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TOPICAL REVIEW

Hydrogen-Integrated Microgrids: A Comprehensive Review of Hydrogen Technologies and Energy Management Strategies

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ABSTRACT With increasing concerns about carbon emissions, greenhouse gases, and energy costs, many sustainable development goals and related agreements have been introduced by governing bodies worldwide. As a result, hydrogen-based microgrids integrated with Renewable Energy Sources (RESs) have received significant attention. In such power systems, electrolysers convert excess renewable energy into hydrogen, which is stored and later utilized through fuel cells or hydrogen gas turbines. However, due to the intermittent nature of RES and the unexplored behavior of hydrogen generation, storage, and utilization systems, the combined operation of a power system consisting of both renewable sources and hydrogen energy poses significant challenges, including system stability, energy balancing, safety, and regulation issues. In such situations, Energy Management Systems (EMSs) are employed to achieve stable operation while obtaining various optimal operational solutions. This study presents a detailed illustration of microgrids and hydrogen systems, and provides a comprehensive breakdown of various EMSs for hydrogen technology-based microgrids. Unlike many existing review studies that discuss hydrogen technologies in general terms, this review specifically focuses on the integration and operational strategies of hydrogen techniques, comprising electrolysers, hydrogen storage systems, and fuel cells, within the EMS. By emphasizing the role of hydrogen components in EMS operation and optimization, this paper offers an application-oriented review uniquely focused on the operational integration of hydrogen technologies within EMS frameworks, a gap often overlooked in broader literature.

INDEX TERMS Energy management, hydrogen storage, microgrids, polymer electrolyte membrane (PEM) electrolyser, PEM fuel cell, renewable energy sources.

ABBREVIATIONS

RES	Renewable Energy Source.
EMS	Energy Management System.
ESS	Energy Storage System.
PV	Photovoltaic.
AC	Alternative Current.
DC	Direct Current.
PEM	Polymer Electrolyte Membrane.
SOC	State of Charge.
MILP	Mixed Integer Linear Programming.
MOEA	Multi-Objective Evolutionary Algorithm.

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NSGA	Non-Sorted Genetic Algorithm.
PPA	Parasitism Prediction Algorithm.
PSO	Particle Swarm Optimization.
FPA	Flower Pollination Algorithm.
ECMS	Equivalent Consumption Minimization Strategy.
CCUS	Carbon Capture Utilization and Storage.
HER	Hydrogen Evolution Reaction.
FC	Fuel Cell.
SMES	Superconduct Magnetic Energy Storage.
ACO	Ant Colony Optimization.
GA	Genetic Algorithm.
GWO	Gray Wolf Optimization.
DA	Dragonfly Algorithm.
ALO	Ant Lion Optimizer.
HESS	Hybrid Energy Storage System.
SSA	Salp Swarm Algorithm.
MFOA	Moth-flame Optimization Algorithm.
DP	Dynamic Programming.
SBODP	Subsection Bi-Objective Optimization Dynamic Programming.
HBCS	Hysteresis Band Control Strategy.
MPC	Model Predictive Control.
SMC	State Machine Control.
PID	Proportional Integral Derivative.
FLC	Fuzzy Logic Control.
PLC	Programmable Logic Control.
LPSP	Loss of Power Supply Probability.
PEWP	Potential Energy Waste Probability.
GOA	Grasshopper Optimization Algorithm.
ACS	Annualized Cost of System.
LCOE	Levelized Cost of Energy.
TNPV	Total Net Present Value.
NPC	Net Present Cost.
OER	Oxygen Evolution Reaction.
CHP	Combined Heat and Power.
DG	Diesel Generators.
EVS	Electric Vehicle Systems.

I. INTRODUCTION

In the legacy centralized power system, the typical energy sources include hydro, natural gas, oil, coal, and nuclear sources. However, with the development of Renewable Energy Sources (RESs), alongside distributed generation and growing concerns about the environment, power system developments are undergoing a paradigm shift towards eco-friendly solutions. This global trend toward RES presents the electrical industry with numerous opportunities and challenges simultaneously. In 2023, renewable electricity generation reached approximately 8791 TWh, representing nearly 30% of total electricity generation. Wind power and Solar Photovoltaics (PV) accounted for nearly half of the generation, while hydropower and other renewables accounted for the rest [1]. This trend significantly contributes to global strategies aimed at achieving zero-carbon emissions. Several international agreements, such as the Paris Agreement [2], Kyoto Protocol [3], and the Kigali Amendment [4], have been established to control carbon emissions. Meanwhile, energy-related CO_2 emissions in 2024 reached a level of 37.8 Gigatons (GT), which is the highest-ever annual level. This accounts for a record CO_2 concentration in the atmosphere of 422.5 ppm with a 3ppm increment from 2023 [5]. From that, fossil fuel-powered energy sources in conventional power systems account for a large portion of electrification-based CO_2 production.

In a traditional power system, hydro, coal, and oil-powered power stations are located far away from the points of power consumers. So, they generate electricity in bulk, step up the voltage and transmit long distances, then step down to a voltage suitable for end consumers [6]. However, due to various reasons, including environmental pollution, lack of security, and increased losses, this traditional structure is discouraged, and small-scale renewable energy-based distributed generation is encouraged. However, this transition has introduced fundamental changes in power system operations, including bidirectional power flows due to the connection location of distributed generators [7]. This shift has opened the door to cluster small areas of the traditional power systems to operate with their own power sources, loads, and energy storages. These small-scale areas, which have the necessary qualities of a power system, are identified as microgrids [8]. Traditionally, microgrids have been operating in the Alternating Current (AC) domain, with AC sources and loads directly connected, while Direct Current (DC) sources, loads, or Energy Storage Systems (ESS) require power conversion stages. RESs, including PV, generate power as DC, which is also natively used by modern loads and ESS like batteries, fuel cells, and supercapacitors, either directly or through internal conversions [9]. Small-scale power systems operated in the DC domain are referred to as DC microgrids [10]. Currently, a substantial proportion of RESs consists of solar PV and wind energy systems. However, several emerging RESs, including tidal, wave, biomass, and geothermal energy, are also gaining prominence [1]. Due to the intermittent behavior of these RESs, managing a high RES-integrated system presents challenges, including decreasing reliability, increasing costs, and complexity. To address these issues, energy storage devices such as battery systems, supercapacitor-connected battery systems, and pumped hydroelectric systems are commonly integrated [11]. Hydrogen energy has received increased interest as a promising energy carrier in decarbonization alongside renewable energy generation. Several ongoing bodies of research are focused on utilizing electrolyser systems capable of splitting water into hydrogen and oxygen [12], as well as fuel cell systems that convert chemical energy into electrical energy [13]. These electrolyser and fuel cell systems can be integrated into power systems to store and dispatch excess power, while stored hydrogen is applicable in industries, hydrogen transportation applications, and heating solutions. In particular, islanded microgrids that heavily rely on RESs can incorporate hydrogen systems to mitigate the stochastic behavior of RESs. Researchers have proposed various Energy Management Systems (EMSs) for operational control in hydrogen-RES-based microgrids [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127], [128], [129], [130], [131]. High integration of RESs and hydrogen technologies, including fuel cells, affects the stability of the microgrid [14], [15]. Therefore, EMSs capable of delivering optimal solutions have emerged as the preferred approach for such microgrids.

There are various review studies on microgrid EMS, addressing different perspectives such as objective formulations, problem-solving strategies, operating power modes, grid topologies, and the availability of hydrogen. In [16], a comprehensive review of microgrid EMS is discussed, focusing on objective function formulation and solving strategies. In-depth classifications are considered in optimization strategies, together with a review of problem-solving tools. EMS for fuel cell systems is discussed beyond techno-economic objectives in [17], providing a design methodology to integrate other objectives such as environmental and socio-political considerations. In [18], the perspective of grid connectivity and objective formulation is discussed, providing a detailed review of the strengths and weaknesses of each strategy. In [19], microgrid EMSs are classified in terms of problem-solving strategies alongside several real-world applications. Microgrid EMS techniques are further discussed in [20], where they are categorized into supervisory level controlling, operating time platforms, and decision-making strategies with a specific focus on demand response. In [21], special consideration is given to hybrid renewable systems where hydrogen technologies are present. In [22], the impact of ESS on EMS operations is discussed, focusing on hydrogen technologies. In [23], microgrid EMSs are classified and studied considering the applied optimization techniques, with insight into the objective formulation in each category. Microgrid EMSs are discussed considering applied optimization techniques, with a comprehensive discussion on Artificial Intelligence (AI)-based EMS in [24]. In [25], EMSs are comprehensively categorized considering components, control, EMS and grid topology. In [26], an analysis of EMSs considering problem-solving strategies where hydrogen technologies are present is provided, alongside insight into the evaluation of EMSs.

Most EMSs in the current literature primarily focus on achieving technical or economic objectives, such as reduced cost, power balance, and system reliability. Environmental impacts and hydrogen system operations have received relatively little attention. Among the review studies on EMSs in microgrids, both with and without hydrogen integration [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], significant gaps remain. In particular, there is a lack of focus on the unique operational characteristics of hydrogen technologies, such as electrolysers and fuel cells, and their impact on EMS performance and design. To address these gaps, this paper provides the following contributions.

- This study presents a comprehensive and up-to-date review of hydrogen technologies within microgrid systems, encompassing their definitions, key characteristics, and practical applications.
- A critical analysis of EMS strategies is conducted, with particular emphasis on their role in addressing operational challenges and promoting the development of hydrogen-based energy systems.
- The review also provides a focused evaluation of EMS objectives, highlighting the importance of integrating hydrogen-specific performance indicators such as hydrogen conversion efficiency, storage utilization, and optimal fuel cell operation.
- Furthermore, the paper offers a detailed examination of EMS frameworks that incorporate hydrogen pathways, including electrolysers, hydrogen storage systems, and fuel cells, emphasizing integration approaches and control strategies that are often overlooked in existing literature.

The remaining sections of this paper are organized as follows. Section II discusses the background of microgrid systems and their applications. Section III describes the background and context of hydrogen at the global and Australia, discussing hydrogen storage, hydrogen generation, and hydrogen utilization technologies applied in microgrids. In Section IV, EMSs applied in microgrids are discussed with a focus on problem-solving techniques. In Section V, the paper presents key findings, contributions, and recommendations for future research. Finally, section VI concludes this study.

II. BACKGROUND OF MICROGRIDS

Microgrids typically consist of energy sources, loads, energy storage, distribution networks, protection equipment, and control schemes to ensure power, voltage, and frequency regulation, as in Fig. 1. Microgrids are usually connected to the grid at the point of common coupling through a static transfer switch. This configuration allows the microgrid to be treated as a single unit by the main grid, enabling it to export excess power to the grid and import power when there is a deficit [27], [28]. Moreover, microgrids can intentionally disconnect from the main grid during instances of power quality violations to ensure a stable power supply for local devices. If a microgrid is equipped with sufficient energy sources and energy storage devices, it can be designed to operate independently from the main grid, usually referred to as an islanded/standalone microgrid [29]. These island

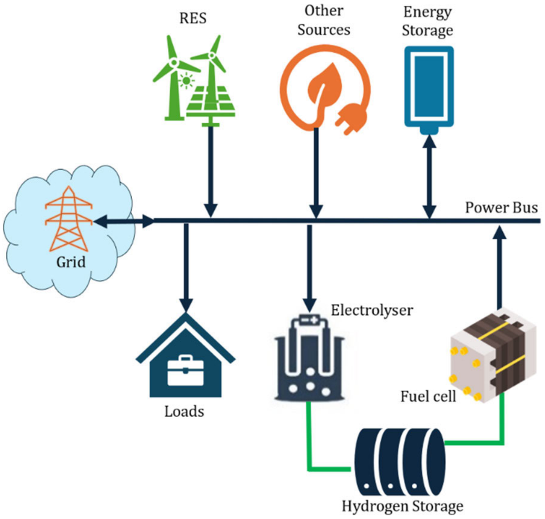


FIGURE 1. Typical hydrogen-integrated microgrid structure.

microgrids have various applications, including rural electrification, marine and space applications, building power systems, and vehicle power systems. Additionally, microgrids are classified based on the operating power of the distribution network as AC, DC, and hybrid microgrids.

Over the years, microgrids have been used in several industrial and academic applications for electrification and research purposes, as shown in Table 1 [30], [31], [32]. Some literature also discusses concepts such as pico-grids and nano-grids, apart from the microgrid concept [33], [34], [35]. Typically, microgrids can be divided into a few main layers in operation: physical, communication, intelligence, and business layers. AC microgrids have evolved significantly, and several research publications regarding their structures, control strategies, energy management, and protection have been published [36], [37]. AC microgrids usually have either single-phase or three-phase distribution networks. Some of the benefits of AC microgrids are interoperability, standardization, compatibility, and resiliency. In DC microgrids, the power distribution network operates using DC power. With advancements in power electronics devices and improvements in DC-operable sources, loads, and ESSs, DC microgrids have become a highly applicable solution in modern applications [10], [38], [39]. DC microgrids can distribute power in monopolar, bipolar, and homopolar systems. Some of the benefits of DC microgrids compared to AC are easy integration of RESs and ESSs, elimination of AC-related issues (synchronization, frequency control, reactive power, and harmonics), reduced conversion stage/improved efficiency, and reduced cost of operation. Currently, industries utilize independent operating conditions and levels within microgrids. Over the past decade, IEEE has developed several standards specifically for DC microgrids [40] including guidelines for transient voltage surge level, transient voltage drop levels, and voltage ripple limits. These standards help ensure stable and reliable operation within the microgrid. The IEEE 2030.7-2017 standard outlines the functional architecture for microgrid controllers, with a focus on islanding, reconnection, and scheduling functions. This is complemented by IEC 62898:2019, which provides guidelines for the design, operation, and control of DC microgrids, including voltage level definitions, protection coordination, and system stability. These standards emphasize maintaining DC voltage within acceptable boundaries to ensure system stability, equipment compatibility, and proper functioning of control systems.

III. BACKGROUND OF HYDROGEN: GLOBAL AND AUSTRALIAN PROSPECTIVE

Global hydrogen production reached nearly 97 Mt in 2023, marking a 2% increment compared to 2022 [41]. When categorized by production method, 62% of hydrogen was produced from natural gas without Carbon Capture, Utilization, and Storage (CCUS), 20% from unabated coal, and 15% as a by-product of industrial processes. Despite this high overall production, low-emission hydrogen made up only about 1% of the total, of which 0.6% came from fossil fuels with

TABLE 1. Microgrid voltage levels based on applications [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40].

Application	Common voltage	Analysis
		DC microgrid
Marine applications	>1000V	Beneficial for handling the constraints introduced by the ship's nature, such as constant requirement of a power supply, space and weight restrictions, and pulse load availability.
Transport	750V, 1000V, 3000V	Increased system efficiency with high presence of DC, Reduced environmental impacts.
Data centers	380V – 400V	Low occupancy of surface space, increased system efficiency due to high presence of DC loads.
Household	3.3V – 48V	Increased efficiency with minimized loss in power transmission. Reduced environmental impacts.
Lighting	24V	Increased overall efficiency and reduced cost due to minimized conversion losses
EV Charging	400V – 900V	Reduced environmental impacts.
		AC microgrid
Transport		
Railways	15kV-25kV	Efficient power transmission over long distances, Reduced energy losses with high voltage levels.
Busses, cars	3.3kV-11kV	Providing a reliable and efficient power supply.
Marine	1-11kV	Offering flexibility in integrating different power sources and loads into the power system.
Data centers	10-35kV	A higher voltage level is supported for large-scale data centers.
Household	230V - 400V	Supporting a wide range of appliances and ensuring safety and efficiency in the household.
Lighting	230V	Standard voltage of the common lighting applications, ensuring compatibility and efficiency.
EV Charging	400V - 800V	Offering quick and efficient power delivery for electric vehicles.

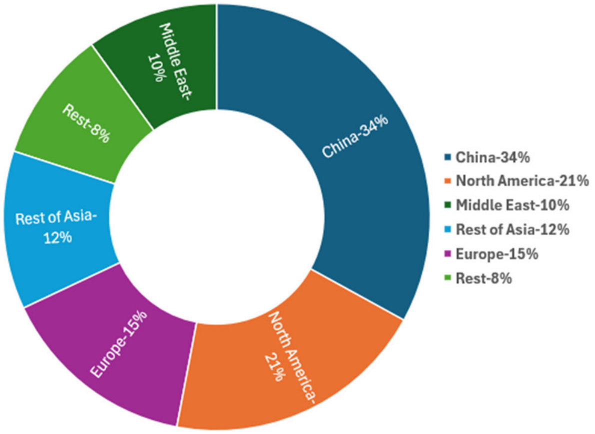


FIGURE 2. **Hydrogen utilization by region [41].**

CCUS, and just 0.1% was produced using electricity [41]. Geographically, China was responsible for almost 30% of the total production, with the rest of the world contributing nearly 70%. The International Energy Agency (IEA) estimated that global low-emission hydrogen production will reach 16 Mt by 2030. However, the 2023 report estimates this figure to exceed 20 Mt, reflecting over 30% growth driven by announced projects. Electrolyser-based hydrogen production is expected to account for more than 70% of low-emission hydrogen by 2030 [41]. As illustrated in Fig. 2, global hydrogen consumption has grown across most regions, except in Europe, where high prices have reduced usage, especially in the chemical industry. While current demand is largely driven by fossil-fuel-based refining and chemical sectors, hydrogen's impact on climate goals remains limited. For meaningful progress toward net-zero emissions, broader adoption is necessary in sectors such as industry, transportation, and electricity. Among hydrogen applications, electricity generation is a key area of interest in this study, though it currently contributes less than 0.2% to global electricity production [41]. Even within this small share, the majority does not stem from pure hydrogen but rather from mixed gas supplies from production plants. However, with ongoing advancements in hydrogen technologies such as electrolysis, fuel cells, internal combustion engines, and hydrogen gas turbines, hydrogen-based electricity generation is poised for exponential growth [41]. The use of hydrogen or high-percentage hydrogen gases can mitigate emissions from existing power plants.

In Australia, the Energy Council has set a vision to become a major global player in a clean, innovative, and safe hydrogen industry by 2030. Geoscience Australia reports indicate that 11% of Australia's land area is highly suitable for renewable integrated hydrogen production, considering the quality of wind, solar, and hydro resources. Additionally, 3% of Australia is deemed suitable for renewable energy-based hydrogen production, factoring in water resource requirements, potentially exceeding global production estimates by 2050 [42]. Apart from that, Australia can generate low-emission hydrogen with the availability of coal and natural gas. Consequently, various activities are underway to prepare for these anticipated developments. Most Australian states are initially focusing on developing supply and demand aspects. Pilots, trials, and demonstration projects have been launched to scale up operations, advance technological developments, gather industry expertise, foster international collaboration, and innovate business models. On the governmental front, regulations are being developed to support the growth of hydrogen within the legal framework. Additionally, international collaborations are being coordinated to target key markets and enhance the skilled workforce. Importantly, several research and development phases are planned to further support industry improvements.

A. HYDROGEN TECHNOLOGIES BASED MICROGRIDS

Most renewable-based microgrids have the potential to increase energy capture and store it for dispatch when needed. In this regard, hydrogen systems can be integrated into microgrids to increase renewable energy penetration while reducing greenhouse gas emissions. Hydrogen systems are comprised of three key components: hydrogen generation, hydrogen storage, and hydrogen utilization. These components can be integrated into microgrids in various configurations, such as hydrogen generation-only, generation-storage, consumption-only, storage-consumption, or generation-storage-consumption [43]. In general, hydrogen generation is achieved through electrolysis, steam methane reforming, and biomass gasification [44]. Electrolysers, which utilize excess energy to produce hydrogen, are the most common method for energy storage. The produced hydrogen can be stored using techniques, as compressed gas, liquid gas, chemical hydrides, and absorbents [45]. To convert stored hydrogen back to electricity, methods include the use of fuel cells or hydrogen microturbines [46]. Hydrogen-integrated microgrids can be seamlessly combined with RESs. Excess electricity can be used to produce hydrogen and store hydrogen storing. This stored hydrogen can then convert back to electricity during periods of low renewable generation, ensuring a balanced and reliable energy supply. Details of hydrogen-integrated microgrids are summarized in Table 2. The table highlights the types of energy sources, ESS, and other key components in the reviewed microgrids. It specifies the grid connection (Grid), RESs (PV, wind, hydro), energy storage options (batteries (Bat), Supercapacitors (SC)), and hydrogen technologies, including electrolyzers (Elec), Hydrogen Storage (HS), and Fuel Cells (FC). In addition, other important components such as Diesel Generators (DG), Retired EV Batteries (REVB), biogas systems, reformers, Electric Vehicles Systems (EVS), Combined Heat and Power (CHP) systems, and hydrogen Microturbines (MT) are also indicated. Furthermore, the table presents

TABLE 2. Research on hydrogen technologies based microgrids [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127].

PV	Wind	Other RESs	Grid	Bat	Elec	HS	FC	SC	Other	Demands	Ref
√	-	-	-	-	√	√	-	-	REVB	Utility loads	[80]
√	-	-	-	√	-	-	√	√	-	Aircraft emergency supply	[81]
√	√	-	√	-	√	√	√	-	Reformer	Utility loads	[82]
√	√	-	√	-	√	√	√	-	-	Utility loads	[83]
√	-	-	√	√	√	√	√	-	-	Utility loads	[84]
√	-	-	-	-	√	√	√	-	-	Utility and dump loads	[85]
√	-	-	-	√	√	√	√	-	-	Utility loads, H_2 Demand	[86]
√	√	-	-	-	√	√	√	-	DG	Utility and dump loads	[87]
√	√	Hydro	-	-	√	√	√	√	Biogas	Utility, dump load, H_2	[88]
√	-	-	-	-	√	√	√	-	Reformer	Utility loads(elec, thermal)	[89]
√	-	-	√	√	√	√	√	-	-	Utility loads	[90]
√	√	Hydro	-	√	√	√	√	-	-	Utility loads	[91]
√	-	√	-	√	√	√	√	-	-	Utility loads, H_2 Demand	[92]
√	√	Hydro	-	√	√	√	√	-	-	Utility loads	[93]
√	-	-	-	√	√	√	√	-	SMES	Utility loads	[97]
√	-	-	√	√	√	√	√	-	-	Utility loads and EV charge	[98]
√	-	-	-	√	√	√	√	-	-	Utility loads	[99]
√	-	-	-	√	√	√	√	-	-	Utility loads	[100]
√	√	-	√	√	√	√	√	-	EVS	Utility loads	[105]
√	-	-	-	√	√	√	√	-	-	Utility loads	[106]
√	-	-	√	-	√	√	√	-	EVS	Utility loads, H_2 Demand	[107]
√	-	-	-	-	√	√	√	-	CHP, EVS	Utility loads, H_2 Demand	[108]
√	-	-	-	√	√	√	√	-	CHP	Utility loads	[113]
√	√	-	√	√	√	√	√	-	-	Utility loads, H_2 Demand	[114]
√	-	-	-	√	√	√	√	-	-	Utility loads	[115]
√	√	Hydro	-	√	√	√	√	-	DG, Biogas	Utility loads	[121]
√	-	-	-	√	√	√	√	-	CHP	Utility loads	[122]
√	-	-	√	√	√	√	√	√	-	Utility loads	[123]
√	√	-	√	√	√	√	√	-	-	Utility loads	[124]
√	-	-	√	√	√	√	√	-	-	Utility loads	[125]
√	-	-	-	√	-	-	√	√	-	Utility loads	[126]
√	-	-	-	√	√	√	√	-	EVS	Utility loads	[127]
√	-	-	-	√	√	√	√	-	√	Utility and dump loads	[94]
√	-	-	√	√	√	√	√	-	-	Utility loads	[95]
√	√	-	√	√	√	√	√	-	MT	Utility loads	[101]

the types of electrical and hydrogen loads integrated into microgrids.

B. HYDROGEN STORAGE TECHNIQUES

A key challenge in fully integrating hydrogen as an ESS lies in selecting the appropriate storage method. Hydrogen storage can be categorized into two principal types: physical storage (compressed gas, liquid gas, and cryo-compressed gas) and material-based storage (metal hydrides, complex hydrides, absorbents, and liquid organic compounds). Compressed gas storage of hydrogen typically requires high-pressure tanks, typically with pressures of up to 700 bars. This method offers a high rate of hydrogen filling and release without additional energy requirements for release. However, hydrogen is typically stored in cylindrical vessels, which are often unsuitable for industrial applications [47]. Liquid hydrogen storage involves maintaining hydrogen at very low temperatures, as the boiling point of hydrogen at atmospheric pressure is -252.8°C. However, this method has a much higher volumetric energy density of around 8 MJ per litre. In industry, it is often stated that four compressed hydrogen gas cylinders are approximately equivalent to one liquid hydrogen cylinder in terms of total stored hydrogen. However, this 4:1 ratio reflects the practical storage capacity per vessel (considering factors like pressure rating, thermal insulation, and usable volume), rather than just the per-liter volumetric energy or mass densities. As shown in Table 3, liquid hydrogen has approximately twice the energy and mass density of compressed gas, but in practice, liquid storage vessels typically hold significantly more usable hydrogen than individual high-pressure gas cylinders, thereby supporting the general 4:1 equivalence when considering total deliverable hydrogen per container. With increased energy density and reduced cylinder requirements, liquid hydrogen has become a well-established technology. The hydrogen liquefaction process consumes 30-40% of the Lower Heating Value (LHV) of hydrogen, making it more expensive than compression [48]. Furthermore, liquid hydrogen faces boil-off losses, typically resulting in a daily evaporation of 1.5-3%. Its widespread adoption in the transportation sector may be limited due to the extremely low storage temperature required and the associated boil-off losses. Cryo-compressed hydrogen is a combination of both compressed gas and liquid hydrogen, as it stores at liquid hydrogen temperatures and at significantly higher pressures. This process increases the density by nearly 10g per litre while substantially reducing boil-off losses [48]. However, the high requirements for storage vessels lead to increased costs. Another hydrogen storage approach is through materials. Hydrogen chemically interacts with metals and metal alloys to produce metal hydrides. This process is initiated by direct reaction with the metal or by the electrochemical dissociation of water, which causes a 20-30% expansion of the original volume [48]. Since this reaction

TABLE 3. **Analysis of common hydrogen storage techniques [47], [48], [49], [50].**

Method	H_2 content ($wt\%H_2$)	Vol-energy density (MJ/L)	Vol density (g/L)	Analysis
Compressed gas	100	5.6 - 6.2	30 - 40	Stored under high pressure (350-700 bar). Widely used in transportation, stationary storage, and industry. Simple technology, relatively low cost. Comparatively low energy density requires robust and heavy tanks.
Liquid Hydrogen	100	8.5-9.1	70-80	Cooled to cryogenic temperatures (-253°C). Suitable for aerospace, large-scale storage, and transportation. Higher energy density compared to compressed gas. Requires higher energy for the liquefaction process, with boil-off losses over time.
Cryo-compressed	100	7.1 - 8.5	40-50	Combines cryogenic cooling and compression (lower temperatures, higher pressures). Used in advanced vehicle fuel systems and space applications. Improved density compared to compressed gas, reduced boil-off compared to liquid H_2. Requires a complex system for high pressure and cryogenic temperatures.
Metal Hydrides	1-7	8-10	50-100	Hydrogen is absorbed by metal alloys, forming hydrides. Used in stationary storage, portable applications, and backup power. High volumetric density, safe storage at low pressures. Heavy, slow kinetics, and high costs for materials.
Complex hydrides	5-12	8-12		Stored in complex chemical compounds (sodium borohydride). Potential for portable applications, automotive use. High hydrogen content, good volumetric density. Complex release mechanisms, high costs, and stability issues.
Adsorbents	1-2	3-5	20-30	Hydrogen is stored on the surface of materials (activated carbon). Experimental and under development for portable and stationary applications. Potential for high storage capacities, safe storage. Low volumetric density requires low temperatures for effective adsorption.
Liquid organic	5-7	6-7	60-70	Hydrogen is chemically bonded to liquid organic carriers, which can release hydrogen on demand. Suitable for large-scale stationary storage and transportation. It offers high safety, remains liquid at ambient conditions, and is compatible with existing fuel infrastructure. Energy required for hydrogenation and dehydrogenation.

releases heat energy, external energy is required to reverse the reaction for hydrogen generation, usually by increasing temperature or decreasing pressure. However, there are some issues with metal hydrides, including higher release temperatures, the formation of undesired gases, and onboard energy requirements for hydrogen release.

Complex hydrides usually consist of a coordination complex in the material. In contrast to hydrides, physical adsorption involves hydrogen being absorbed onto a solid surface via Van Der Waals interactions, resulting in higher loading and unloading rates and near-zero byproduct losses [49]. Finally, in liquid organic carriers, hydrogen chemically reacts with hydrogen-deficient organic molecules. The stored hydrogen is released through a dehydrogenation process, which can be carried out in application environments such as vehicles or power plants. The hydrogenated organic part can then be used to load hydrogen again, which helps the carbon atom remain in the process without being released into the environment [50].

C. HYDROGEN GENERATION TECHNIQUES

At standard conditions, hydrogen exists as a diatomic molecule, comprising two hydrogen gaseous atoms. There are different processes to produce hydrogen, including electrolysis, thermochemical, and biological. In electrolysis, electricity is used to split H_2O into hydrogen and oxygen with techniques such as alkaline, PEM, solid oxide, and molten carbonate electrolysis [51]. Thermochemical processes utilize heat energy and chemicals to extract hydrogen from organic materials, such as biomass. Primary techniques include steam methane reforming and biomass gasification [52]. Biological processes produce hydrogen through biological reactions using sunlight or organic components [53]. Among these, electrolysis and thermochemical processes are the most applied in hydrogen microgrids for hydrogen generation.

1) ELECTROLYSER TECHNIQUES

An electrolyser can split water into hydrogen and oxygen using an electrical current, with the potential for zero-carbon emissions, as shown in Fig. 3 [54]. Electrolysis techniques include PEM, alkaline, solid oxide, and molten carbonate electrolysis [51]. Typically, a PEM electrolyser is comprised of two sections, the cathode and anode, separated by a thin polymer electrolyte membrane. It allows protons to pass through while preventing electron flow [55]. The characteristics of different types of electrolysis techniques are illustrated in Table 3 [12], [56], [57]. Previous studies have shown that, at a constant temperature, the conductivity of the electrolyser cell decreases non-linearly as pressure increases. This leads to a rise in the system's initial resistance and ultimately results in a higher voltage profile. Likewise, at constant pressure, the conductivity of the electrolyser system increases linearly with temperature. Thus, an increase in conductivity results in a decrease in the initial resistance of the electrolyser, eventually leading to a decrease in the voltage profile [58]. Furthermore, since the cell voltage of electrolyser systems decreases with increasing temperature at constant pressure conditions, the voltage efficiency of the system improves with temperature [59]. Research shows that the system achieves better overall efficiency at a stack temperature of 60°C under moderate current density compared to 90°C. Nonetheless, when the current density exceeds 3.5 A/cm^2, the system with superior voltage efficiency becomes more efficient overall [60]. This is because, even though voltage efficiency increases with temperature, Faraday efficiency decreases, which elaborates on the chemical process of the electrolyser. Similarly, the Faraday efficiency of the electrolyser system

TABLE 4. Analysis of common electrolyser techniques [12], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61].

Type	Alkaline	PEM	Solid Oxide	Molten Carbonate
Electrolyte	KOH solution	Solid specialty plastic material	Supported tubular (ZrO_2 doped with Y_2O_3)	Liquid solution of lithium, sodium, or potassium carbonate
Operating temperature	40-90 °C	20-100 °C	650-1000 °C	600-700 °C
Electrical efficiency	50-60 %	45-60 %	76-81 %	50-60 %
Energy Required (kWh/kg H_2)	50-55	52-60	40-50	-
Application	Hydrogen production	Power to gas applications	R&D studies	R&D studies
Advantages	Establish technology Long-term operations Low-cost production	Fast response times High-purity gas production Dynamic operations	High efficiency High-pressure operation	High efficiency Fuel processing ability
Challenges	Low-purity production Low current densities	Higher costs Low durability	Not well established High temperature	Unstable electrolyte High temperature

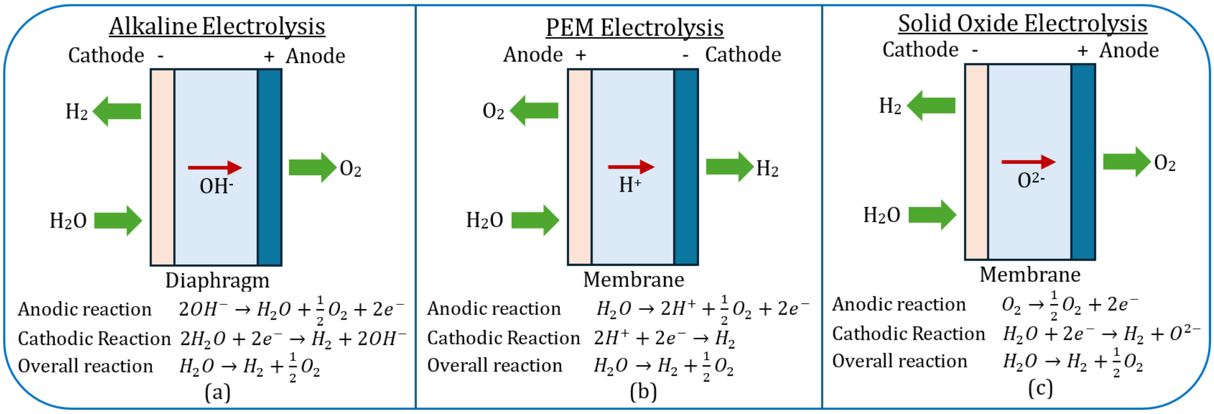


FIGURE 3. Reactions and operation of common electrolysis techniques.

decreases with increasing pressure conditions [61]. Table 4 summarizes the electrical energy required to produce 1?kg of H_2 using different electrolyser technologies. Alkaline electrolysers typically require 50-55?kWh per kg of H_2, achieving efficiencies between 50-60% based on the LHV. PEM operates at slightly lower efficiency. SOFC offers the highest efficiency potential, consuming as low as 40-50?kWh per kg H2 when thermal input is considered.

2) STEAM REFORMING

Steam reforming is applied in approximately 70-80% of the world's hydrogen production due to its cost-effective operation when paired with natural gas [62]. More recently, ethanol and methanol have been frequently used in hydrogen production. During methanol steam reforming, a syngas mixture of hydrogen, CO2, and CO is generated from methanol and steam. The hydrogen is then separated from the other gases through a pressure swing adsorption process. Further details on ongoing studies, recent advancements, and associated challenges can be found in [63].

3) GASIFICATION

Hydrogen production via gasification contributes approximately 10-15% of global hydrogen production [64]. The gasification process is generally divided into two main types: coal gasification and biomass gasification. In coal gasification, hydrogen is produced by reacting coal with steam and oxygen under standard conditions, generating several byproducts, including nitrogen, hydrogen sulfide, ammonia, oils, and tars. Biomass gasification, on the other hand, produces hydrogen by heating biomass, yielding byproducts like CO, CO2, and water. After filtering the resulting gas, steam is injected to convert carbon monoxide gas into hydrogen through a water-gas shift reaction [65], [66].

D. HYDROGEN UTILIZATION TECHNIQUES

The higher energy density of hydrogen makes it suitable for long-term storage applications in both power generation and transportation sectors. In power generation, hydrogen is utilized in fuel cells, hydrogen gas turbines, and CHP systems. In the transportation sector, hydrogen powers fuel cell vehicles and hydrogen internal combustion engine vehicles [67].

1) FUEL CELL TECHNIQUES

Fuel cells are the commonly applied method in microgrid applications. A fuel cell can generate electricity by utilizing hydrogen and oxygen while producing only water as a byproduct, which is a zero-carbon emission strategy, as shown in Fig. 4. Fuel cell technologies include PEM, alkaline, solid oxide, and molten carbonate [68]. The most common strategy among these is the PEM fuel cell process.

TABLE 5. Analysis of common fuel cell techniques [68], [69], [70], [71], [72], [73], [74].

Type	Alkaline	PEM	Solid Oxide	Molten Carbonate
Electrolyte	KOH Solution	solid specialty plastic material	Oxide ion conducting ceramic)	
Operating temperature	T_r–90 °C	T_r–80 °C	800-1000 °C	600-650 °C
Electrical efficiency	60-70 %	40-60 %	60-65 %	50-60 %
Energy Output (kWh/kg H_2)	15-22	16-23	20-25	-
Fuel Type	H_2	H_2	Natural, biogas	Natural, biogas, methanol
Application	RES integrations Space programs	RES integrations Transportations applications Backup power systems	RES integrations Power system applications	Auxiliary power systems RES integrations
Advantages	Lower capital costs Fast response times Flexibility	Reduced corrosion/ maintenance Low temperature operations Fast response time	High efficiency Flexible fuel supply	Fuel flexibility High efficiency
Challenges	High sensitivity to fuel impurities	High sensitivity to fuel impurities, High cost	High temperature Slow response	High temperature Frequent corrosion

A fuel cell consists of an oxidizing anode, a reducing cathode, and an electrolyte. At the anode, hydrogen is split into protons and electrons. These protons pass through the electrolyte membrane, while electrons travel via an external circuit, generating electric power. At the cathode, oxygen reacts with protons and electrons to produce water and heat [68], [69], [70]. The characteristics of commonly available fuel cell techniques are illustrated in Table 5. Three major losses associated with fuel cell operation are: activation losses, ohmic losses, and concentration losses. Activation losses arise from the lagging reaction rates at the electrodes, resulting in a nonlinear reduction in voltage across the fuel cell's terminals. While activation losses occur at both the anode and the cathode, they are generally more severe at the cathode. On the other hand, ohmic losses come from the internal resistance of the fuel cell, leading to a voltage drop due to two main resistance sources: electron movement through electrodes and external circuits, and proton transport across the proton exchange membrane [71]. Concentration losses mainly result from difficulties in mass transport, where the concentration of hydrogen and oxygen at elevated currents leads to a nonlinear drop in voltage. Apart from that, the open circuit voltage of the fuel cell changes due to variations in temperature and pressure conditions of the fuel cell [72], [73]. A study on PEM fuel cell performance showed that the polarization curve improves as the temperature increases from 65°C to 75°C, remains relatively stable between 75°C and 80°C, and starts to decline when the temperature exceeds 85°C. Due to the variation in temperature, gas diffusivity and membrane conductivity initially increased. However, membrane conductivity decreases at higher temperatures due to reduced relative humidity of gases and lower water content in the membrane. Furthermore, the fuel cell operating temperature was kept at 80°C, while the pressure varied from 1-4 atm. The mole fraction of oxygen increases with operating pressure, and fuel cell performance also improves [74]. Table 5 presents the amount of electrical energy that can be generated from 1 kg of H_2 using different fuel cell technologies. PEM fuel cells convert with an efficiency of 40-60%, 16-23 kWh per kg of H2. Alkaline fuel cells achieve slightly higher efficiencies in controlled applications, while SOFC can deliver up to 25 kWh per kg of H_2 with efficiencies of 60-65%%. These output values are based on the LHV of hydrogen and reflect typical steady-state operations.

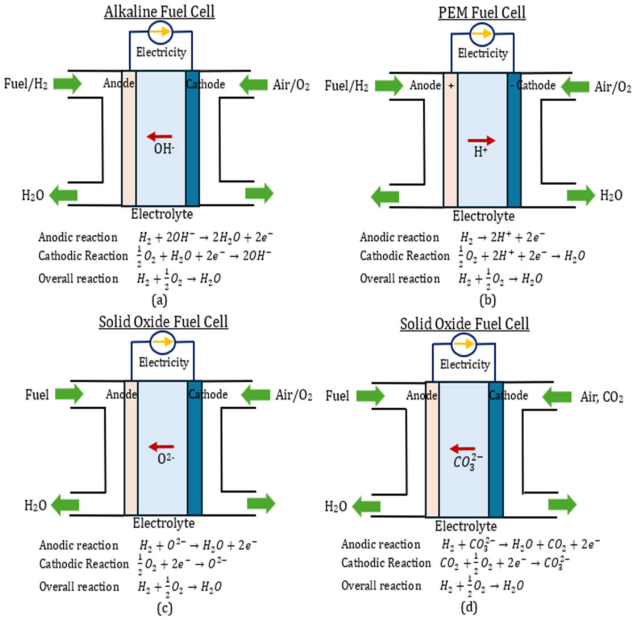


FIGURE 4. Reactions and operation of fuel cell techniques.

2) HYDROGEN GAS TURBINES

Hydrogen gas turbines utilize compressed air and fuel to produce electricity through combustion at high temperatures. Hot air passes through the turbine, spinning the connected generator via a shaft, converting the chemical energy of hydrogen into mechanical energy, then into electrical energy. When pure hydrogen is used, hydrogen gas turbines can operate at zero-carbon emission, critical for greener power systems. Further details of studies, advancements, and drawbacks can be found in [75].

3) COMBINED HEAT AND POWER

With an intensifying focus on decarbonization, significant efforts are underway to develop and implement resilient and sustainable power generation technologies, such as CHP systems. CHP systems generate electricity and heat simultaneously from a single fuel source. Key components of a CHP system include a power generation unit, a heat recovery unit, and a heating system. The heat generated during electricity production is captured and used for heating purposes [76].

IV. ENERGY MANAGEMENT IN HYDROGEN MICROGRID

In power systems and microgrids, EMSs are utilized to monitor, control, and optimize generation, storage, and load to maintain power balance while meeting technical, economic, and environmental objectives. In hydrogen-integrated microgrids, EMSs must also coordinate electrolysers, fuel cells, and hydrogen storage. Typical EMS tasks include load forecasting, supervisory control, and real-time decision-making for system efficiency, cost reduction, and emissions control [23]. An overview of the hydrogen-integrated microgrid energy management system operation in a microgrid system is illustrated in Fig. 5.

The EMS design process begins with defining objectives, such as minimizing costs, improving reliability, or reducing emissions, followed by identifying system constraints like power balance, storage limits, and hydrogen system capacities [20]. Based on these, suitable EMS strategies are selected, including rule-based methods, fuzzy logic, Model Predictive Control (MPC), metaheuristic algorithms, or hybrid techniques. These strategies are then implemented and tested through simulation models of the microgrid [27].

1) OBJECTIVE FUNCTIONS

An objective function in energy management is a mathematical function that governs the criteria to be optimized, including minimization and maximization. Generally, objective functions can be categorized into various types, including technical, economic, environmental, and other considerations, based on the intended optimization goals. One commonly utilized strategy involves technical objectives. Technical objectives applied in the industry include energy efficiency, power loss reduction, voltage stability, maximum energy penetration, and capacity selection. Economic objectives encompass various costs, such as operating and maintenance, capital, power loss, battery degradation, Levelized Cost of Energy (LCOE), reliability expenses, unit operation scheduling, load management, etc. Until recently, environmental objectives were not considered as important as economic and technical objectives. With the global trend towards green energy and low-emission power systems, several objectives related to environmental aspects have been introduced to power system energy management. Greenhouse gas emissions, energy waste, renewable energy penetration, and pollutant emissions are some of the applied environmental objectives in microgrid EMSs. Furthermore, objectives including energy security, energy policy, social awareness, reliability, and safety are integrated into the EMS.

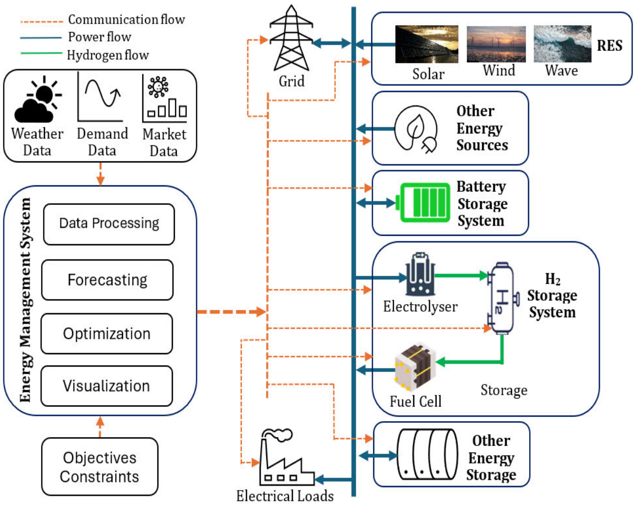


FIGURE 5. Overview of hydrogen-integrated microgrid EMS.

2) CONSTRAINTS:

Each microgrid component has its specific operational requirements, known as constraints. Some commonly used constraints are related to demand-supply balance, upper and lower power limits, upper and lower energy limits, transmission constraints, and power ramp constraints. Especially for hydrogen systems, constraints include the operating power limits, hydrogen storage limits, and fuel consumption limits. Exemplary illustrations of power demand, unit power limits, and energy storage limits are given in the expressions below.

$$P_{\text{gen}} = P_{load} \tag{1}$$

$$P_{min} \leq P_{unit} \leq P_{max} \tag{2}$$

$$SOC_{min} \leq SOC_{unit} \leq SOC_{max} \tag{3}$$

A. PROBLEM-SOLVING STRATEGIES

Solving energy management-related problems in microgrid applications typically involves minimizing or maximizing objectives related to microgrid operations. To achieve optimal solutions under defined constraints, several strategies have been utilized in EMSs. This review examines a range of techniques, including heuristic/meta-heuristic algorithmic approaches, fuzzy logic approaches, model predictive approaches, uncertainty-based approaches, and classical rule-based approaches.

1) HEURISTIC/METAHEURISTIC ALGORITHM APPROACH

Heuristic and metaheuristic optimization techniques are employed to tackle complex problems, where finding an optimal solution using traditional methods is challenging or time-consuming. Heuristic algorithms take a practical approach to quickly reach a solution by relying on domain knowledge, simplification, and assumptions. Generally, they

TABLE 6. **Analysis of heuristic/metaheuristic algorithm-based EMS [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95].**

Technique	Objectives	Analysis	Ref
MOEA/D NSGA-II	Minimize LPSP Minimize PEWP Minimize ACS	Inclusion of EV battery degradation in the EMS increases the LPSP, while neglecting the energy waste parameter can reduce hydrogen component interaction to nearly zero. Integrating hydrogen system degradation can be impactful, since frequent operation of FC and electrolyser is observed to compensate for battery degradation.	[80]
PPA	Minimize the hydrogen consumption	Proposed PPA-based EMS can achieve the lowest hydrogen consumption and significantly increased efficiency compared to the nine EMSs. Battery current fluctuations are significantly reduced. However, it has neglected the electrolyser when calculating efficiency, which has a significant impact for fuel cell operation due to hydrogen SOC.	[81]
PSO	Optimal capacity of electrolyser and hydrogen storage	Introducing the electrolyser system to the microgrid has reduced the annual utilization of natural gas by 10% and annual CO_2 emissions by more than 150 tons. Increased electrolyser efficiency showcases a correlation with decreased natural gas consumption of FC. This correlation can be integrated into the EMS to further reduce carbon emissions.	[82]
NSGA-II	Minimize op-cost Minimize pollution emission	Proposed EMS operates with higher switching times of electrolyser with low-cost increments compared to complete day-ahead dispatching. The environmental cost objective can be improved by introducing replacement costs of electrolyser and fuel cell to add to the grid purchase power.	[83]
PSO	Minimize LCOE	Integrating alkaline electrolysis into the system has a lower cost compared to PEM electrolysis, and any type of electrolyser significantly reduces the LCOE. Furthermore, the effect of temperature on electrolyser and fuel cell systems is considered. However, EMS is designed to achieve LCOE considering only one temperature point.	[84]
FPA	Minimize TNPV	A sensitivity study is carried out by varying the FC, electrolyser, H2 storage, and PV system from 50% to 120% of the current value. Results indicate that the variation of the FC system has the highest contribution to the LCOE of the system compared to the other three parameters.	[85]
PSO	Minimize the annual cost of energy	Identified that introducing a potential energy waste parameter and an effective adjustment tilt angle in the objectives has a direct impact on the system cost. Developed an EMS approach that directly relates the capacity of battery, fuel cell, and hydrogen systems with energy waste.	[86]
MILP	Minimize operating cost	Identified that the RES wastage and load shedding can be managed by selecting a proper initial state and threshold state of SOC for the battery system. However, due to a lack of real time integration, RES including wind and tidal energy utilized in this application, are restricted to constant power frequently.	[87]
ACO UPSO	Minimize LCOE	Identified significant impact of fuel cells on LCOE, compared to electrolyser and hydrogen storage. Even with maximum expected prices in 2035, integrating hydrogen storage into a developed microgrid showcases its capability to sustain particularly increasing RES penetrations.	[88]
GA, PSO, MFOA, DA, GOA, SSA,ALO	Minimize NPC	Proposed EMS considers the self-discharging rates of the battery as an objective. Hybrid battery-super capacitor systems can be replaced by fuel cell-super capacitor, if appropriate penalties are introduced. However, hydrogen systems are operated in series with a battery, considering only one operating point of temperature.	[89]
PSO	Minimize total operating cost	A feature in biogas production is introduced, which utilizes residential and municipal waste in the community for gas production. FC's natural gas consumption is reduced by 6.2% and 26.7% respectively, when utilizing residential waste and both residential and municipal waste.	[90]
HBCS, MPC, SMC, ECMS	Minimize operating costs Minimize hydrogen consumption	Verified that the battery is preferable for short-term, while hydrogen storage is suited for handling long-term operations. Furthermore, identified that MPC is preferred considering activation/deactivation of high-cost components such as the electrolyser. Provides a smooth state transition in components, reducing the frequency of activation/deactivation.	[91]
Hybrid generic-annealing GA, SA	Minimize cost	A single optimization function is developed by weighing five objectives: cost per unit of electricity, unmet load, dumped energy, final and initial capacity gaps of the battery, and hydrogen storage suitable for application. However, EMS does not account for the environmental effects and efficiency of the hydrogen system.	[92]
SBODP MOGA	Minimize ECMS Minimize power curtailment rate	The SBODP strategy can achieve higher fuel efficiency compared to MOGA. MOGA strategy tends to operate expensive components more frequently, impacting cost and the lifetime of components. However, this study does not consider the efficiency of the hydrogen system, and uncertainties related to RESs and hydrogen systems.	[93]
PSO	Minimize NPC Minimize LPSP	Proposed PSO-based EMS performed rapidly and suggested an optimal configuration of the hybrid system compared to other algorithms.	[94]
PSO	Minimize LPSP Minimize COE	A multi-objective sizing problem is transformed to a single optimization, with defining COE as the objective and NRU, LPSP as constraints. Results indicate that, grid-PV combination is economically optimal and grid-PV-H_2 is a good choice for the renewable hydrogen energy systems.	[95]

begin with a local search-based strategy using an initial solution. However, this strategy does not guarantee the best solution in every scenario, and its performance depends on the problem's characteristics [77]. In contrast, metaheuristic algorithms employ high-level problem-solving strategies and a set of rules to explore the entire solution space through iterative searches [78]. Their specialty lies in their ability to balance exploration and exploitation within the search domain. This introduces the ability to balance exploring the complete search domain and intensifying the search around a good solution set [79]. This strategy is adaptable to various problems and provides a reasonable balance between solution quality and required computational power. Fig. 6 illustrates a discussed microgrid application of a PSO-based optimization technique.

Table 6 summarizes the heuristic and metaheuristic techniques employed, the main objectives of the EMS, as well as the key advancements and limitations reported in each study. In [80], the REVB are integrated into the EMS with the objectives of Loss of Power Supply Probability (LPSP), Annualized Cost of System (ACS), and Potential Energy Waste Probability (PEWP). PEWP is formulated to increase the penetration of solar power by operating PV at the maximum power level, thereby reducing energy waste. From an EMS perspective, a multi-objective Non-Sorted Genetic Algorithm (NSGA)-II EMS is developed. Compared to the Multi-Objective Evolutionary Algorithm (MOEA)/D-based EMS, this method exhibits a more even distribution of solutions in the solution space, despite both methods yielding the same Pareto front. An EMS based on the Parasitism Prediction Algorithm (PPA) is developed in [81] to minimize hydrogen consumption in an aircraft emergency power system. Formulated as a minimization of the negative power of combined supercapacitor and battery energy, which leads to the minimum hydrogen consumption through fuel cell systems. In [82], a microgrid with high-RES penetration is developed to evaluate the effectiveness of two hydrogen generation techniques, electrolysis and gas refining. The Particle

Swarm Optimization (PSO) algorithm is used in the EMS with the objectives of reducing natural gas consumption, CO_2 emission, and cost related to the microgrid system, as shown in Fig. 6. In [83], a piecewise linearization-based optimization addresses operating and environmental costs, solved using a modified NSGA-II approach. This strategy achieves a 4% reduction in environmental costs with only a 2% increase in operating costs by increasing electrolyser switching times from 198 to 521. In [84], an islanded microgrid powered by RESs, battery, and hydrogen is studied to optimize the energy storage arrangement of LI batteries, LA batteries, PEM electrolysers, and alkaline electrolysers. A PSO-based EMS utilizes LPSP as the sizing objective index and LCOE for operation control. In the LCOE formulation, the lifetimes of the electrolyser and fuel cell are calculated based on operating hours and switching times, representing the stack replacement due to the drop in energy efficiency in both systems. An investigated case study for Ginostra village in southern Italy indicates that a combination of PV, LI batteries, and alkaline electrolyser yields the lowest LCOE, even when compared to an existing diesel generator-based system. In [85], a Flower Pollination Algorithm (FPA)-based EMS is developed with the objective of reducing the Total Net Present Value (TNPV) of system operation by optimizing the capacities of PV, fuel cells, electrolysers, and hydrogen storage. The proposed EMS strategy is compared with PSO and ABC-based EMS, and the results indicate that the developed EMS strategy exhibits higher convergence capability. A microgrid with both electrical and hydrogen demand is developed in [86], utilizing a PSO-based EMS. The study suggests that increasing the LPSP from 0 to 0.05 results in significant cost saving while still supplying 95% of the available loads. The remaining 5% can be met by a non-intermittent energy source, which would still result in significant cost savings.

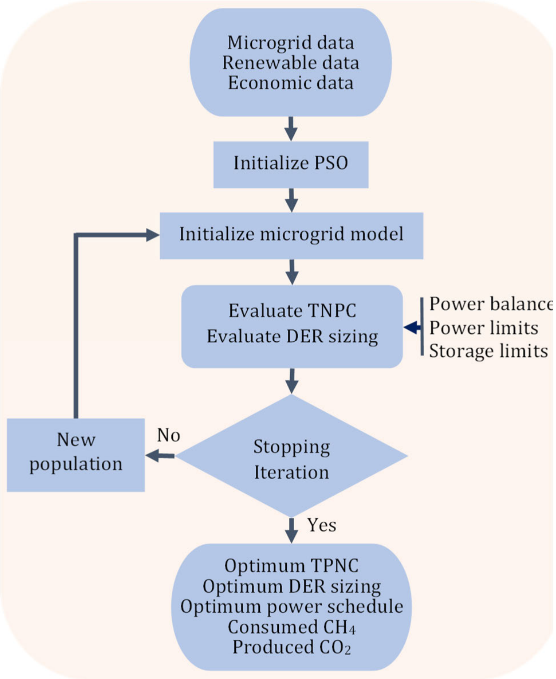


FIGURE 6. **Microgrid EMS application for PSO approach [82].**

In [87], special consideration is given to an islanded DC microgrid situated in an area with higher tidal energy potential. A Mixed Integer Linear Programming (MILP) EMS strategy is developed in two stages, incorporating one-time communication between EMS layers to reduce communication bandwidth usage. In [88], a hybrid PSO-Ant Colony Optimization (ACO) -based EMS strategy is validated in three different sites, demonstrating reduced GHG emission in each location. This EMS can achieve a reduced energy cost compared to ACO and PSO-based EMS strategies. A comprehensive risk and maturity analysis, including technology and integration readiness levels, indicates that integration of hydrogen storage into the microgrid is safer. A minimum Net Present Cost (NPC)-based EMS is developed in [89]. Moth-flame Optimization Algorithm (MFOA) outperforms both PSO and Genetic Algorithm (GA) in solution quality. A case study for Felding, New Zealand, models hydrogen demand for a refueling station within the microgrid, revealing that the levelized costs of electricity and hydrogen are notably lower than New Zealand's current benchmarks. In [90], hydrogen required for fuel cell operation is produced using two strategies: one utilizes the reformer connected to the gas network, while the other generates hydrogen from residential and municipal waste. Results indicate that waste utilization significantly reduces reliance on the gas network for FC. Furthermore, integrating a Fuel Cell as a CHP unit can potentially reduce CO_2 emissions by 40% over the project's lifecycle. Four key EMS approaches, including MPC, Hysteresis Band Control Strategy (HBCS), Equivalent Consumption Minimization Strategy (ECMS), and SMC, are investigated in [91], where particular attention is given to electrolyser-FC switching and operating costs. Special constraints are derived for electrolyser and FC systems to restrict power ramping during transient operations, reducing the switching times. In [92], a GA-SA-based EMS is developed to investigate the feasibility of integrating various energy sources, including PV, wind, and microhydro, into a hydrogen-based microgrid. Although the micro-hydro-based configuration demonstrates the highest overall efficiency, the wind system configuration achieves higher overall efficiency than the PV configuration when integrated with the hydrogen system. The performance of Subsection Bi-Objective Optimization Dynamic Programming (SBODP) and Multi-Objective Generic Algorithm (MOGA) based EMS strategies are compared in [93]. The objective functions are defined to account for power curtailment and equivalent hydrogen consumption of the systems, with the latter calculated by using the equivalent hydrogen consumption of the battery system, electrolyser hydrogen generation rate, and FC hydrogen consumption rate. The SBODP method outperforms MOGA in both case studies, achieving significant improvements in power curtailment and

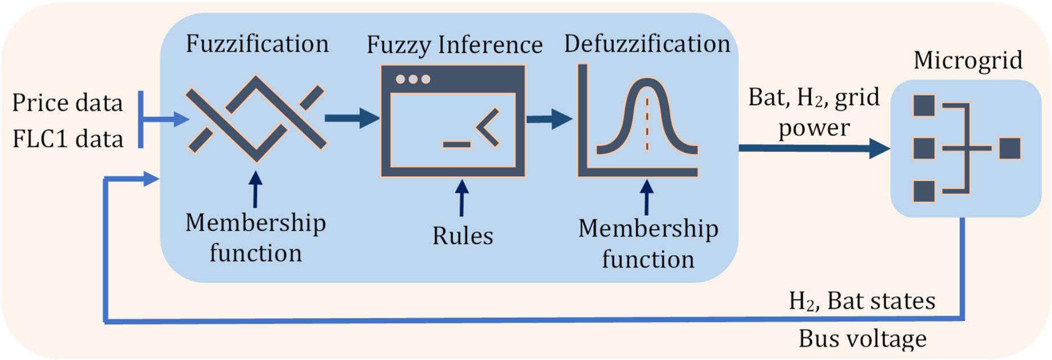


FIGURE 7. Microgrid application of fuzzy logic control approach [99].

TABLE 7. Analysis of fuzzy logic approach-based EMSs [97], [98], [99], [100], [101], [102].

Technique	Objectives	Analysis	Ref
FLC with PLC	Power balance Reduce peak demand Reduce Op-Cost	Individual and combined impacts of the applied hydrogen technologies and the load management on microgrid operation are investigated. EMS strategy with both demand response and hydrogen systems can achieve the optimal solution for reducing the cost of energy not supplied, cost of excessive energy, and total cost of the system.	[97]
FLC	Power balance	The proposed method can achieve reduced frequent fluctuations at the device controller level in response to sudden load changes. Also, it indicates a reduced grid purchase compared to traditional EMSs. However, it does not evaluate the capability of operation without a grid.	[98]
FLC	Power balance Increase lifespan Reduce cost	Novel rules are introduced in the EMS to reduce the stress on electrolyser and fuel cell operation through hydrogen storage SOC. However, introducing an electrolyser and fuel cell through hydrogen storage neglects the important parameters like rated power and rate of power change.	[99]
FLC	Power balance Fuel economy enhancement	The proposed approach operates the fuel cell at its optimal power value frequently, and the change of battery State of Charge (SOC) is less than 2%. However, this strategy does not consider economic aspects, which proposed approach could result in higher operating costs compared to traditional methods.	[100]
FLC	Minimum Operating and emission cost	A fuzzy logic approach-based EMS for managing the battery system optimally is developed. The proposed algorithm is capable of achieving the majority of battery storage system demands, but the maintenance costs of battery systems are not considered.	[101]
FLC	Minimum operating cost	Scheduling and developing the developed fuzzy system are handled at the same time. It automatically adjusts the expert system parameters relative to microgrid configurations. The proposed strategy is comparatively complex, and execution time is comparatively high. This will introduce operational issues when applied to a real-time application.	[102]

fuel economy. Further analyzed studies are also listed in Table 6 [94], [95].

2) FUZZY LOGIC APPROACH

Fuzzy logic-based optimization offers a mathematical framework for addressing uncertainty and imprecision in system optimization, thereby leveraging the designer's expertise. It enables the representation of diverse information and offers a structured method for decision-making based on degrees of truth, rather than strict binary values. It introduces a membership function to map the degree of truth into a specific set, allowing for a more flexible representation of the problem. Then, the inference process constructs the fuzzified sets to output parameters by following the fuzzy rules established by the designer. Fuzzy rules are applied to the fuzzified inputs and passed to the defuzzification stage. Finally, the defuzzification process converts the fuzzy outputs back into values that can be applied to control the microgrid components [96]. A flow diagram of a microgrid application using a fuzzy system is illustrated in Fig. 7. Fuzzy logic offers benefits such as uncertainty handling capability, flexibility, simplicity, and the integration of expert knowledge.

Table 7 presents the details of Fuzzy Logic Control (FLC)-based techniques, highlighting the primary EMS objectives along with the major advancements and challenges identified in the reviewed studies. For example, a hybrid FLC and Programmable Logic Control (PLC) approach is developed in [97] to examine the impact of demand response and hydrogen systems. Compared to cases involving only hydrogen systems, this configuration shows a significant reduction in hydrogen storage charging and discharging costs. In [98], a two-level EMS employs an FLC-based main layer for a hydrogen microgrid. The main layer provides fuzzy outputs for the FC, electrolyser, and Superconduct Magnetic Energy Storage (SMES), while the secondary layer employs novel NBF-FOSMC controllers. Specially, these controllers adapt to disturbances and unknown upper bounds, eliminating the need for additional data, which suits intermittent RES penetrations. In [99], a two-layer FLC is proposed. The first layer contributes to grid exchange decisions, mainly in two sections, while layer 2 contributes to energy storage-related decisions. Fuzzy sets for hydrogen storage are based on maximum capacity, elaborating the minimum operating pressure. This system is designed to operate as a long-term energy storage system, with batteries handling transient operations. A multi-objective EMS for electric vehicles consisting of FC, battery, and ultracapacitor systems is developed in [100] using a GA-assisted FLC. The objectives are to minimize energy consumption, maximize average supply efficiency, and optimize battery SOC during driving. This configuration

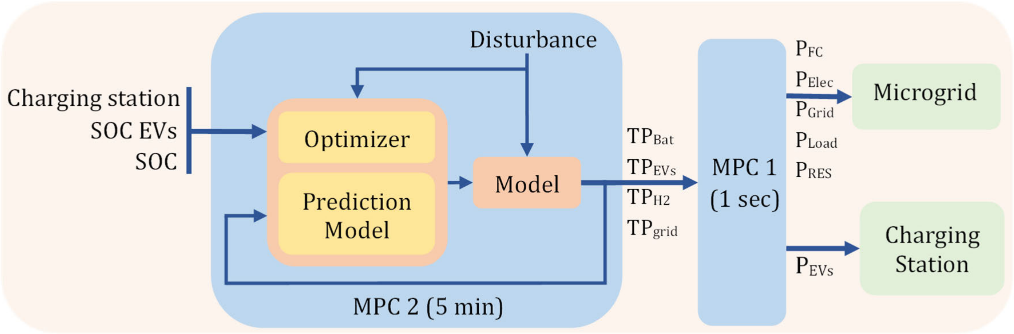


FIGURE 8. Microgrid application of model predictive control approach [107].

TABLE 8. Analysis of model predictive approach-based EMSs [105], [106], [107], [108], [109], [110].

Technique	Objectives	Analysis	Ref
SMC with ECMS	Minimize utilization costs	Results of battery SOC and hydrogen storage SOC are compared between the series minimum cost-MPC and SMC systems. Indicate that the MPC reduces the efficiency of the hydrogen system compared to the series method. This strategy does not consider the degradation of components or the impact of pressure and temperature in the hydrogen system.	[105]
MPC with generation scheduling	Minimize cost Power Balance	Results of the study suggest that the OGS-based EMS can achieve stable operation of the microgrid. Furthermore, a comparative analysis with an EMS, based solely on MPC and an OGS-MPC-based EMS, illustrates that the OGS-MPC-based EMS focuses on maintaining the battery SOC within a suitable range without providing priority for the hydrogen devices.	[106]
MPC	Power balance Optimize purchase Manage V2G	Results for different RES conditions indicate that the proposed EMS strategy can reduce the number of times hydrogen-related devices are switched on/off, while effectively utilizing the V2G station with the microgrid as an energy storage system.	[107]
Event-based SSMPC	Power balance Reduce grid purchase, reduced degradation	An event detector in the MPC unit detects the events that occur in the microgrid and sends signals to the controller unit, where separate controllers are assigned for each type of event. Results demonstrate a significant reduction in the number of changes in the control signal, albeit with a slightly reduced system performance.	[108]
MPC/ Rolling Horizon Control	Minimum operation cost Optimal power flow	The objective function is formulated using electricity costs, battery operation costs, and especially the power demand of the microgrid. However, performance is not verified with dynamic uncertain microgrid configurations. Furthermore, the generalized model developed in the proposed strategy is not analyzed for multi multi-microgrid scenario.	[109]
MPC	Minimum operation cost Energy exchange	The proposed MPC-based novel strategy is applicable in modern load-based applications. It can simultaneously operate a number of microgrids with the capability to scale. However, the proposed strategy depends on several uncertain parameters with the same prediction errors.	[110]

achieves the highest acceleration, lowest final SOC variation of the battery system, optimal FC power operation, and improved fuel economy. Further analyzed studies are listed in Table 7 [101], [102].

3) MODEL PREDICTIVE APPROACH

The MPC approach involves utilizing a predictive model of the actual system to generate control decisions. Typically, MPC predicts the system's behavior over a future period and optimizes control decisions to achieve optimal solutions. MPC is effective in dealing with the dynamics and constraints of microgrids, handling multiple objectives and uncertainties. It involves complex control techniques and demands high computational resources. MPC consists of key steps, including system modeling, defining the prediction/control horizon, formulating the objective function, and solving the objective function [103]. Initially, a system model is developed to govern the dynamics of components in the system. Then, a prediction horizon, minutes to hours, and a control horizon are selected. MPC optimizer attempts to solve an objective while satisfying the constraints [104]. Discussed microgrid application of MPC is illustrated in Fig. 8. This strategy is well-suited for high RES and hydrogen-based microgrids due to the intermittent and unpredictable nature of these devices. Applications of MPC in microgrids encompass energy management, grid integration, and load forecasting, offering benefits such as enhanced uncertainty handling, informed decision-making, and multi-objective optimization.

Table 8 provides an overview of model predictive control–based studies, emphasizing EMS objectives and the principal contributions and limitations identified. A two-level EMS is developed for an islanded hydrogen microgrid in [105], with real-time simulation conducted using the RT-LAB platform. A minimum-cost approach based on cycle analysis of charging and discharging profiles can enhance the independent operation of fuel cell and electrolyser systems in hydrogen energy setups. However, since hydrogen SOC is used for the state definition process, the overall efficiency of the hydrogen system is reduced, resulting in very low SOC levels, which may lead to microgrid instability. An EMS for a DC microgrid consisting of fuel cells, hydrogen storage, electrolyser, and battery storage is developed in [106]. The proposed EMS is divided into two layers: the Optimal Generation Scheduler (OGS) and MPC. The OGS layer analyses the forecasted generation and demand profile of the microgrid and calculates the predicted SOC levels of the battery and hydrogen storage, considering the uncertainties of solar and demand responses for robust operation. To address uncertainty, a scenario tree method is introduced,

TABLE 9. Analysis of uncertainty approach-based EMSs [113], [114], [115], [116], [117], [118].

Technique	Objectives	Analysis	Ref
Hybrid two-stage stochastic programming	Minimize cost	Real-time strategy controls the effects of uncertainty in day-ahead prices, and EMS is utilized for PV generation, vehicle demand, and real-time price profiles. Results suggest that both investigated and interval-based strategies perform equally well. However, for defined uncertainties, the discussed strategy can provide operation with no risky conditions but at higher costs.	[113]
Stochastic optimization	Energy balance Minimize costs	Results suggest integrating the hydrogen storage and plug-in EV can reduce the cost reduction up to 9.28% daily. However, electrolyser and fuel cell uncertainties, such as electrolyte degradation, could also be included as uncertainties.	[114]
Two-stage robust optimization	Minimizing cost Reduce negative impact on grid	Proposes a novel strategy based on expected scenarios without focusing on a worst-case scenario strategy. Comparison results suggest that this strategy can achieve cost-effective operation and minimize the negative impact on the utility grid.	[115]
Stochastic optimization	Minimum operational and emission cost	The proposed multi-objective-based EMS model considers RER as a demand-side management strategy where the augmented epsilon constraint method is applied. Furthermore, the concept of portable renewable energy sources can be improved to be suitable for real-time applications.	[116]
Robust optimization	Maximum revenue Minimum cost	Evaluates the reliability of microgrids by examining indicators such as loss of load expectation and loss of expected energy. However, the proposed method's performance has not been validated under uncertain events within a microgrid.	[117]
Two-stage stochastic optimization	Minimum expected operational cost	In the study, residential, commercial, and industrial consumers can join demand response to contribute energy reserve. Based on the results, it appears that the microgrid's reliance on the main grid has increased, which could potentially raise the demand on the power system.	[118]

which considers three scenarios for solar irradiation and five scenarios for demand responses. The OGS-MPC-based EMS can achieve stable microgrid operations even under fluctuating renewable energy inputs. In [107], an EMS strategy is proposed for energy management in a hydrogen-based DC microgrid consisting of solar power, fuel cells, electrolyser, hydrogen storage, V2G EV stations, and battery storage. MPC 1 objectives are to maintain the power balance of the microgrid, considering the V2G station management. MPC 2 objectives are the economic operation of the microgrid and maintaining sales and purchases from the grid. A key consideration in this EMS is the management of the V2G charging station, which acts as an ESS for handling power transients in the microgrid. Additionally, the switching times of hydrogen-related components are considered a primary constraint in the EMS strategy. An EMS for a hydrogen-based DC microgrid utilizing MPC is developed in [108]. An event-based state-space MPC is proposed with the objectives of power balance, reduced energy purchase from the grid, and reduced component degradation. The system introduces two types of events: threshold-based and time-based events. The event detector in the MPC unit detects events occurring in the microgrid and sends signals to the corresponding controller units, each designed to respond to a specific type of event. Further analyzed studies are listed in Table 8 [109], [110].

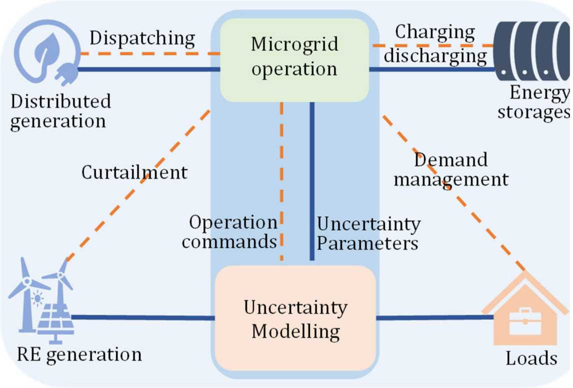


FIGURE 9. Microgrid application of uncertainty approach.

4) UNCERTAINTY APPROACH

Stochastic and robust programming are two techniques commonly used in energy management strategies to address the uncertainties and risks inherent in energy systems. They are particularly valuable for managing variations in renewable energy sources, market prices, and demand fluctuations. Stochastic programming is a mathematical optimization technique used to optimize energy management decisions in the presence of uncertain parameters. Uncertainties can arise from weather conditions affecting RESs, fuel prices, and energy demand. Stochastic programming addresses uncertainties by modelling them as probability distributions, enabling decision-making over a range of possible scenarios. In the EMS application, this approach enables optimized energy management that accounts for variations in factors such as renewable generation and load demand across different probable scenarios [111]. However, robust programming is designed to minimize the impact of uncertainties on decisions by focusing on resilience rather than probability. Instead of modelling uncertainty directly, robust programming seeks solutions that perform well under a range of possible variations and disturbances. In EMS applications, this approach is often used to optimize operations by minimizing worst-case scenarios, ensuring stability and reliability in energy management under different conditions [112]. A typical microgrid EMS application of the uncertainty approach is illustrated in Fig. 9.

Table 9 presents an overview of uncertainty-based techniques, focusing on EMS objectives as well as the key contributions and limitations reported in the literature. In [113], an EMS is examined for a hybrid charging station system consisting of electrolysers, fuel cells, and hydrogen storage. Uncertainties related to solar PV, market prices, and demand profiles are introduced into the two-stage stochastic programming-based EMS. Additionally, interval-based stochastic programming is used for accuracy and robustness validation. The real-time strategy manages the impact of uncertainties in day-ahead prices, while the EMS optimizes the dispatch of PV units, meets vehicle

TABLE 10. **Analysis of rule-based and other approach-based EMSs [121], [122], [123], [124], [125], [126], [127], [128], [129], [130].**

Technique	Objectives	Analysis	Ref
Flow chart (Efficiency adaptive control)	Operate HPU at maximum efficiency	Identified a peak efficiency point in the hydrogen production energy conversion efficiency curve depending on current and temperature. An efficiency-adaptive control strategy is introduced for hydrogen production to maintain energy conversion efficiency at the maximum value. However, does not include the effect of pressure on hydrogen production efficiency.	[121]
Flow chart	Power balance	Proposed EMS strategy delivers better parallel operation of hydrogen storage and battery storage compared to conventional EMS strategies by keeping SOC levels of both systems under linear operation. However, this strategy cannot achieve an optimal solution in the system.	[122]
ECMS	Minimize hydrogen consumption	The proposed strategy performs the best operating economy with the lowest equivalent hydrogen consumption compared to classical PI and SMC. However, this study does not focus on hydrogen generation and supply. Better utilization of the battery and PV could have been achieved by introducing cost-related functions.	[123]
Hybrid Automata	Power balance	This strategy does not allow the electrolyser and fuel cell to operate independently of the battery system. Also, electrolyser and fuel cell operations are modelled related to hydrogen storage SOC, where most of the critical electrolyser and fuel cell operating conditions are neglected.	[124]
Flow chart	Power balance	It is identified that the rate of battery charging, the rate of hydrogen production, the efficiency of hydrogen utilization, and fuel cell power saving are higher in DC microgrid systems compared to AC microgrid systems with the same specifications. However, this strategy does not have an optimal solution, while electrolyser and fuel cell frequent switching are also introduced.	[125]
Flow chart	Minimize primary energy consumption Minimize cost	Smart transition regulation and smooth shift from islanded mode to grid-connected mode are introduced in this study. However, this study lacks a hardware implementation of the proposed strategy for result verifications.	[126]
Flow chart	Power balance Minimize cost	Comparison results with an available EMS strategy indicate that the proposed strategy can achieve improved battery power, battery voltage profile, and hydrogen level profile.	[127]
MPC and DP algorithms	Minimize cost Power balance	DP-MPC can correct operational errors in real-time and optimize the effects of MPC, while capitalizing on the advantages of both DP and MPC in complementing each other. The results suggest that the proposed strategy can achieve reduced working time, increased operational speed, and lower costs under the same initial conditions when compared to traditional EMS methods.	[128]
Fuzzy, frequency and SMC	Minimize hydrogen consumption Optimize SOC	Compared with the standalone FLC and state machine control-based EMS, the proposed strategy can reduce hydrogen consumption by 19.6% while maintaining an increased battery SOC of 5.4%.	[129]
ECMS	Minimize the instantaneous hydrogen consumption	The introduced virtual capacitance droop control method can reduce the overshoot and increase the transient response in the bus voltage compared to the virtual impedance droop control method. Stable operation of the microgrid is achieved by ECMS-based EMS, but no comparison is carried out to verify the reduced hydrogen consumption of the proposed EMS strategy.	[130]

demand, and responds to real-time price changes. A stochastic programming-based EMS for a microgrid consisting of PV, electrolysers, hydrogen storage, and fuel cells with a heating system and hydrogen refueling system is investigated in [114]. Several associated uncertainties in the microgrid, including solar energy profiles, price profiles, load profiles, and EVs' arrival and departure times, are introduced for risk management in the system. Results show that hydrogen storage and plug-in EVS can reduce the operational costs by up to 9.28% daily. In [115], an EMS based on robust optimization is discussed for a microgrid aiming to minimize the impact on the utility grid. This strategy proposes a novel approach based on expected scenarios, rather than focusing on a worst-case scenario strategy. Compared with traditional methods, this strategy can achieve cost-effective operation and minimize the negative impact on the utility grid. Further analyzed studies are listed in Table 9 [116], [117], [118].

5) HYBRID AND OTHER APPROACHES

In addition to the abovementioned EMSs, several other EMSs, including flowchart control, State Machine Control (SMC), and hybrid techniques, have been discussed. A classical rule-based approach for EMSs in microgrids uses predefined rules to manage operations. This approach relies on simple, deterministic rules informed by experts and historical data, making the decision-making process transparent, easy to implement, and easy to understand. However, its limitations include difficulty in achieving optimal system performance and an inability to adapt to varying conditions, as predefined rules are static by nature [119]. A SMC approach for EMSs in microgrids uses finite state machines to model the different operating states of the microgrid and the transitions between these states. State transitions are controlled by a predefined set, which is structured and deterministic, making it effective for managing complex systems with clear and well-defined operational states and transitions [120]. However, a major drawback of this approach is scalability. Once states and transitions are defined, updating every state and transition is complex. A hybrid approach for EMSs in microgrids combines multiple strategies, such as classical approaches, heuristic algorithms, and SMC, to utilize their respective strengths and mitigate their limitations.

Table 10 summarizes other EMS approaches, such as rule-based and hybrid techniques, outlining the EMS objectives and the key strengths and weaknesses identified. A decentralized strategy is investigated for a DC microgrid consisting of hydrogen systems in [121]. The DC bus voltage governs system operations, while the hydrogen production unit is controlled to maximize efficiency. A peak efficiency point, determined by current and temperature, has been identified on the energy conversion efficiency curve. Thus, the efficiency of the hydrogen production unit is directly influenced by these two parameters. In [122], a decentralized EMS is proposed for a DC microgrid that includes hydrogen storage, an electrolyser, and a battery system. This EMS is structured into two layers: the mode division layer and the droop control layer. The mode division layer divides the operation into two sections, and each of those into four sections, considering the bus voltage of the DC microgrid. The performance is verified through real-time simulations using RT-Lab technology under eight scenarios. In [123], a two-level EMS is used for a DC microgrid system. The proposed system control level is based on an ECMS to minimize the equivalent hydrogen consumption of the DC microgrid. Compared to a classical PI controller-based EMS and a Sliding Mode Control-based EMS, the proposed EMS achieves the lowest hydrogen consumption. In [124], an EMS utilizing a hybrid automata strategy for a hydrogen-based DC microgrid is developed. The SOC levels of the hydrogen system and battery systems are introduced as main state division factors. However, the electrolyser and fuel cell systems are linked to the battery, preventing independent operation. An EMS using a rule-based flowchart approach is studied for both AC and DC microgrids in [125], focusing on electrolyser power thresholds, battery SOC limits, and hydrogen storage SOC limits. The study reveals that the DC microgrid can achieve better performance in hydrogen production, PV power usage, fuel cell power savings, and electrolyser operation compared to the AC microgrid.

In [126], an EMS is developed for a DC microgrid connected with AC loads and the main power system, achieving a reduction in both operational costs and CO_2 emissions. An EMS for a DC microgrid to achieve technical and economic operation is developed in [127]. This EMS performs both short-term and long-term operations using a control-oriented state-space model. Specifically, it offers a comprehensive study on modelling battery efficiency, battery SOC, hydrogen storage level, hydrogen system efficiency, hydrogen generation-consumption ratio, battery degradation, fuel cell degradation, and electrolyser degradation. In [128], an EMS based on combined MPC-Dynamic Programming (DP) is investigated for cost minimization. This strategy operates on a limited timescale, utilizing rolling optimization as the input for the DP to create a feedback loop between DP and MPC. DP-MPC can correct operational errors in real-time. A hybrid EMS strategy is proposed to minimize hydrogen consumption and optimize battery SOC levels in [129]. The proposed EMS comprises a fuzzy logic system and a frequency decoupling-SMC system, which automatically switch between these two systems based on preassigned functions. Specifically, the frequency decoupling method aims to minimize power fluctuations in the battery system, maintaining a constant power state with the involvement of the fuel cell. Further analyzed studies, such as [130], are listed in Table 10.

B. HYDROGEN-RELATED OBJECTIVES WITHIN MICROGRIDS

At present, most microgrid EMSs address multiple objectives, including economic, technical, social, and environmental goals. Hydrogen systems are commonly used for energy storage, helping to stabilize supply and demand in high-RES penetration microgrids. Though including direct hydrogen-related objectives in the EMS can increase complexity, it offers significant benefits, such as enhancing energy storage capabilities and reducing carbon emissions. Fig. 10 presents an overview of hydrogen system integration across the different layers of the EMS. Hydrogen demand from transportation applications (buses, vessels, and cars), chemical industries, and other sectors can potentially be forecasted within the EMS. Based on the defined objectives of the microgrid, the EMS subsequently generates dispatch signals for electrolyzers, fuel cells, and hydrogen exports from storage systems.

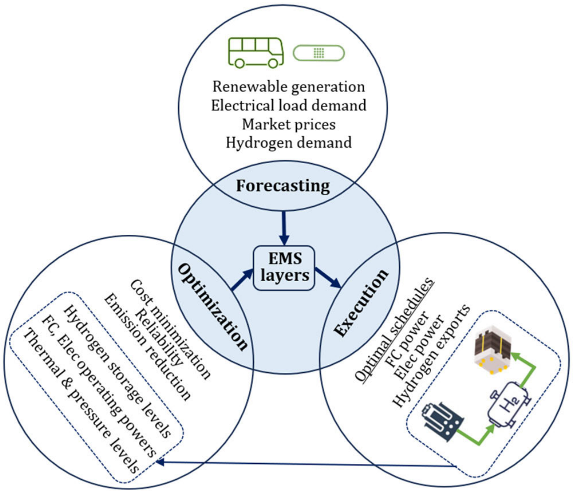


FIGURE 10. Hydrogen system interactions with EMS.

1) COST OF PRODUCTION

Most studies consider the cost of electricity used for hydrogen production, which varies with the time of day and RES availability [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [99], [100], [101], [102], [105], [106], [107], [108], [109], [110], [115], [116], [117], [118], [126], [127]. Real-time pricing and time-use pricing have been utilized in many studies for hydrogen production when the price is low [82], [83], [84], [113]. Furthermore, electrolyser efficiency affects electricity requirements. Some studies have utilized a high-efficiency electrolyser to reduce the overall cost as well. Further cost-saving strategies include factoring in electrolyser lifetime variables, such as switching times, which can extend operational life and lower annualized capital costs [83]. Finally, some studies have introduced larger production units that benefit from economies of scaling, reducing the per-unit cost of hydrogen.

2) COST OF STORAGE

Hydrogen storage involves significant upfront costs, including tanks, compression or liquefaction equipment, and safety infrastructure. However, these factors are rarely addressed in existing literature [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [99], [100], [101], [102], [105], [106], [107], [108], [109], [110], [115], [116], [117], [118], [126], [127]. Furthermore, storage costs vary depending on the process type, covering energy costs for compression or liquefaction, facility maintenance, and energy losses due to storage inefficiencies. Depreciation and lifespan factors are occasionally considered, impacting long-term cost calculations [88], [99], [122].

3) COST OF FUEL CELL

Fuel cell systems require a substantial capital investment, including fuel cells and additional infrastructure such as inverters and cooling systems, which represent major costs [91], [92], [93], [94], [95], [97], [98], [99], [100], [101], [105], [106], [107], [108], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127]. However, these additional costs are not often included in past studies. Potential inclusions could cover fuel cell maintenance, hydrogen supply costs, and expenses related to regulatory compliance and safety measures.

4) LIFECYCLE EMISSIONS

This factor is rarely covered in the literature. It is possible to integrate emissions associated with electricity for the electrolysis process. Even with RESs, emissions from manufacturing and transporting infrastructure can be factored in. Considerations might include maintenance emissions and potential leaks during storage. Comprehensive lifecycle analyses could reveal emission hotspots across the production, storage, and utilization phases, offering a positive impact on environmental strategy.

5) CONVERSION EFFICIENCY

Recent advancements in electrolyser technology have improved operational efficiency, with current efficiencies ranging from 60-80%. Some studies consider electrolyser efficiency in objective functions, but few address fuel cell system efficiency [81], [93], [113], [123], [129], [130]. Introducing these efficiency objectives could reduce hydrogen demand, thereby optimizing resource utilization.

6) RES INTEGRATION

In existing studies, hydrogen production is often used for power management, absorbing excess renewable generation and providing a flexible load that can be adjusted according to grid needs [82], [83], [84], [90], [98], [105], [107], [123], [124], [125]. Apart from that, hydrogen systems could participate in demand response programs, adjusting production/consumption in response to real-time operations and pricing.

C. HYDROGEN-RELATED CONSTRAINTS AND VARIABLES

A key limitation identified in most of the reviewed studies is the simplification of hydrogen system models. In particular, electrolyzers and fuel cells are frequently represented by fixed efficiencies, whereas in practice their performance is influenced by multiple variables ranging from thermal, electrical, and chemical domains. Neglecting these dynamics results in energy management strategies that appear cost-optimal in simulations but are not practically feasible.

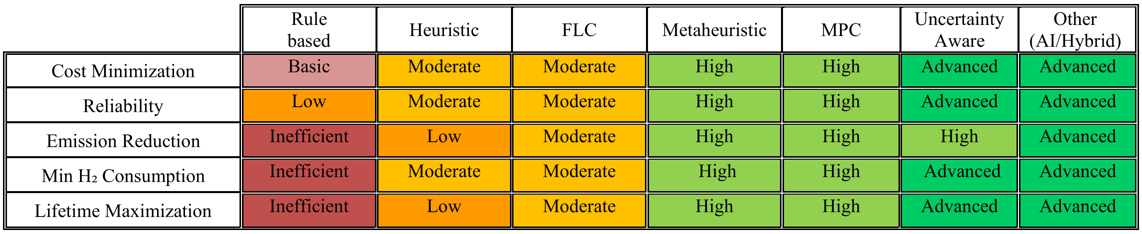
For electrolyzers, efficiencies typically range between 45-80% (LHV basis), with peak performance generally achieved at certain operating temperature and pressure ranges, depending on the technology [51], [54]. Also, efficiency drops sharply at partial load operation below approximately 20% of rated capacity. Additionally, high ramp rates accelerate membrane and catalyst degradation, resulting in a reduced stack lifetime. Start-up processes introduce further penalties, as cold-start conditions often require auxiliary heating and several minutes before stable operation can be established. However, prior studies rarely account for these operational behaviors, often assuming frequent start-stop cycles and high ramping, which in reality shorten the service life of electrolyzer stacks. Another critical aspect is the water requirements. This water must undergo treatment to achieve the required conductivity, adding to the auxiliary energy demand of the electrolyzer system. Despite its importance, electrolyser water requirement is frequently overlooked in existing literature.

Fuel cells also exhibit the same sensitivities as electrolyzers. Under nominal conditions, stack efficiencies typically range from 40-60%; however, performance deteriorates significantly when temperature deviates from the optimal range or when operating pressure falls outside the designated window, depending on the fuel cell type [67], [72], [74]. Such deviations result in voltage losses of approximately 50-100 mV per cell, directly increasing hydrogen consumption. Also, frequent cycling elevates hydrogen consumption and accelerates long-term degradation. Voltage decay rates of 5-10 μV/h are commonly reported under dynamic operation, corresponding to stack lifetimes of 20,000-30,000 operating hours, with shorter lifespans reported at highly variable renewables [73]. Additionally, effective water and thermal management are crucial, as stable operation requires specific relative humidity levels.

Hydrogen storage introduces further complexity, which is often overlooked in EMS studies unless storage is the primary focus. High-pressure tanks (350-700 bar) experience temperature rises of 10-20 °C during rapid charging, reducing usable capacity and triggering safety mechanisms that are rarely incorporated into EMS formulations [47], [48], [49], [50]. Similarly, cryogenic hydrogen storage is subject to continuous boil-off losses, which can relate to significant issues during long-duration islanded operation.

When these practical operational conditions are ignored, EMS strategies tend to miscalculate hydrogen demand, neglect degradation-related costs, and overestimate system reliability. This mismatch between modeled and actual performance of hydrogen systems is particularly highlighted in renewable-based microgrids, where frequent cycling and variable supply worsen component stresses. To bridge this gap, EMS formulations should introduce comprehensive models that capture the dependence on temperature, pressure, and current density; dynamic and start-up constraints, such as ramp rates and auxiliary loads; degradation-aware scheduling that reflects stack life costs and storage cycle limits; and resource management, including water and thermal interactions.

Fig. 11 presents a decision matrix designed to support the selection of appropriate EMS techniques for



	Rule based	Heuristic	FLC	Metaheuristic	MPC	Uncertainty Aware	Other (AI/Hybrid)
Cost Minimization	Basic	Moderate	Moderate	High	High	Advanced	Advanced
Reliability	Low	Moderate	Moderate	High	High	Advanced	Advanced
Emission Reduction	Inefficient	Low	Moderate	High	High	High	Advanced
Min H_2 Consumption	Inefficient	Moderate	Moderate	High	High	Advanced	Advanced
Lifetime Maximization	Inefficient	Low	Moderate	High	High	Advanced	Advanced

FIGURE 11. **Primary decision matrix for EMS selection based on objectives.**

hydrogen-integrated microgrids. The matrix is constructed based on the principal EMS approaches, their objectives, hydrogen-related constraints, and the key variables identified in prior studies. This does not provide a complete classification, but it highlights the main patterns observed in the reviewed studies. Accordingly, the matrix provides a practical reference for researchers and practitioners in evaluating, selecting, or developing EMS strategies for future hydrogen-integrated microgrid applications.

V. REVIEW FINDINGS AND DISCUSSION

This section provides a comprehensive summary and critical insights in terms of comparative analysis of the findings related to hydrogen storage, hydrogen generation, hydrogen utilization technologies, and EMS strategies.

A. HYDROGEN STORAGE TECHNIQUES.

Hydrogen storage can store hydrogen, generated from excess energy, and convert it back to electricity during periods of high demand or low generation. This approach has been utilized in most studies [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [99], [100], [101], [102], [105], [106], [107], [108], [109], [110], [115], [118], [126], [127]. In contrast, hydrogen can be used as a long-term energy storage solution, crucial for maintaining grid reliability, where it is rarely applied in the discussed microgrid EMS. Furthermore, several microgrid EMSs have integrated hydrogen storage with RESs to create a sustainable and self-sufficient islanded energy system, reducing grid dependency [80], [81], [85], [86], [87], [88], [89], [91], [92], [93], [94], [114], [115], [116]. Hydrogen storage systems also offer flexibility for scalable applications, in small-scale residential microgrids and larger commercial/industrial microgrids. Moreover, hydrogen storage is often used in conjunction with other storage technologies such as batteries [81], [84], [86], [90], [91], [92], [93], [97], [106], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127]. This can leverage the strengths of different storage technologies, such as the fast response time of batteries and the high energy density of hydrogen.

At present, liquid and cryo-compressed hydrogen storage methods have seen declining interest due to their extremely low temperature requirements. Physical adsorbents also have low capacity at room temperature. Compressed hydrogen is well-established and the most practical for stationary applications. Meanwhile, metal hydrides and liquid organic carriers have promising potential with the capability to integrate into existing fuel infrastructures. Critically, no single storage method outperforms others; instead, each involves trade-offs between energy density, efficiency, safety, cost, and application suitability. A comparative analysis illustrates that the optimal choice depends heavily on context, whether for mobile, stationary, short-term, or seasonal storage, highlighting the need for hybrid or integrated storage strategies. For example, compressed hydrogen is well-suited for mobile applications, such as fuel cell vehicles, due to its fast refueling and relatively lightweight system, despite having a lower volumetric energy density. Conversely, liquid hydrogen offers higher storage density and is preferable for long-range transport or aerospace applications, although it requires high energy for liquefaction and complex thermal insulation. Solid-state storage options, such as metal hydrides, provide safer and more compact alternatives for stationary applications, but their slow kinetics limit mobility use. Chemical storage methods, such as ammonia or liquid organic hydrogen, present promising opportunities for large-scale applications, particularly when hydrogen needs to be transported over long distances or stored for extended periods. The analysis highlights that no single storage technology can meet all performance demands. This illustrates the development of hybrid or integrated

TABLE 11. **Comparison of hydrogen and battery storage [45], [46], [130], [131], [132], [133].**

Aspect	Hydrogen storage system	Battery storage system (Li-ion)
Gravimetric energy density	33.3 kWh/kg (H_2 LHV)	0.1–0.25 kWh/kg
Volumetric energy density	1–2kWh/L, compressed 2.4 kWh/L ,liquid	0.25–0.7 kWh/L
Round-trip efficiency	25–45%	85–95%
Response time	s - min (FC)	ms - s
Cycle life	High (if pressure and purity controlled)	4,000–10,000 cycles
Degradation	Minimal for stored hydrogen.	Gradual capacity fade due to cycling
Long-term storage	Excellent (weeks to months)	Limited (self-discharge, thermal loss)
Capital cost	$1,000–2,000/kWh (electrolyser, tank, FC)	$200–600/kWh
O&M costs	Medium to high (due to multiple components)	Low to medium
Maturity & availability	Emerging, growing in grid-scale applications	Highly mature and widespread
Safety considerations	High-pressure, flammable, strict safety	Thermal runaway

storage strategies, where multiple methods are combined or adapted based on specific system requirements, ultimately enabling more resilient, flexible, and efficient future hydrogen infrastructures.

Table 11 provides a comparative overview of the technical and economic characteristics of hydrogen storage systems and lithium-ion battery systems. While batteries offer high round-trip efficiency, fast response, and lower capital cost, hydrogen systems provide superior energy density by mass and long-duration storage capability.

B. HYDROGEN PRODUCTION TECHNIQUES

Most of the discussed studies utilize PEM electrolysers due to their higher efficiency and operability with varying loads [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [99], [100], [101], [102], [105], [106], [107], [108], [109], [110], [115], [116], [117], [118], [126], [127]. A few studies have utilized alkaline electrolysers, which are known for their durability, cost-effectiveness, and capability for large-scale hydrogen production [84]. The biomass gasification method leverages waste biomass and agricultural residues. Only one study discussed the potential for integrating this strategy in the reviewed literature [88], [121]. While traditional SMR relies on natural gas and produces significant CO_2 emissions, the integration of carbon capture and storage technologies can make it a cleaner option. This method is widely used in industrial applications due to its maturity and cost-effectiveness [82], [89].

Even though SMR dominates in scale, electrolysis holds the most promise for sustainable hydrogen production. Biomass pathways provide a transitional option that balances renewability and carbon intensity. Analysis reveals that the choice of generation method should align with regional energy resources, emission targets, and integration potential within energy systems. For instance, regions with abundant RESs are well-positioned to adopt water electrolysis for green hydrogen production, leveraging clean electricity to minimize lifecycle emissions. In contrast, areas with established natural gas infrastructure can initially rely on SMR, coupled with CCS, transitioning toward low-carbon hydrogen. The viability of biomass gasification depends on the consistent availability of organic waste and regional policies supporting bioenergy. Furthermore, generation methods must be compatible with the existing energy infrastructure, including grid capacity and demand profiles.

C. HYDROGEN UTILIZATION TECHNIQUES

PEM fuel cells are widely used in microgrid studies due to their high efficiency, quick startup capabilities, and ability to handle variable loads [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [97], [98], [99], [100], [105], [106], [107], [108], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127]. Additionally, hydrogen-utilizing CHP systems can simultaneously generate electricity and useful heat, improving overall energy efficiency. This is particularly beneficial in applications requiring both power and thermal energy, such as residential complexes and industrial facilities [89], [103], [113], [122]. Furthermore, modified internal combustion engines are applicable for backup power generation and can be easily integrated into existing infrastructure with minimal modifications [101]. Hydrogen can also be tested as a feedstock in various industrial processes, including ammonia production and chemical manufacturing. Moreover, hydrogen fuel cell vehicles, as well as hydrogen-powered buses and trucks, have been discussed in some studies, supporting clean transportation solutions [87,108,93,109,115].

Overall, fuel cells offer higher efficiency and emissions performance, especially in integrated or decentralized energy systems. Critical comparisons highlight that the optimal hydrogen utilization strategy must carefully balance several factors. Infrastructure readiness refers to the existing or planned availability of hydrogen production, storage, and distribution systems, which significantly influence the feasibility and deployment speed of different applications. Application-specific efficiency considers how effectively hydrogen can be converted into useful energy in each case. For example, fuel cells offer high electrical efficiency for vehicles and stationary power, while combustion-based systems may be more suitable where heat is the primary demand. Lastly, long-term decarbonization goals require evaluating the lifecycle emissions of each utilization pathway, prioritizing technologies that align with net-zero objectives, such as fuel cells powered by green hydrogen. Therefore, selecting the most appropriate hydrogen end-use pathway must align with technological maturity, economic viability, regional energy strategies, and climate targets.

D. HYDROGEN MICROGRID EMS

1) HEURISTIC/METAHEURISTIC ALGORITHMIC APPROACH

Heuristic and metaheuristic algorithms are flexible and adaptable to various configurations, sizes, and operational requirements. They excel at searching large solution spaces to find near-optimal solutions. These approaches can achieve fast convergence to the global solutions with high accuracy [86], [87]. Hydrogen-based microgrid optimization problems are often complex and nonlinear due to the nature of RESs and hydrogen systems. Consequently, most of the discussed literature achieves optimal solutions by introducing heuristic/metaheuristic algorithms [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95]. These algorithms can efficiently explore a wide range of possible solutions to identify optimal or near-optimal operating points. Some population-based and naturally inspired metaheuristic algorithms, including the genetic algorithm and the PSO algorithm, can directly obtain the global solution, thereby neglecting local solutions. Their low dependency on the initial solution and significant individual distribution around the design space contribute to these capabilities. Furthermore, quick convergence is crucial for real-time or near-real-time applications such as microgrid EMSs [79]. This is essential for microgrid EMSs, where the system may need to adjust its operation in response to sudden changes in RESs, load demand, and hydrogen system behaviours. Especially due to the intermittent nature of renewables and the temperature sensitivity of hydrogen systems, a real-time EMS strategy can achieve better solutions. However, much of the discussed literature tends to apply a schedule-based EMS strategy for microgrid operations without considering these issues. Additionally, microgrid EMS problems typically involve multiple conflicting objectives, including cost minimization, energy efficiency, and environmental impact. Metaheuristic algorithms can support multi-objective optimization by providing a set of solutions that represent trade-offs between different objectives, allowing decision-makers to choose based on their priorities [80], [81], [82], [83], [86], [87], [90], [91], [92], [93], [94], [95]. However, these approaches require high computational power, which affects the speed of convergence to the solutions.

2) FUZZY LOGIC APPROACHES

The fuzzy logic approach can operate without precise inputs, which is suitable for stochastic systems. This approach provides a framework for incorporating expert knowledge into the control system, where experts can introduce their experience in defining rules and membership functions [97], [98], [99], [100], [101], [102]. Especially since hydrogen systems like electrolysers and fuel cell systems are still developing, expert knowledge can be integrated into the EMS through the fuzzy logic approach. Some literature discusses introducing electrolyser and fuel cell switching times into the EMS to achieve reduced operational costs [98], [99]. However, none of the discussions introduce rules related to optimizing electrolyser and fuel cell systems considering temperature and pressure variations. Besides expert knowledge, operators are required to adjust several parameters, including membership functions, fuzzy sets, and fuzzy rules, which is a time-consuming process.

3) MODEL PREDICTIVE CONTROL APPROACH

MPC generally works with an accurate model. MPC allows the controller to proactively optimize control actions, considering anticipated changes in renewable energy generation, load demand, and storage conditions [105], [106], [107], [108], [109], [110]. This literature introduces predictive models of electrolyser and fuel cell systems in the MPC-based EMS. However, these studies do not consider factors such as hydrogen system efficiencies in the prediction procedure. MPC can predict the states of a system and optimally control it during disturbances. However, MPC highly relies on accurate mathematical models of the system. If the models used are not precise or if uncertainties exist in the system dynamics, the performance of MPC can be compromised [103]. Given the challenges of accurately modeling the effects of temperature and pressure on hydrogen systems, MPC may struggle to generate optimal solutions. Furthermore, MPC aims to make decisions that optimize specific objectives. MPC often includes a state estimation component, allowing the controller to incorporate real-time measurements into the optimization process [103]. However, available literature on hydrogen-based DC microgrids often does not operate in real-time. Introducing real-time operations could potentially respond to hydrogen system sensitivities more effectively.

4) UNCERTAINTY APPROACH

An uncertainty approach allows the EMS to make decisions that are robust in the face of unpredictable variations in renewable energy generation, load demand, and other uncertainties. By explicitly considering uncertainties, the EMS can assess and mitigate risks associated with deviations from expected values [113], [114], [115], [116], [117], [118]. This is particularly important in microgrids, where variations in renewable energy production and load demand can impact overall system performance. Some uncertainty approaches, such as stochastic optimization, explicitly consider uncertainty in the optimization process. Most of the available literature addressing uncertainties focuses on issues related to RESs, energy market prices, demand profiles, and specific scenarios like refueling stations and combined heat-power systems [113], [114]. However, uncertainties related to hydrogen systems, such as electrolysers and fuel cells, must be addressed properly. The operation of these systems depends on conditions like temperature, pressure, flow rates, and electrolyte status. Moreover, the uncertain behaviour of other emerging RESs, such as wave and tidal energy, can also be addressed in future research studies.

5) OTHER APPROACHES

Flow charts provide a visual representation of the decision-making process within the microgrid EMS. This visual aid facilitates a clearer understanding of the logic and sequence of operations for system operators and stakeholders [121], [122], [123], [124], [125], [126], [127], [128], [129], [130]. However, microgrid operations are dynamic, with varying renewable energy generation, load demands, and hydrogen systems. Flow charts, being static representations, do not easily adapt to these dynamic changes without frequent revisions, leading to potential inefficiencies. The discussed flow chart-based literature does not achieve optimal operation of the microgrid, such as optimal hydrogen consumption, minimum cost, and maximum efficiency, due to this aspect [121], [122], [125], [126], [127]. In a microgrid EMS, where optimization of energy resources is crucial, a flow chart alone might lack the sophistication needed to achieve optimal operation under various conditions. Furthermore, rule-based systems may not handle uncertainties in the system. Changes in RESs, load variations, unexpected faults, hydrogen system sensitivities, and market variations may not be adequately addressed by predetermined rules, leading to suboptimal performance.

By combining different optimization techniques within a hybrid approach, the EMS can achieve optimal resource allocation. A hybrid approach can adapt to a broader range of operating conditions and uncertainties, making the microgrid more resilient to changes in renewable energy generation, load fluctuations, system disturbances, and the integration of hydrogen systems [128], [129]. Some commonly executed hybrid approaches apply different techniques for different microgrid operating states. In these scenarios, hydrogen systems are often operated using algorithmic optimization techniques or MPC [128]. This approach enables flexibility in switching between control strategies based on current operating conditions, providing adaptability and performance optimization in diverse situations. By combining methods with complementary strengths, a hybrid approach may reduce the overall computational complexity compared to relying on a single, computationally intensive technique. Furthermore, several current studies combine metaheuristic optimization algorithms to optimize outputs to prevent being caught by local solutions.

In hydrogen storage-based microgrids, the selection of an appropriate EMS is critical due to the complex interactions between RESs, hydrogen production, storage, and load variabilities. Rule-based strategies, though simple and fast, often lack adaptability and optimality, especially under varying hydrogen generation or load demand conditions. Fuzzy logic-based EMS enhances flexibility by incorporating human reasoning, making it more robust to uncertainties in renewable generation and hydrogen loads. However, it still relies heavily on expert knowledge and lacks optimization capabilities. In contrast, heuristic and metaheuristic algorithms offer strong global search abilities to optimize hydrogen production and fuel cell operation but are computationally intensive and unsuitable for real-time control, particularly when hydrogen dynamics and degradation effects are considered. MPC stands out by integrating future forecasts and system constraints, enabling predictive hydrogen production scheduling and efficient utilization of fuel cells. Yet, it requires accurate system modeling and can be computationally demanding. Finally, uncertainty-based approaches, such as stochastic or robust optimization, provide a systematic way to handle renewable and load uncertainties, which is crucial in hydrogen-based systems due to the nonlinear behavior of electrolysers and storage tanks. However, these methods often involve high model complexity and are less suited for real-time applications. Overall, while no single EMS method is superior, MPC and metaheuristic methods show better performance in utilizing hydrogen technologies.

VI. RECOMMENDATIONS

Future research studies on microgrids and hydrogen systems can address these points.

- Forecasting renewable generation and expected demand is vital for EMS operations. However, few research studies integrate forecasting techniques into the proposed EMS. Forecasting models for solar irradiance, wind speed, wave propagation, and energy demand can contribute to better utilization of hydrogen systems, since EMS can be designed for high penetration of renewables through hydrogen systems.
- While many studies apply combined electrolyser and fuel cell systems for short-term energy storage, hydrogen's high energy density positions it as a viable option for long-term storage in microgrids. Future research should explore control strategies and EMS frameworks that effectively leverage hydrogen for seasonal or extended-duration storage.
- Most of the discussed literature has considered technical and economic aspects, such as cost and reliability, with few research studies focusing on environmental objectives, such as reducing greenhouse gas emissions, CO_2 emissions, and pollution. Future studies should consider environmental objectives, including reducing fossil fuel operations, increasing efficiency, reducing water usage, and enhancing waste management.
- Most reviewed studies prioritize cost minimization as the primary objective in EMS design for hydrogen systems. However, there is a need to incorporate hydrogen system efficiency, including conversion and storage losses, as a core performance metric. Multi-objective optimization approaches can help balance cost with improved integration of renewable energy sources.
- Almost all discussed EMS studies do not consider the temperature and pressure sensitivity of fuel cell and electrolyser systems in their objectives. Including these factors could reduce high-cost operations in hydrogen systems.
- Hydrogen has high potential as a fuel and can be utilized in FC-powered vehicle filling stations, steel and chemical plants, and building heating services. These hydrogen usage areas can be included in future research studies.
- A significant number of studies rely on simplified or static models of electrolysers, fuel cells, and hydrogen storage systems, often excluding internal losses and dynamic behavior. The review highlights the need for more realistic, physics-based models to support accurate EMS design and evaluation.
- Since electrolyser and fuel cell systems are primarily power-electronics-based devices, they lack rotational inertia, which may aggravate the low-inertia challenges already observed in systems with high RESs. Future research could investigate the impact of hydrogen integration on microgrid inertia and frequency stability, providing valuable insights into strategies for enhancing dynamic stability in hydrogen-integrated microgrids.
- Existing EMS studies primarily focus on technical and economic objectives such as cost, reliability, and energy security. Social dimensions, including commu-

nity satisfaction, energy access, and public acceptance, are rarely addressed. Integrating these social-oriented metrics into EMS design can enhance the sustainability and acceptance of hydrogen-based microgrids.

VII. CONCLUSION

This study has provided a comprehensive review of hydrogen technologies within microgrids, with a particular focus on their integration into EMS frameworks. Unlike surveys that examine electrolysers, fuel cells, and hydrogen storage in isolation, this review highlights their operational interconnections and optimization strategies. By comparing heuristic and metaheuristic algorithms, MPC, fuzzy logic, and hybrid approaches, the paper contributes a focused perspective on how EMS can improve efficiency, reduce costs, and enhance system reliability in hydrogen-based microgrids. This unique contribution addresses a gap often overlooked in the literature by linking hydrogen-specific constraints directly with EMS operation. The findings indicate that current EMS research has made notable progress but remains limited in several areas. Many studies prioritize cost minimization while paying less attention to the efficiency of hydrogen systems, environmental performance, or social acceptance. Likewise, most models simplify electrolyser, fuel cell, and storage system dynamics, often overlooking operational conditions such as temperature and pressure sensitivity, which significantly influence cost and efficiency. These gaps underscore the need for more realistic EMS formulations that strike a balance among technical, economic, environmental, and social objectives. A study addressing some of the above issues is currently underway at the School of Electrical and Data Engineering, University of Technology Sydney (UTS). The research aims to integrate the efficiency of electrolyser systems and the fuel economy of fuel cell systems into the microgrid EMS.

Future work should therefore focus on integrating renewable generation and demand forecasting, leveraging hydrogen's potential for long-term storage, and employing physics-based component models that capture dynamic behavior. Introducing environmental goals, such as lowering CO2 emissions, water usage, and waste, alongside cost and reliability, will broaden the scope of EMS objectives. Furthermore, expanding research into hydrogen applications beyond microgrid storage, including transport, industry, and heating, can position hydrogen as a central element in sector-coupled energy systems. Addressing these areas will help advance more efficient, resilient, and sustainable hydrogen-integrated microgrids.

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