRAINT

The work comprehensively reviews the potential of Proton Exchange Membrane (PEM) fuel cell-based systems integrated with renewable energy sources, specifically solar and wind, for stationary applications in the telecommunications industry. It highlights the critical role these hybrid systems play in addressing the increasing demand for reliable and continuous power supply while mitigating the environmental and operational drawbacks associated with traditional diesel generators.
Through an analysis of microgrid architectures, energy management strategies, hydrogen storage solutions, and various optimization approaches, the work provides a comprehensive overview of the current state of technology and the challenges that must be addressed to enable wider deployment.

The findings demonstrate that PEM fuel cells hold strong potential to become a central component of future hybrid energy systems. Their high efficiency, rapid dynamic response, modularity, and compatibility with green hydrogen make them well-suited for integration with intermittent renewable sources such as solar and wind. When properly sized and managed, PEM fuel cells can significantly improve microgrid reliability, reduce dependence on fossil fuels, and contribute to the overall decarbonization of stationary power sectors.

Despite this promise, several limitations still hinder the large-scale implementation of PEMFC-based microgrids. Hydrogen production and storage remain costly, especially when compressed at high pressures for long-term or large-capacity applications. The durability and lifetime of PEM fuel cell stacks, particularly under dynamic load conditions typical of microgrids, continue to be areas requiring further technological advancement. Additionally, system-level coordination between renewables, batteries, electrolyzers, and hydrogen storage depends heavily on advanced energy management systems, many of which are still being developed and tested at a research or pilot scale.

The work also highlights that optimization techniques, ranging from classical mathematical models to modern AI-based algorithms are increasingly necessary to achieve economically and technically sound system designs. These tools can help identify optimal component sizing, improve operational decision-making, and enhance long-term system efficiency. However, most existing optimization models are tailored to specific case studies and lack generalization across different geographical, economic, or operational conditions.

Overall, the analysis confirms that PEM fuel cell technologies, when integrated within a well-designed and intelligently controlled microgrid, can significantly enhance the sustainability and resilience of stationary energy systems. Continued research efforts are essential to overcoming the remaining barriers, particularly in reducing hydrogen storage costs, improving fuel cell durability, and developing universal EMS frameworks that can be adapted to various microgrid configurations.

PEM fuel cell systems, when integrated with renewable energy sources, offer significant reductions in greenhouse gas emissions and operational costs compared to diesel generators. This shift supports the industry's move towards more sustainable and eco-friendly power solutions.

Effective energy management and advanced storage solutions are vital for optimizing the performance and reliability of PEM fuel cell systems. The integration of sophisticated control algorithms and energy management strategies enhances the efficiency and stability of these systems, making them suitable for high-power applications in telecommunications. Despite the progress, several challenges remain, including high costs, storage efficiency, and the need for more extensive infrastructure. The article recommends further research into improving hydrogen production and storage technologies, alongside developing rigorous safety regulations to enhance public acceptance and policy support. Future research should focus on improving diagnostic accuracy, developing cross-scale and multi-physics simulation studies, and advancing data-driven diagnostic methods for efficient and stable PEM fuel cell operation. These efforts are crucial for the commercialization and broader application of PEM fuel cells in achieving carbon neutrality and sustainable energy solutions.

In conclusion, leveraging PEM fuel cell systems integrated with renewable energy can significantly reduce the telecommunications industry's reliance on fossil fuels, lower operational costs, and minimize environmental impact, thus enhancing the reliability and sustainability of power supply infrastructure.

Additionally, the ongoing evolution of hydrogen technologies, combined with increased investment in renewable energy integration, positions PEM fuel cell based microgrids as a promising pathway toward achieving long-term energy sustainability. The insights presented in this work provide a foundation for future innovations and contribute to the broader understanding needed to advance hybrid microgrids toward commercial viability and widespread adoption.

REFERENCES:

[1] Chuanyu Sun, Enrico Negro, Keti Vezzù, Gioele Pagot, Gianni Cavinato, Angeloclaudio Nale, Yannick Herve Bang, Vito Di Noto, Hybrid inorganic-organic proton-conducting membranes based on SPEEK doped with WO3 nanoparticles for application in vanadium redox flow batteries, Electrochimica Acta 309 (2019) 311-325

[2] Hossain, M. S., & Mekhilef, S. (2014). Renewable energy integration: An approach for diesel generator replacement in telecommunication tower. Energy Procedia, 2014, 61, 2073-2076.

[3] Lasseter, R. H. Smart distribution: Coupled microgrids. Proceedings of the IEEE, 2011, 99(6), 1074-1082.

[4] Nair, N.-K. C., & Zhang, L. SmartGrid: Future networks for New Zealand power systems incorporating distributed generation. Energy Policy, 2009, 37(9), 3418-3427.

[5] Turkdogan, S. Optimisation of a Renewable-Based Hybrid Energy System for Residential and Transportation Applications Using HOMER. Renewable Energy Journal, 2019, 134, 845-856

[6] Castañeda, M., Cano, A., Jurado, F., Sánchez, H., & Fernández, L. M. Optimization and Management of a Hybrid Energy System Combining Photovoltaic, Hydrogen, and Battery Storage. Energy Conversion and Management, 2018, 172, 69-81

[7] National Renewable Energy Laboratory (NREL). Analysis of Renewable Energy Hybrid Systems for Off-Grid Telecom Towers. 2017, NREL/TP-7A40-70552

[8] Nawaz, A., Kamel, S., Alam, M., & Khan, F. Multi-Microgrids: Concept, Control, and Applications for Enhancing RES Integration. Applied Energy, 2020, 277, 115570

[9] Guan, X., Xu, Z., and Jia, Q. S., Energy-Efficient Buildings Facilitated by Microgrid, IEEE Transactions on Smart Grid, 2010, (Volume 1, Issue 3, pages 243-252)

[10] Zhou, Y., Li, W., & Chan, K. W. Smart Home Energy Management Systems: Concept, Configurations, and Scheduling Strategies. Renewable and Sustainable Energy Reviews, 2014, 34, 669-685.

[11] Palensky, P., and Dietrich, D., Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads, IEEE Transactions on Industrial Informatics, 2011, (Volume 7, Issue 3, pages 381-388).

[12] Arshad Nawaz, Min Zhou, Jing Wu, Chengnian Long, A comprehensive review on energy management, demand response, and coordination schemes utilization in multi-microgrids network, Applied Energy 323 (2022) 119596

[13] Pavitra Sharma , Hitesh Dutt Mathur, Puneet Mishra , Ramesh C. Bansal, A critical and comparative review of energy management strategies for microgrids, Applied Energy 327 (2022) 120028

[14] Mahmudul Hasan, Zannatul Mifta , Nafisa Atia Salsabil , Sumaiya Janefar Papiya , Mehnaz Hossain , Paromita Roy , Nahid-Ur-Rahman Chowdhury , Omar Farrok, A critical review on control mechanisms, supporting measures, and monitoring systems of microgrids considering large scale integration of renewable energy sources, Energy Reports 10 (2023) 4582–4603

[15] Ramesh Gugulothu, Bhookya Nagu, Deepak Pullaguram, Energy management strategy for standalone DC microgrid system with photovoltaic/fuel cell/battery storage, Journal of Energy Storage 57 (2023) 106274

[16] Atul S. Dahane, Rajesh B. Sharma, Hybrid AC-DC microgrid coordinated control strategies: A systematic review and future prospect, Renewable Energy Focus 49 (2024) 100553

[17] Peng Wu, Xiaoqing Mei, Microgrids energy management considering net-zero energy concept: The role of renewable energy landscaping design and IoT modeling in digital twin realistic simulator, Sustainable Energy Technologies and Assessments 63 (2024) 103621
[18] Reagan Jean Jacques Molu, Serge Raoul Dzonde Naoussi, Patrice Wira, Wulfran Fendzi Mbasso, Saatong Tsobze Kenfack, Salah Kamel, Optimization-based energy management system for grid-connected photovoltaic/battery microgrids under uncertainty, Case Studies in Chemical and Environmental Engineering 8 (2023) 100464
[19] Ali Reza Abbasi, Dumitru Baleanu, Recent developments of energy management strategies in microgrids: An updated and comprehensive review and classification, Energy Conversion and Management 297 (2023) 117723
[20] Long Phan Van, Kien Do Chi, Tuyen Nguyen Duc, Review of hydrogen technologies based microgrid: Energy management systems, challenges and future recommendations, international journal of hydrogen energy 48 (2023) 14127 -14148
[21] Tajjour, S., & Chandel, S. S. Metaheuristic and Machine Learning Techniques for Solving Challenges in Renewable Energy Systems. Energy,2023, 262, 125487
[22] Nguyen, Q. M., Nguyen, D. L., Nguyen, Q. A., Pham, T. N., Phan, Q. T., & Tran, M. H. (2024). A Bi-level optimization for the planning of microgrid with the integration of hydrogen energy storage. International Journal of Hydrogen Energy, 63, 967-974.
[23] Phan-Van, L., Takano, H., & Duc, T. N. (2023). A comparison of different metaheuristic optimization algorithms on hydrogen storage-based microgrid sizing. Energy Reports, 9, 542-549
[24] Ammara, U., Zehra, S. S., Nazir, S., & Ahmad, I. (2024). Artificial neural network-based nonlinear control and modeling of a DC microgrid incorporating regenerative FC/HPEV and energy storage system. Renewable Energy Focus, 49, 100565
[25] Rezaei, N., Pezhmani, Y., Jordehi, A. R., & Mansouri, S. A. (2024). A two-layer hybrid robust-stochastic model for energy management of isolated multi-energy microgrids with mobile storage systems and hydrogen refueling stations. Journal of Energy Storage, 90, 111905.
[26] Kilic, H. (2024). Improving the performance of microgrid-based Power-to-X systems through optimization of renewable hydrogen generation. International Journal of Hydrogen Energy.
[27] Yousri, D., Farag, H. E., Zeineldin, H., & El-Saadany, E. F. (2023). Integrated model for optimal energy management and demand response of microgrids considering hybrid hydrogen-battery storage systems. Energy Conversion and Management, 280, 116809
[28] Shi, R., Tang, K., & Lee, K. Y. (2023). Optimal Configuration of Self-Consistent Microgrid System with Hydrogen Energy Storage for Highway Service Area. IFAC-PapersOnLine, 56(2), 7960-7965.
[29] Abdelghany, M. B., Al-Durra, A., Daming, Z., & Gao, F. (2024). Optimal multi-layer economical schedule for coordinated multiple mode operation of wind–solar microgrids with hybrid energy storage systems. Journal of Power Sources, 591, 233844
[30] Zhang, X., Pei, W., Mei, C., Deng, W., Tan, J., & Zhang, Q. (2022). Transform from gasoline stations to electric-hydrogen hybrid refueling stations: An islanding DC microgrid with electric-hydrogen hybrid energy storage system and its control strategy. International Journal of Electrical Power & Energy Systems, 136, 107684.
[31] Chamout, M. W., Perl, A., Hengeveld, E. J., & Aué, J. J. (2024). Simulation and analysis of hybrid hydrogen-battery renewable energy storage for off-electric-grid Dutch household system. International Journal of Hydrogen Energy, 70, 170-182
[32] Lyu, C., Zhang, Y., Bai, Y., Yang, K., Song, Z., Ma, Y., & Meng, J. (2024). Inner-outer layer co-optimization of sizing and energy management for renewable energy microgrid with storage. Applied Energy, 363, 123066.

[33] Sun, X., Cao, X., Li, M., Zhai, Q., & Guan, X. (2024). Seasonal operation planning of hydrogen-enabled multi-energy microgrids through multistage stochastic programming. Journal of Energy Storage, 85, 111125
[34] Zhu, Z., Liu, X., Kong, X., Ma, L., Lee, K. Y., & Xu, Y. (2024). PV/Hydrogen DC microgrid control using distributed economic model predictive control. Renewable Energy, 222, 119871
[35] Fang, X., Dong, W., Wang, Y., & Yang, Q. (2022). Multiple time-scale energy management strategy for a hydrogen-based multi-energy microgrid. Applied Energy, 328, 120195.
[36] Dong, Y., Zheng, W., Cao, X., Sun, X., & He, Z. (2023). Co-planning of hydrogen-based microgrids and fuel-cell bus operation centers under low-carbon and resilience considerations. Applied Energy, 336, 120849
[37] Shen, X., Li, X., Yuan, J., & Jin, Y. (2022). A hydrogen-based zero-carbon microgrid demonstration in renewable-rich remote areas: System design and economic feasibility. Applied Energy, 326, 120039.
[38] K/bidi, F., Damour, C., Grondin, D., Hilairet, M., & Benne, M. (2022). Multistage power and energy management strategy for hybrid microgrid with photovoltaic production and hydrogen storage. Applied Energy, 323, 119549
[39] Fang, X., Dong, W., Wang, Y., & Yang, Q. (2024). Multi-stage and multi-timescale optimal energy management for hydrogen-based integrated energy systems. Energy, 286, 129576.
[40] Huangfu, Y., Tian, C., Zhuo, S., Xu, L., Li, P., Quan, S., ... & Ma, R. (2023). An optimal energy management strategy with subsection bi-objective optimization dynamic programming for photovoltaic/battery/hydrogen hybrid energy system. International Journal of Hydrogen Energy, 48(8), 3154-3170.
[41] Lund, H., Andersen, A. N., Østergaard, P. A., Mathiesen, B. V., & Connolly, D. (2012). From Electricity Smart Grids to Smart Energy Systems – A Market Operation Based Approach and Understanding. Energy, 42(1), 96-102.
[42] Chamout, M. W., Perl, A., Hengeveld, E. J., & Aué, J. J. (2024). Simulation and analysis of hybrid hydrogen-battery renewable energy storage for off-electric-grid Dutch household system. International Journal of Hydrogen Energy, 70, 170-182.
[43] Jahanbin, A., Abdolmaleki, L., & Berardi, U. (2024). Techno-economic feasibility of integrating hybrid-battery hydrogen energy storage in academic buildings. Energy Conversion and Management, 309, 118445.
[44] Ge, L., Zhang, B., Huang, W., Li, Y., Hou, L., Xiao, J., ... & Li, X. (2024). A review of hydrogen generation, storage, and applications in power system. Journal of Energy Storage, 75, 109307
[45] Khare, V., & Chaturvedi, P. (2023). Design, control, reliability, economic and energy management of microgrid: A review. e-Prime-Advances in Electrical Engineering, Electronics and Energy, 100239.
[46] Van, L. P., Hieu, L. H., Do Chi, K., Takano, H., & Duc, T. N. (2023). An improved state machine-based energy management strategy for renewable energy microgrid with hydrogen storage system. Energy Reports, 9, 194-201
[47] Bouaouda, A. & Sayouti, Y. (2024). An optimal sizing framework of a microgrid system with hydrogen storage considering component availability and system scalability by a novel approach based on quantum theory. Journal of Energy Storage, 92.
[48] Karimi, H. (2024). A tri-objectives scheduling model for renewable-hydrogen-based microgrid system considering hydrogen storage system and demand-side management. International Journal of Hydrogen Energy, 68, 1412-1422.
[49] Abdelghany, M. B., Mariani, V., Liuzza, D., & Glielmo, L. (2024). Hierarchical model predictive control for islanded and grid-connected microgrids with wind generation and hydrogen energy storage systems. International Journal of Hydrogen Energy, 51, 595-610.

[50] Wu, J., Li, S., Fu, A., Cvetković, M., Palensky, P., Vasquez, J. C., & Guerrero, J. M. (2024). Hierarchical online energy management for residential microgrids with Hybrid hydrogen–electricity Storage System. Applied Energy, 363, 123020
[51] Giovanniello, M. A., & Wu, X. Y. (2023). Hybrid lithium-ion battery and hydrogen energy storage systems for a wind-supplied microgrid. Applied Energy, 345, 121311.
[52] Yousri, D., Farag, H. E., Zeineldin, H., & El-Saadany, E. F. (2023). Integrated model for optimal energy management and demand response of microgrids considering hybrid hydrogen-battery storage systems. Energy Conversion and Management, 280, 116809.
[53] Majji, R. K., Mishra, J. P., & Dongre, A. A. (2022). Model predictive control based autonomous DC microgrid integrated with solar photovoltaic system and composite energy storage. Sustainable Energy Technologies and Assessments, 54, 102862
[54] Li, J., Xiao, Y., & Lu, S. (2024). Optimal configuration of multi microgrid electric hydrogen hybrid energy storage capacity based on distributed robustness. Journal of Energy Storage, 76, 109762.
[55] Deng, H., Wang, J., Shao, Y., Zhou, Y., Cao, Y., Zhang, X., & Li, W. (2023). Optimization of configurations and scheduling of shared hybrid electric hydrogen energy storages supporting to multi-microgrid system. Journal of Energy Storage, 74, 109420.
[56] Shi, R., Tang, K., & Lee, K. Y. (2023). Optimal Configuration of Self-Consistent Microgrid System with Hydrogen Energy Storage for Highway Service Area. IFAC-PapersOnLine, 56(2), 7960-7965.
[57] Qiu, Y., Li, Q., Ai, Y., Wang, T., Chen, W., Bai, H., ... & Gao, F. (2024). Optimal scheduling for microgrids considering long-term and short-term energy storage. Journal of Energy Storage, 93, 112137.
[58] Naseri, N., El Hani, S., El Harouri, K., & Mediouni, H. (2022). Primary and secondary control of an autonomous solar microgrid based power-to-X: Renewable hydrogen conversion. International Journal of Hydrogen Energy, 47(58), 24421-24438
[59] Shao, Z., Cao, X., Zhai, Q., & Guan, X. (2023). Risk-constrained planning of rural-area hydrogen-based microgrid considering multiscale and multi-energy storage systems. Applied Energy, 334, 120682.
[60] Er, G., Soykan, G., & Canakoglu, E. (2024). Stochastic optimal design of a rural microgrid with hybrid storage system including hydrogen and electric cars using vehicle-to-grid technology. Journal of Energy Storage, 75, 109747
[61] Xiang, Y., Cai, H., Liu, J., & Zhang, X. (2021). Techno-economic design of energy systems for airport electrification: A hydrogen-solar-storage integrated microgrid solution. Applied energy, 283, 116374.
[62] Kumar, S., Sharma, R., Murthy, S. S., Dutta, P., He, W., & Wang, J. (2022). Thermal analysis and optimization of stand-alone microgrids with metal hydride based hydrogen storage. Sustainable Energy Technologies and Assessments, 52, 102043.
[63] Zhang, X., Pei, W., Mei, C., Deng, W., Tan, J., & Zhang, Q. (2022). Transform from gasoline stations to electric-hydrogen hybrid refueling stations: An islanding DC microgrid with electric-hydrogen hybrid energy storage system and its control strategy. International Journal of Electrical Power & Energy Systems, 136, 107684.
[64] Li, L., Wang, B., Jiao, K., Ni, M., Du, Q., Liu, Y., ... & Wang, C. (2023). Comparative techno-economic analysis of large-scale renewable energy storage technologies. Energy and AI, 14, 100282.
[65] Xu, H., Fan, H., Yang, H., Chen, H., Zhang, J., & Zhao, H. (2024). Design, construction, and operation of hydrogen energy storage system for zero-carbon pumping units. International Journal of Hydrogen Energy

[66] Pignataro, V., Liponi, A., Bargiacchi, E., & Ferrari, L. (2024). Dynamic model of a Power-to-Gas system: role of hydrogen storage and management strategies. Renewable Energy, 120789.
[67] Abdolmaleki, L., & Berardi, U. (2024). Hybrid solar energy systems with hydrogen and electrical energy storage for a single house and a midrise apartment in North America. International Journal of Hydrogen Energy, 52, 1381-1394.
[68] Liu, S., Zhou, J., Liang, G., Du, P., Li, Z., & Li, C. (2024). Optimizing large-scale hydrogen storage: A novel hybrid genetic algorithm approach for efficient pipeline network design. International Journal of Hydrogen Energy, 66, 430-444
[69] Dong, Y., Zheng, W., Cao, X., Sun, X., & He, Z. (2023). Co-planning of hydrogen-based microgrids and fuel-cell bus operation centers under low-carbon and resilience considerations. Applied Energy, 336, 120849.
[70] K/bidi, F., Damour, C., Grondin, D., Hilairet, M., & Benne, M. (2022). Multistage power and energy management strategy for hybrid microgrid with photovoltaic production and hydrogen storage. Applied Energy, 323, 119549.
[71] Bai, F., Zhao, F., Liu, X., Mu, Z., Hao, H., & Liu, Z. (2024). A Comparative Well-to-Wheel Analysis of Renewable Energy Pathways for Hydrogen and Battery Electric Vehicles. Journal of Cleaner Production, 142832
[72] Osman, A. I., Nasr, M., Eltaweil, A. S., Hosny, M., Farghali, M., Al-Fatesh, A. S., Abd El-Monaem, E. M. Advances in hydrogen storage materials: harnessing innovative technology, from machine learning to computational chemistry, for energy storage solutions. International Journal of Hydrogen Energy. 2024
[73] Ba-Alawi, A. H., Nguyen, H. T., Aamer, H., & Yoo, C. (2024). Techno-economic risk-constrained optimization for sustainable green hydrogen energy storage in solar/wind-powered reverse osmosis systems. Journal of Energy Storage, 90, 111849
[74] Yin, L., Yang, H., & Ju, Y. (2024). Review on the key technologies and future development of insulation structure for liquid hydrogen storage tanks. International Journal of Hydrogen Energy, 57, 1302-1315.
[75] Hu, H., Di, J., Lang, Z., Meng, Z., Shi, X., Du, D., & He, Q. (2024). Thermodynamic modeling and analysis of hydrogen storage systems in hydrogen refueling stations. International Journal of Hydrogen Energy, 57, 1101-1110
[76] Li, Y., Li, Q., Peng, W., Hua, Z., & Zheng, J. (2024). A comparative analysis of the regulations, codes and standards for on-board high-pressure hydrogen storage cylinders. International Journal of Hydrogen Energy, 54, 894-907.
[77] Meda, U. S., Bhat, N., Pandey, A., Subramanya, K. N., & Raj, M. L. A. (2023). Challenges associated with hydrogen storage systems due to the hydrogen embrittlement of high strength steels. International Journal of Hydrogen Energy
[78] Pleshivtseva, Y., Derevyanov, M., Pimenov, A., & Rapoport, A. (2023). Comparative analysis of global trends in low carbon hydrogen production towards the decarbonization pathway. International Journal of Hydrogen Energy
[79] Hassan, Q., Sameen, A. Z., Salman, H. M., Jaszczur, M., & Al-Jiboory, A. K. (2023). Hydrogen energy future: Advancements in storage technologies and implications for sustainability. Journal of Energy Storage, 72, 108404
[80] Schiaroli, A., Scarponi, G. E., Antonioni, G., & Cozzani, V. (2024). Hazard footprint of alternative fuel storage concepts for hydrogen-powered urban buses. International Journal of Hydrogen Energy, 50, 1430-1442
[81] Sikiru, S., Oladosu, T. L., Amosa, T. I., Olutoki, J. O., Ansari, M. N. M., Abioye, K. J., ... & Soleimani, H. (2024). Hydrogen-powered horizons: Transformative technologies in clean

energy generation, distribution, and storage for sustainable innovation. International Journal of Hydrogen Energy, 56, 1152-1182.
[82] Ghorbani, B., Zendehboudi, S., Saady, N. M. C., & Dusseault, M. B. (2023). Hydrogen storage in North America: Status, prospects, and challenges. Journal of Environmental Chemical Engineering, 11(3), 109957
[83] Ma, N., Zhao, W., Wang, W., Li, X., & Zhou, H. (2023). Large scale of green hydrogen storage: Opportunities and challenges. International Journal of Hydrogen Energy
[84] Abdalla, A. M., Hossain, S., Nisfindy, O. B., Azad, A. T., Dawood, M., & Azad, A. K. (2018). Hydrogen production, storage, transportation and key challenges with applications: A review. Energy conversion and management, 165, 602-627.
[85] Rasul, M. G., Hazrat, M. A., Sattar, M. A., Jahirul, M. I., & Shearer, M. J. (2022). The future of hydrogen: Challenges on production, storage and applications. Energy Conversion and Management, 272, 116326.
[86] BOSU, Subrajit; RAJAMOHAN, Natarajan. Recent advancements in hydrogen storage-Comparative review on methods, operating conditions and challenges. International Journal of Hydrogen Energy, 2024, 52: 352-370
[87] Moran, C., Deane, P., Yousefian, S., & Monaghan, R. F. (2024). The hydrogen storage challenge: Does storage method and size affect the cost and operational flexibility of hydrogen supply chains. International Journal of Hydrogen Energy, 52, 1090-1100
[88] Hassan, Q., Algburi, S., Jaszczur, M., Al-Jiboory, A. K., Al Musawi, T. J., Ali, B. M., ... & Sameen, A. Z. (2024). Hydrogen role in energy transition: A comparative review. Process Safety and Environmental Protection.
[89] Hannan, M. A., Abu, S. M., Al-Shetwi, A. Q., Mansor, M., Ansari, M. N. M., Muttaqi, K. M., & Dong, Z. Y. (2022). Hydrogen energy storage integrated battery and supercapacitor based hybrid power system: A statistical analysis towards future research directions. International Journal of Hydrogen Energy, 47(93), 39523-39548.
[90] Saadat, Z., Farazmand, M., & Sameti, M. (2024). Integration of underground green hydrogen storage in hybrid energy generation. Fuel, 371, 131899
[91] Higgs, K. E., Strogen, D. P., Nicol, A., Dempsey, D., Leith, K., Bassett, K., ... & Rowe, M. (2024). Prospectivity analysis for underground hydrogen storage, Taranaki basin, Aotearoa New Zealand: A multi-criteria decision-making approach. International Journal of Hydrogen Energy, 71, 1468-1485
[92] SaberiKamarposhti, M., Kamyab, H., Krishnan, S., Yusuf, M., Rezania, S., Chelliapan, S., & Khorami, M. (2024). A comprehensive review of AI-enhanced smart grid integration for hydrogen energy: Advances, challenges, and future prospects. International Journal of Hydrogen Energy
[93] VAN, Long Phan; DO CHI, Kien; DUC, Tuyen Nguyen. Review of hydrogen technologies based microgrid: Energy management systems, challenges and future recommendations. International Journal of Hydrogen Energy, 2023.
[94] Sikiru, S., Oladosu, T. L., Amosa, T. I., Olutoki, J. O., Ansari, M. N. M., Abioye, K. J., Soleimani, H. (2024). Hydrogen-powered horizons: Transformative technologies in clean energy generation, distribution, and storage for sustainable innovation. International Journal of Hydrogen Energy, 56, 1152-1182
[95] Yurdagül Bentes¸en Yakut, A new control algorithm for increasing efficiency of PEM fuel cells – Based boost converter using PI controller with PSO method, International Journal of Hydrogen Energy, 2024
[96] Hegazy Rezk, Mokhtar Aly, Ahmed Fathy, A novel strategy based on recent equilibrium optimizer to enhance the performance of PEM fuel cell system through optimized fuzzy logic MPPT, Energy 234 (2021) 121267

[97] Jiankang Wang, Rui Ding a, Feng Cao, Jia Li a, Hui Dong, Tao Shi e, Lei Xing, Jianguo Liu, Comparison of state-of-the-art machine learning algorithms and data-driven optimization methods for mitigating nitrogen crossover in PEM fuel cells, Chemical Engineering Journal 442 (2022) 136064
[98] Abdeljelil Chammam, Abhishek Kumar Tripathi, Jos´e Ricardo Nu˜nez Alvarez, Hashem O. Alsaab, Rosario Mireya Romero-Parra, Abdulilah Mohammad Mayet, Sherzod Shukhratovich Abdullaev, Multiobjective optimization and performance assessment of a PEM fuel cell-based energy system for multiple products, Chemosphere 337 (2023) 139348
[99] Hegazy Rezk, Seydali Ferahtia, Ali Djeroui, Aissa Chouder, Azeddine Houari, Mohamed Machmoum , Mohammad Ali Abdelkareem, Optimal parameter estimation strategy of PEM fuel cell using gradient-based optimizer, Energy 239 (2022) 122096
[100] Chengjun Guoa, Juncheng Luc, Zhong Tiana, Wei Guob, Aida Darvishand, Optimization of critical parameters of PEM fuel cell using TLBO-DE based on Elman neural network, Energy Conversion and Management 183 (2019) 149–158
[101] Wei Zhao, Shahid Zaman, Shuhan Kong, Mengqi Liu, Jiexin Zou, Zhen Zhang, Hui Ning, Feng Peng, Yunfei Li, Min Wang, Mingbo Wua, Optimization strategies and diagnostic techniques for water management in proton exchange membrane fuel cells, Green Chemical Engineering, 2024.
[102] Abdullah G. Alharbi, A.G. Olabi, Hegazy Rezk, Ahmed Fathy, Mohammad Ali Abdelkareem, Optimized energy management and control strategy of photovoltaic/PEM fuel cell/batteries/supercapacitors DC microgrid system, Energy 290 (2024) 130121
[103] Dongfang Chen, Wenlong Wu, Kuanyu Chang, Yuehua Li, Pucheng Pei, Xiaoming Xu, Performance degradation prediction method of PEM fuel cells using bidirectional long short-term memory neural network based on Bayesian optimization, Energy 285 (2023) 129469
[104] de la Cruz-Soto, J., Azkona-Bedia, I., Velazquez-Limon, N., & Romero-Castanon, T. (2022). A techno-economic study for a hydrogen storage system in a microgrid located in baja California, Mexico. Levelized cost of energy for power to gas to power scenarios. International Journal of Hydrogen Energy, 47(70), 30050-30061
[105] Diaz, I. U., de Queiróz Lamas, W., & Lotero, R. C. (2023). Development of an optimization model for the feasibility analysis of hydrogen application as energy storage system in microgrids. International Journal of Hydrogen Energy, 48(43), 16159-16175.
[106] Aba, M. M., Sauer, I. L., & Amado, N. B. (2024). Comparative review of hydrogen and electricity as energy carriers for the energy transition. International Journal of Hydrogen Energy, 57, 660-678.
[107] Le, T. T., Sharma, P., Bora, B. J., Tran, V. D., Truong, T. H., Le, H. C., & Nguyen, P. Q. P. (2023). Fueling the future: A comprehensive review of hydrogen energy systems and their challenges. International Journal of Hydrogen Energy.
[108] Yang, Y., Wu, Z., Yao, J., Guo, T., Yang, F., Zhang, Z., ... & Li, B. (2024). An overview of application-oriented multifunctional large-scale stationary battery and hydrogen hybrid energy storage system. Energy Reviews, 100068.
[109] Er, G., Soykan, G., & Canakoglu, E. (2024). Stochastic optimal design of a rural microgrid with hybrid storage system including hydrogen and electric cars using vehicle-to-grid technology. Journal of Energy Storage, 75, 109747
[110] Ba-Alawi, A. H., Nguyen, H. T., Aamer, H., & Yoo, C. (2024). Techno-economic risk-constrained optimization for sustainable green hydrogen energy storage in solar/wind-powered reverse osmosis systems. Journal of Energy Storage, 90, 111849.
[111] Mehr, A. S., Phillips, A. D., Brandon, M. P., Pryce, M. T., & Carton, J. G. (2024). Recent challenges and development of technical and technoeconomic aspects for hydrogen storage,

insights at different scales; A state of art review. International Journal of Hydrogen Energy, 70, 786-815.
[112] Giovanniello, M. A., & Wu, X. Y. (2023). Hybrid lithium-ion battery and hydrogen energy storage systems for a wind-supplied microgrid. Applied Energy, 345, 121311
[113] Hren, R., Vujanović, A., Van Fan, Y., Klemeš, J. J., Krajnc, D., & Čuček, L. (2023). Hydrogen production, storage and transport for renewable energy and chemicals: An environmental footprint assessment. Renewable and Sustainable Energy Reviews, 173, 113113.
[114] Tariq, A. H., Kazmi, S. A. A., Hassan, M., Ali, S. M., & Anwar, M. (2023). Analysis of fuel cell integration with hybrid microgrid systems for clean energy: A comparative review. International Journal of Hydrogen Energy
[115] Sadeq, A. M., Homod, R. Z., Hussein, A. K., Togun, H., Mahmoodi, A., Isleem, H. F., ... & Moghaddam, A. H. (2024). Hydrogen energy systems: Technologies, trends, and future prospects. Science of The Total Environment, 173622.
[116] Mohammad, S. S., & Iqbal, S. J. (2024). Hydrogen technology supported solar photovoltaic-based microgrid for urban apartment buildings: Techno-economic analysis and optimal design. Energy Conversion and Management, 302, 118146.
[117] Qiu, R., Zhang, H., Wang, G., Liang, Y., & Yan, J. (2023). Green hydrogen-based energy storage service via power-to-gas technologies integrated with multi-energy microgrid. Applied Energy, 350, 121716.
[118] Xingwang Tang, Mingyang Yang, Lei Shi, Zhongjun Hou, Sichuan Xu, Chuanyu Sun, Adaptive state-of-health temperature sensitivity characteristics for durability improvement of PEM fuel cells, Chemical Engineering Journal 491 (2024) 151951
[119] Erik Eikeng, Ashkan Makhsoos, Bruno G. Pollet, Critical and strategic raw materials for electrolysers, fuel cells, metal hydrides and hydrogen separation technologies, International Journal of Hydrogen Energy 71 (2024) 433–464
[120] Veeresh Patil, P.V. Reshmi, S. Prajna, Yashaswi, Yashaswini, D. Haleshappa, A. Jayarama, Richard Pinto, Degradation mechanisms in PEM fuel cells: A brief review, Materials Today: Proceedings (2023)
[121] M. Ait Ziane, C. Join, M. Benne, C. Damour, N. Yousfi Steiner, M.C. Pera, A new concept of water management diagnosis for a PEM fuel cell system, Energy Conversion and Management 285 (2023) 116986
[122] Wenxin Wan, Yang Yang, Yang Li, Changjun Xie, Jie Song, Zhanfeng Deng, Jinting Tan, Ruiming Zhang, Operating conditions combination analysis method of optimal water management state for PEM fuel cell, Green Energy and Intelligent Transportation 2 (2023) 100-105
[123] M. Rahimi- Esbo, A.A. Ranjbar, S.M. Rahgoshay, Analysis of water management in PEM fuel cell stack at dead-end mode using direct visualization, Renewable Energy 162 (2020) 212-221
[124] L. Vichard, F. Harel, A. Ravey, P. Venet, D. Hissel, Degradation prediction of PEM fuel cell based on artificial intelligence, international journal of hydrogen energy 45 (2020) 14953 -14963

LIST OF SYMBOLS AND ABBREVIATIONS:

PEM	Proton Exchange Membrane
PV	Photovoltaic
EMS	Energy Management Systems
DERs	Distributed energy resources
HOMER	Hybrid Optimization of Multiple Energy Resource
GDL	Gas diffusion layer
NREL	National Renewable Energy Laboratory
MMGs	Multi-microgrids
RES	Renewable energy sources
MPC	Model Predictive Control
PSO	Particle Swarm Optimization
Bi-LSTM	Bidirectional Long Short-Term Memory
BESS	Battery energy storage systems
SOC	State of charge
IoT	Internet of Things
LP	Linear programming
MILP	Mixed-integer linear programming
TCR	Total cost rate
GA	Genetic algorithm
GBO	Gradient-Based Optimizer
PSO	Particle Swarm Optimization
PEMFCs	Proton exchange membrane fuel cells
FCHEVs	Fuel cell hybrid electric vehicles
SOH	State-of-health
PFSA	Perfluorinated sulfonic acid
SRMs	Strategic raw materials

ABSTRACT:

The telecommunication industry relies heavily on a reliable and continuous power supply. Traditional power sources like diesel generators have long been the backbone of telecom infrastructure. However, the growing demand for sustainable and eco-friendly solutions has spurred interest in renewable energy sources. Proton exchange membrane (PEM) fuel cell-based systems, integrated with solar and wind energy, offer a promising alternative. This review explores the potential of these hybrid systems in stationary telecom applications, providing a comprehensive overview of their architecture, energy management, and storage solutions. As the demand for telecommunication services grows, so does the need for a reliable power supply. Diesel generators are linked with high operational costs, noise pollution, and significant greenhouse gas emissions, prompting a search for more sustainable alternatives. This review analyzes the current state of PEM fuel cell systems in telecom applications, examines the architecture of microgrids incorporating renewable energy sources, and discusses optimization methods, challenges, and future directions for energy storage systems.

Critical findings and recommendations are presented, highlighting objectives and constraints for future developments. Leveraging these technologies can help the telecom industry reduce fossil fuel reliance, lower operational costs, minimize environmental impact, and increase system reliability.

Keywords: microgrids; solar; hydrogen storage technologies; energy management system; PEM fuel cell.

PROŠIRENI SAŽETAK

Telekomunikacijska industrija jedna je od grana gospodarstva koja najviše ovisi o stabilnoj i neprekidnoj opskrbi električnom energijom. Tradicionalno su u tu svrhu korišteni dizelski generatori koji su desetljećima činili osnovu napajanja baznih stanica, repetitora i komunikacijskih čvorišta. Međutim, zbog sve veće potražnje za održivim, pouzdanim i ekološki prihvatljivim rješenjima, kao i zbog rastućih cijena fosilnih goriva i strožih propisa o emisijama, razvija se interes za primjenu obnovljivih izvora energije i naprednih sustava pohrane energije. U tom kontekstu, sustavi temeljeni na protonskom izmjenjivačkom membranskom (PEM) gorivnom članku, integrirani sa solarnom i vjetroenergijom, predstavljaju vrlo obećavajuće rješenje za napajanje stacionarnih telekomunikacijskih sustava.

Koncept mikromreža omogućuje decentralizirano i fleksibilno upravljanje energijom u takvim objektima, uz mogućnost rada u mrežnom i izvanmrežnom režimu. Mikromreža tipično uključuje više izvora energije, kao što su fotonaponski sustav, PEM gorivni članak, baterijski spremnik te sustav za pohranu vodika. Osnovna ideja je postići optimalnu ravnotežu između proizvodnje, potrošnje i pohrane energije, čime se osigurava visoka pouzdanost i autonomnost rada telekomunikacijskih postrojenja. Takva rješenja posebno su važna u udaljenim ili teško dostupnim područjima, gdje pristup elektroenergetskoj mreži nije pouzdan ili uopće nije moguć.

Središnji element mikromrežnog sustava predstavlja sustav upravljanja energijom (Energy Management System – EMS), čija je uloga koordinirati rad svih komponenti kako bi se postigla maksimalna učinkovitost i stabilnost sustava. EMS u stvarnom vremenu donosi odluke o korištenju raspoloživih izvora energije, o prioritetima punjenja i pražnjenja spremnika te o optimalnom načinu rada gorivnog članka. Razvoj naprednih algoritama i metoda prediktivnog upravljanja, koji uzimaju u obzir vremenske prognoze i uzorke potrošnje, omogućuje povećanje energetske učinkovitosti i smanjenje operativnih troškova sustava. Time se ujedno produžuje vijek trajanja pojedinih komponenti, osobito baterijskih modula i PEM gorivnih članaka, koji su osjetljivi na dinamičke promjene opterećenja.

Upravo zbog promjenjive prirode obnovljivih izvora energije, sustav pohrane energije ima ključnu ulogu u stabilizaciji mikromreže. U suvremenim rješenjima koriste se kombinacije niskotlačnih i visokotlačnih spremnika vodika, baterijskih sustava te u nekim slučajevima superkondenzatora. Vodik se pokazuje kao vrlo učinkovito sredstvo dugoročne pohrane energije jer omogućuje pretvorbu viška električne energije, proizvedene iz obnovljivih izvora, u kemijsku energiju putem procesa elektrolize. Pohranjeni vodik se potom može ponovno pretvoriti u električnu energiju korištenjem PEM gorivnog članka u trenucima kada proizvodnja iz solarnih ili vjetroizvora nije dostatna.

Postoji više pristupa pohrani vodika, uključujući pohranu komprimiranog vodika pod visokim tlakom (350–700 bara), ukapljeni vodik te pohranu u obliku metalnih hidrida. Spremnici na bazi metalnih hidrida pružaju prednosti u pogledu sigurnosti i volumetrijske gustoće pohrane, dok visokotlačni spremnici omogućuju veću fleksibilnost, ali zahtijevaju složenije sigurnosne sustave i redovito održavanje. Glavni izazovi razvoja ovih tehnologija odnose se na visoku cijenu materijala, složenost konstrukcije spremnika, ograničen vijek trajanja te potrebu za poboljšanjem toplinskog upravljanja tijekom procesa punjenja i pražnjenja. Budući razvoj usmjeren je na povećanje energetske gustoće i trajnosti spremnika, smanjenje troškova proizvodnje te integraciju sustava nadzora i upravljanja koji omogućuju praćenje stanja sustava u stvarnom vremenu.

Optimizacija rada mikromreža predstavlja još jedno ključno područje istraživanja. U tu se svrhu primjenjuju različite metode, od determinističkih algoritama do naprednih metaheurističkih pristupa poput genetskih algoritama, optimizacije rojem čestica (PSO) ili višekriterijske optimizacije. Cilj je postići kompromis između pouzdanosti, troškova, učinkovitosti i okolišnih pokazatelja sustava. U telekomunikacijskim primjenama poseban je naglasak na minimiziranju operativnih troškova i emisija CO_2, uz istovremeno održavanje visoke dostupnosti napajanja, budući da čak i kratkotrajni prekidi mogu uzrokovati ozbiljne probleme u radu komunikacijskih mreža.

Analiza postojećih istraživanja i primjena pokazuje da PEM gorivni članci u kombinaciji s obnovljivim izvorima energije i sustavima pohrane vodika mogu značajno doprinijeti dekarbonizaciji telekomunikacijskog sektora. Ključni ciljevi budućeg razvoja odnose se na povećanje učinkovitosti PEM gorivnih članaka i elektrolizatora, smanjenje troškova skupih katalizatora, razvoj naprednih sustava upravljanja energijom te standardizaciju komponenti radi lakše integracije u različite tipove mikromreža. Dodatno, primjena modularnih rješenja omogućit će prilagodbu sustava veličini i potrebama pojedine telekomunikacijske lokacije, dok će primjena metoda umjetne inteligencije omogućiti prediktivno upravljanje i daljinsko nadgledanje sustava u stvarnom vremenu.

Integracija PEM gorivnih članaka s obnovljivim izvorima energije predstavlja održivu i pouzdanu alternativu konvencionalnim dizelskim generatorima. Takvi hibridni mikromrežni sustavi omogućuju smanjenje troškova goriva i održavanja, produljuju životni vijek opreme, smanjuju emisije štetnih plinova i povećavaju energetsku neovisnost telekomunikacijskih objekata. Iako su tehnički i ekonomski izazovi još uvijek prisutni, daljnji razvoj tehnologije pohrane vodika, optimizacijskih metoda i sustava upravljanja energijom otvorit će mogućnosti za široku primjenu ovih rješenja u budućnosti.

Ključne riječi: mikromreže, solarna energija, tehnologije pohrane vodika, sustav upravljanja energijom, PEM gorivni članak.