Latin American Journal of Energy Research - Lajer
periodicos.ufes.br/lajer

Latin American Journal of Energy Research – Lajer (2024) v. 11, n. 2, p. 192–211
https://doi.org/10.21712/lajer.2024.v11.n2.p192-211

A review on microgrids for the distributed integration of renewable hydrogen production with the power system

Microrredes para a integração distribuída da produção de hidrogênio renovável em sistemas elétricos de potência – uma revisão

Gabriel Lucas Nascimento Silva[1,*], Danilo Pinchemel Cardoso Filho[1], Danielly Norberto Araújo[1], André Gama[2], Heloisa Althoff[3]

[1] Pesquisador pelo Centro Integrado de Manufatura e Tecnologia – CIMATEC, Salvador, BA, Brasil
[2] Gestor de Inovação, Galp, Lisboa, Portugal
[3] Engenheira de Inovação, Petrogal, Rio de Janeiro, RJ, Brasil
*Autor para correspondência, E-mail: gabriel.nascimento@fbter.org.br

Received: 30 November 2024 | Accepted: 18 December 2024 | Published online: 26 December 2024

Abstract: Technological advancements in the power system, coupled with the electrification of various sectors, decarbonization policies, and solutions for conflicting demands in the electrical sector, have driven the integration of new distributed resources, increasing the system's complexity. In this context, microgrids stand out as a new power system operational paradigm, along with hydrogen production via clean energy-based electrolysis as a promising source of alternative and renewable resources. However, there are few studies that specifically explore the potential of microgrids as a vector for large-scale distributed production of renewable hydrogen. This article provides a comprehensive review of the different power system dimensions, systematically assessing this potential. An updated overview of the most widely accepted definitions of microgrids is presented, highlighting applicable hydrogen technologies, whether to be used as a primary source, storage method, fuel, or main product. Additionally, examples of studies and projects that contribute to the technical and economic feasibility of microgrids as a means of integrating hydrogen production into the power system are discussed.
Keywords: microgrid; power system; renewable hydrogen; hydrogen production.

Resumo: *Os avanços nas tecnologias dos Sistemas Elétricos de Potência (SEP), associados à eletrificação de diversos setores, políticas de descarbonização e soluções para demandas conflitantes do setor elétrico, têm promovido a inserção de novos recursos distribuídos, aumentando a complexidade do sistema. Nesse contexto, pode-se destacar as microrredes como um novo princípio operativo nos SEP e a produção de hidrogênio via eletrólise a partir de energia limpa como uma fonte alternativa promissora de recursos renováveis. No entanto, são raros trabalhos que explorem, especificamente, a potencialidade das microrredes como vetor para produção distribuída em larga escala de hidrogênio renovável. Este artigo revisa de forma abrangente as diferentes dimensões dos SEP, avaliando essa potencialidade de maneira sistemática. Um levantamento atualizado das definições mais difundidas de microrredes é apresentado, destacando-se tecnologias de hidrogênio aplicáveis, seja para uso como fonte primária, método de armazenamento, combustível ou produto principal. Além disso, são mencionados exemplos de trabalhos e projetos que contribuem para a viabilidade técnica e econômica de microrredes como meio de integração da produção de hidrogênio aos SEP.*
Palavras-chave: microgrid; power system; renewable hydrogen; hydrogen production.

1 Introduction

Historically, power systems were conceived and developed according to a paradigm of large-scale centralized generation, with unidirectional power flows to the load centers. In recent years, however, due to growing technological disruptions and associated environmental concerns, this approach has been losing ground to new generation, transmission, distribution, and consumption strategies (Majeed Butt et al., 2021). In this sense, trends such as distributed generation (DG), intermittent sources, widespread application of power electronic converters, or the introduction of responsive Intelligent Electronic Devices (IEDs) can be highlighted (Arcia-Garibaldi et al., 2018), (Souza Junior and Freitas, 2022), (Muhammad et al., 2020), (Dashti and Rouhandeh, 2023).

Although these new elements are poised make the system more flexible, efficient, reliable and susceptible to higher penetration levels of renewable resources, they can also lead to difficulties, as the operational complexity of the interconnected gird increases (Perez, 2020). Without application of proper control frameworks or the restructuring of the grid's core operational paradigm, such complexity could weaken the network and hinder the economic and technical viability of operation and expansion. Several research efforts are underway to harmonize technical, economic, and environmental aspects, going hand to hand with the creation of new regulations and incentives, whereas, among the most promising technologies explored so far, microgrids and hydrogen (H_2) stand out as appealing alternatives (Arcia-Garibaldi et al., 2018), (Muhammad et al., 2020).

Most essentially, microgrids can be treated as subsystems with local regulation capabilities, which can operate both connected or isolated from the main grid, promoting modularly into the power system (Saeed et al., 2021), (Ton and Smith, 2012). Their application aims to make the operation of distribution networks more flexible, which could increase the overall absorption capacity of alternative energy sources. Furthermore, microgrids enable more active participation of local agents, allowing dynamic participation in energy trading and system stabilization, with distributed controls to regulate voltage, frequency, and manage connections, disconnections, and faults.

In turn, H_2 is already wildly applied in markets that do not directly overlap with the electricity sector or power system-related production and operation chains. However, H_2 has been identified as a promising resource in this sector, as it can be used as a primary source to generate electricity (e.g., through fuel cells or combustion generators) or a product derived from the consumption of electrical energy (e.g., through electrolyzers) and delivered to serve other applications (Ton and Smith, 2012), (Ferreira et al., 2021), (Hassan et al., 2023). In this context, the concept of "Green Hydrogen" has been put forward and is gaining prominence, as it refers to hydrogen production via electrolysis primordially based on renewable energy (EPE, 2021).

Henceforth, a promising approach for H_2 assimilation into the power system is through distributed integration via microgrids that incorporate different types of hydrogen technologies in their composition (BloombergNEF, 2020). This can occur, for example, through H_2-based generators or even energy storage systems, deployed to smooth the operational profile in sites with high intermittency or mismatches between prime generation and consumption periods. Additionally, H_2 can follow the DG paradigm and be produced in a distributed fashion, to be then stored and exported, serving as inputs in other applications, such as in the transportation sector, energy reserves, or chemical industries (BloombergNEF, 2020), (Rasul et al., 2022), (Muhammed et al., 2023).

Given all the discussed, this work's main objective is the presentation of a systematic review regarding microgrids, hydrogen, and their integration, considering different critical power systems dimensions. More specifically, given the lack in the current established literature, H_2 production-related applications are highlighted, so this review can serve as a starting point for new researchers specifically focusing on this approach. The remainder of this paper is structured as follows: Section 2 presents an overview of microgrid classifications, primary aspects, and components, whereas H_2 specific technologies are described in more detail; Section 3 provides a review of different technical, economic and regulatory aspects of hydrogen production integration with the power system; Section 4, highlights some case studies related to hydrogen production plants through water electrolysis; and Section 5 presents the conclusions and closing remarks.

2 Microgrids fundamentals overview

There is still no universally adopted formal definition of the microgrid concept in the literature. Different propositions have been put forward, whereas one of the most widely recognized was established by the United States Department of Energy, which states that a microgird is "an energy distribution system with distributed energy sources and loads, associated control and storage capabilities, that can operate in interconnected mode with the main grid or in isolation, if necessary" (Saeed et al., 2021). From the interconnected power system perspective, a microgrid can be understood as a dispatchable unit, capable of contributing to frequency regulation, load balancing, and meeting operational requirements (Sepasi et al., 2023).

From the end-user perspective, the microgrid increases energy supply reliability, improves local voltage stability, and reduces energy losses (Zhou et al., 2015). The diagram in Figure 1 represents integration between the essential dimensions composing a microgrid. Some possible elements that can be deployed to implement each highlighted functionality are illustrated, whereas devices typically reliant on static conversion interfaces are outlined. The figure also differentiates electrical and data/control connections, emphasizing the importance of the communication infrastructure.

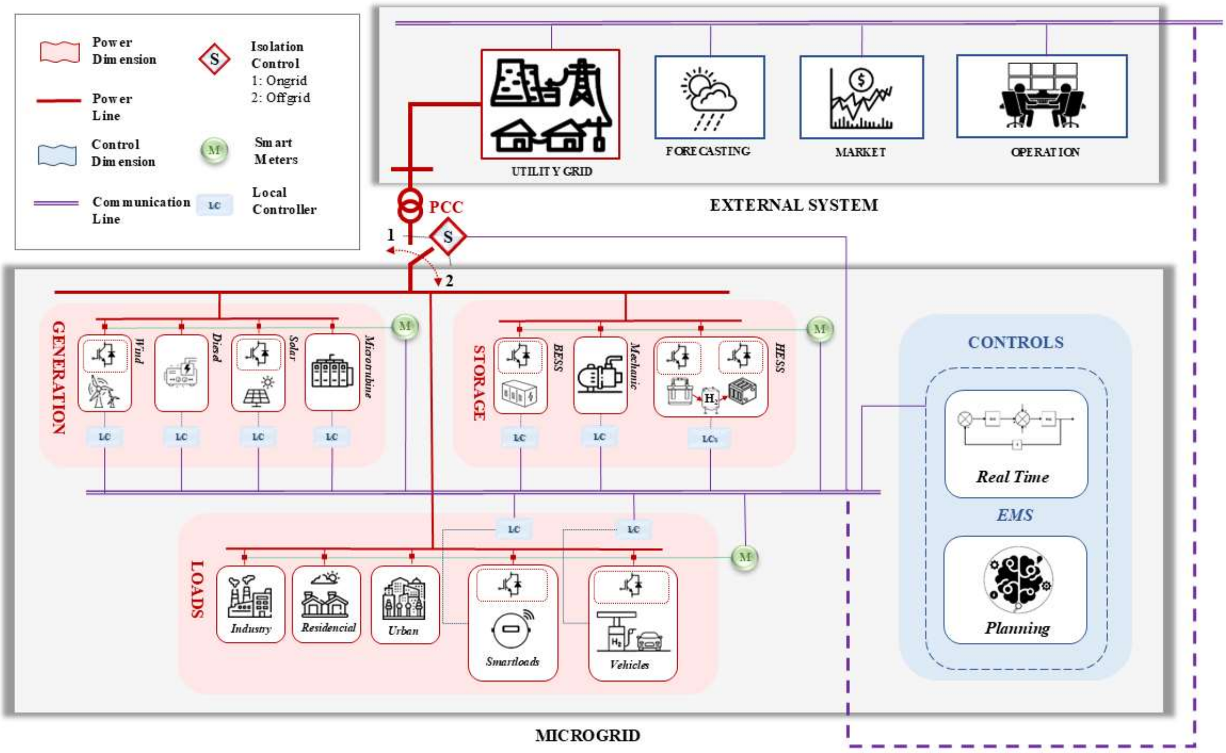

Figure 1. Generalized Composition of a Microgrid.

A microgrid, in great measure, is defined by its ability to toggle between interconnected and isolated operation, which implicates a Point of Common Coupling (PCC) with the main network is necessary, as made explicit in Figure 1. A PCC is the electrical connection point in which remote-controlled circuit-breaking/switching devices allow for decoupling (open state) /coupling (close state) between the microgrid inner circuits and the external grid, whereas application of static switching strategies is conceivable. Also, to be considered a microgrid, the system must be capable of autonomously manage transitions between islanded and connected states without compromising the stability of the external grid or the continuity of supply to local loads (Abbasi et al., 2023).

Furthermore, other essential features of microgrids include the presence of integrated energy storage systems, due to the need for stabilization in islanded mode, control of power flow through the PCC in connected mode, and integration of distributed generation, especially intermittent renewable sources (Shahzad et al., 2023). Note that the stabilization and power flow regulation can be aided by demand-side control, whereas loads can be hierarchized into critical and non-critical, allowing the microgrid to prioritize continuous supply to the critical loads in contingency situations, thereby increasing the system's robustness and security (Hossain et al., 2019). Additionally, microgrid operation is highly dependent on proper definition and implementation of its dynamic control architecture, which must adequately respond to demands and operational conditions. Among the possible applications, centralized control approaches have been seen as an appealing solution, to the degree Microgrid Central Controller (MGCC) devices became widely referenced in the literature, establishing a field of research in itself (Shukla and Pandit, 2021; Uddin et al., 2023; refer to MGCC-specific references).

As suggested by Figure 1, multiple microgrids categories can be derived as each implementation focuses on different types of devices (based on a myriad of operation principles and technologies), arrangements, control modes, and targeted applications, whereas each combination adopted yields different systems classes. Typically, classification of microgrids considers factors such as size, control philosophy, load types, application, technological composition, circuit topology, location, and integration with the grid (Uddin et al., 2023; Dagar et al., 2021; Kanakadhurga and Prabaharan, 2022; Williams et al., 2023; Hirsch et al., 2018). Several studies have already proposed complementary classification schemes (Saeed et al., 2021; Shahzad et al., 2023; Abbasi et al., 2023; Shukla and Pandit, 2021; Shahgholian, 2021; Altaf et al., 2022), each with approaches tailored to their specific objectives.

Therefore, the following topic highlights a compiled classification map tackling multiple discernible aspects. Further, an overview of basic working principals of both typical components necessary for microgrid implementation and basic integration features required for the operation of the system as a whole is presented, whereas H_2-related technologies are discussed in more detail at the end of the section.

2.1 Classifications

Typically, unified compilations of basic concepts, classification, control schemes, and simulation aspects of microgrids are not addressed together in a single work (Uddin et al., 2023). As examples, (Hossain et al., 2019; Ahmethodzic and Mustafa Music, 2021; Shahgholian, 2021) present recent and comprehensive overviews of various related themes. In this sense, considering its wider scope, the classification framework proposed by Uddin et al. (2023) is adopted as a basic reference, to be complemented and expanded. The following topics discuss each dimension of microgrid classification in accordance with what is presented in Figure 2, whereas additional remarks are highlighted when relevant.

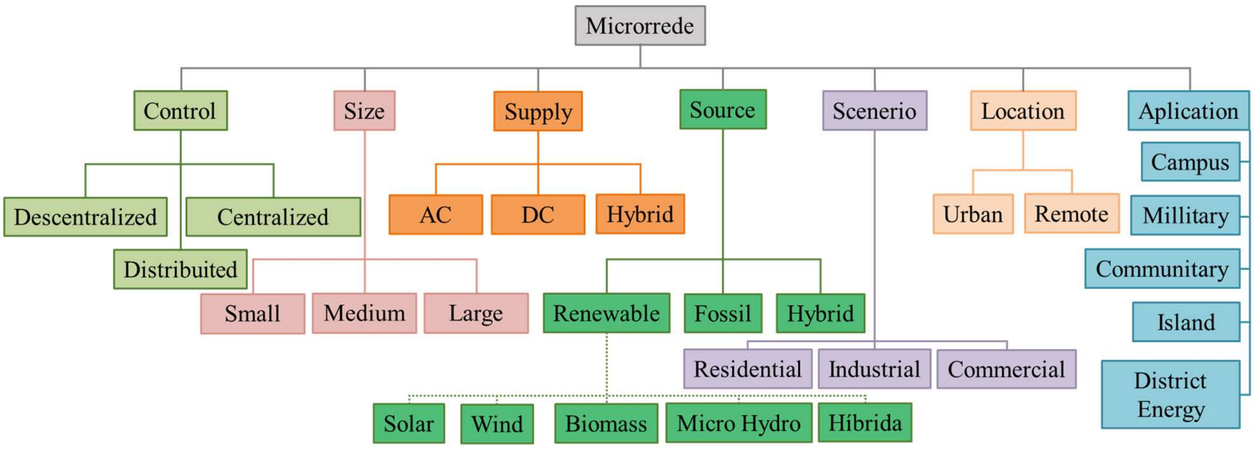

Figure 2. Reference Diagram for Microgrid Classification. Source: Adapted from Uddin et al. (2023).

2.1.1 Control paradigm

An appropriate control strategy is essential to achieve and maintain voltage and frequency stability, power balance between distributed generators and loads, manage transition between operational modes, and guarantee adequate energy exchange with the distribution network. Additionally, dispatch optimization can promote economic and energy efficiency (Perez, 2020; Uddin et al., 2023; Bihari et al., 2021; Ali and Kumar, 2021; Ahmad et al., 2023; Ahmed et al., 2020).

To accomplish these aims, different control frameworks can be defined, typically categorized as centralized, decentralized, or distributed (Ahmethodzic and Mustafa Music, 2021). In the first case, a single controller centralizes all monitoring information about the system and concentrates all decision-making processes related to distributed generation units and other controllable elements (Ahmed et al., 2023). In turn, the second strategy can still use a central controller, but much of the measurements, monitoring and processing is attributed do local devices, which require fewer connections and reduces the need for high computational capacity and communication bandwidth (Ahmed et al., 2020). At last, the third alternative resembles more of a pear-to-pear paradigm, in which information is shared horizontally among controllers, enhancing the performance and reliability of the system (Espina et al., 2020); this approach must be predicated on more sophisticated consensus-based algorithms.

2.1.2 Size

Regarding their size, microgrids are typically classified into three ways: small (less than 10 MW), medium (10 MW to 100 MW), and large (greater than 100 MW). Small-sized microgrids are used to supply energy to residential buildings, small regional electric grids, islands, and remote areas. In turn, medium-sized can be applied in factories and industrial zones. Large-scale microgrids, can generate electricity to encompass whole areas with large-scale industries (Uddin et al., 2023).

2.1.3 Supply

Microgrids can also be classified according to whether the electricity flowing through the local circuits and the end-use devices' connection terminals are supposed to be in alternating or direct form, which, in turn, can yield AC, DC, or AC/DC (hybrid) microgrids. AC microgrids allow for simpler and more straightforward connection and synchronization to traditional networks without special requirements (Hossain et al., 2019).

Further, the distribution system of an AC microgrid can be subdivided into single-phase or three-phase, with or without a neutral point conductor, and also be classified based on its frequency, that is: high, low, and standard (Dagar et al., 2021). Regarding DC microgrids, energy is supplied directly in its DC form. This can be advantageous, since DG and storage technologies are often predicated on DC primary sources, which could be connected directly through a local DC bus, dispensing with output terminal inverters. However, coupling with the existing external grid would require larger converters interfaces to handle all power flow at the PCC (Hossain et al., 2019; Uddin et al., 2023). A DC microgrid distribution network can be further classified into three types: monopolar, bipolar, and homopolar. Finally, hybrid microgrids combine AC and DC sections in the same local circuit, leveraging the benefits of both architectures. This flexibility allows for optimized usage of available energy resources (Dagar et al., 2021).

2.1.4 Energy sources

Energy sources can also be used to distinguish between microgrids, yielding three fundamental categories: renewable, fossil fuel, and hybrid microgirds. A system is deemed renewable when it exclusively utilizes renewable resources (e.g., wind, solar, hydro, biofuels) as its primary energy source. In these microgrids, fast-response electrical energy storage systems, such as battery energy storage systems (BESS) are commonly applied to circumvent problems associated with intermittence (Uddin et al., 2023; Bihari et al., 2021).

In turn, fossil fuel-based microgrids produce electricity through generators that utilize natural gas or diesel, making them more common in remote regions and islands. Although easier to plan, operate and to realize long-term energy storage simply through the maintenance of a fuel reserve, they come with negative environmental impacts and higher operational costs (Uddin et al., 2023). On the other hand, hybrid microgrids combine various sources, including fossil fuels, renewable sources, and batteries. This approach aims to take advantage of fossil fuels-based generation for grid controllability and stabilization while still maximizing the usage of renewable resources, thereby reducing costs and environmental impacts (Rangel et al., 2023).

2.1.5 Consumption class

Another feature sometimes used to differentiate between Microgrids are the consumption profiles, which typically encompass three categories (cited from largest to smallest demand group): industrial, residential and commercial. Steady electricity supply is crucial for various processes in industrial environments, such as metal production, oil refining, and manufacturing of chemicals, cement, and pulp. Therefore, enhancing the security and reliability profiles are key factors for implementing microgrids in industrial applications, as interruptions can lead to significant losses and prolonged downtime. In turn, residential microgrids are designed to meet the needs of homes seeking to integrate local generation and support new loads (Kanakadhurga and Prabaharan, 2022; Hirsch et al., 2018), whereas commercial clients, such as airports, hospitals, and data centers, also turn to microgrids to meet a variety of requirements, including heating, cooling, lighting, and powering electronic devices (Uddin et al., 2023; Williams et al., 2023).

2.1.6 Application

The implementation of a microgrid depends on the specific energy requirements of consumers and the infrastructure available in the region where it will be installed (Hirsch et al., 2018). In this sense, Microgrid applications can be classified into five categories: campus/institutional, military, community, islanded, and utility. Campus/institutional microgrids are designed to serve corporate, government, university, and college facilities, typically requiring a moderate level of reliability in energy supply and a high quality of service (Hossain et al., 2019; Hirsch et al., 2018). In contrast, military microgrids are small-scale electrical infrastructures that operate almost autonomously, ensuring a secure and reliable energy supply (Shahzad et al., 2023; Uddin et al., 2023).

Community microgrids emerge as an alternative to provide electricity to remote rural areas, often disconnected from the conventional power grid. Electrification in these regions is slow due to geographical and economic barriers, leading to reliance on diesel generators, whereas hybrid systems can present a solution, integrating renewable sources as a complement to fossil fuel-powered generators (Hossain et al., 2019). Islanded microgrids are self-sufficient, generating their own electricity and being entirely disconnected from the main grid, while district energy microgrids provide thermal and electrical energy to various facilities (Uddin et al., 2023).

2.1.7 Location

At last, microgrids can be classified by as urban or remote, depending on their location. Urban microgrids are typically connected to an electrical distribution network, enabling them to inject or receive energy from the main grid through a point of interconnection. They can also operate as isolated microgrids during contingency or instability scenarios, when there is degradation in power quality, outages or scheduled maintenance in the main distribution network.

This type of microgrid can be implemented in both residential settings and commercial facilities, such as hospitals, data centers, communities, industries, and shopping malls. On the other hand, remote microgrids are established in areas where a utility does not provide power due to geographical reasons, such as military installations, islands, and mountainous regions. For geographically isolated communities and developing countries, remote microgrids emphasize distributed and diverse energy sources (Hossain et al., 2019; Uddin et al., 2023).

2.2 Primary aspects and components

The various classifications discussed so far point to the possibilities of overlap between the multiple dimensions of microgrid, which results in systems with specific features and capabilities combinations. Hence, this section aims to characterize the essential proprieties of their potential technological compositions, which also encompasses aspects related to planning, operation, control, communication, and protection.

2.2.1 Generation sources

Electricity is produced through the transformation of a primary source of energy, whereas there are many resources that can be explored, each depending on different possible technological arrangements to enable conversion, and which can be classified as renewable or non-renewable (De Barros et al., 2014; Pinto, 2014). Renewable energy is generally defined as a resource that regenerates in nature (e.g., solar, wind, hydro, biomass), whereas non-renewable are those which are exhaustible (e.g., coal, petroleum) (Marques et al., 2022). Table 1 briefly summarizes energy sources commonly found in microgrids, also indicating basic conversion principles and technologies can be deployed to attain electricity generation.

Table 1. Energy sources for conversion into electricity within the context of microgrids.

Source	Basic Principle	Conversion technologies
Solar	Solar radiation that reaches Earth's atmosphere is split into reflected and absorbed portions (Von Schuckmann et al., 2020), whereas some of the energy that could be absorbed by the planet's surface is converted into electricity though different applicable techniques.	Photovoltaic panels; solar thermal collectors; solar concentrators.

Wind	Kinetic energy of an air mass is converted into rotational energy in an axis, which is coupled with the prime mover of an electromechanical conversion system to produce electricity from the wind (Vian et al., 2021).	Horizontal axis wind turbine (WT); vertical axis WT; offshore WT; small WT; floating turbines; traditional windmills.
Fuels	Chemical energy stored in a fuel (be it a fossil or a biofuel) is released, primordially through combustion, and the heat obtained from the process is converted into electricity through thermodynamic cycles, with a thermomechanical circuit coupled to a generator, yielding different forms of thermal generation. (Kanakadhurga and Prabaharan, 2022), (Göksel, 2022).	Diesel generator; steam turbine; gas-steam combined turbine; internal/external combustion engine.
Hydrogen	Hydrogen is a highly flammable, odorless gas, with an energy density greater than conventional fuels (Azad and Khan, 2021; Da Rosa, 2012) and could be used in similar fashion to them. However, the chemical energy stored in its molecules can also be converted into electricity directly and statically, through a controlled electrochemical reaction.	Fuel cell; internal combustion engine.
Biomass	The conversion of the chemical energy contained in biomass, such as wood, to obtain electricity occurs primarily through technologies based on thermodynamic cycles (Ciotta, 2023).	Gas turbine; steam turbine; gas-steam combined turbine.
Hydropower	Kinetic energy from an inflowing water mass (be it from a horizontal stream, falling stream, tide or wave), is converted into mechanical energy for the prime mover of an electromechanical conversion system to produce electricity. Note that it is possible and convenient to store energy in the form of water potential in a reservoir, whereas both total water mass and waterfall heights are relevant (Pinto, 2014).	Pelton turbine; Francis turbine; Kaplan turbine; Bulb turbine; tidal power; wave power.

2.2.2 Loads

Any device, equipment, or machinery that consumes electrical energy is considered to be load, whereas billable units or sets of units (e.g., commercial buildings, hospitals, urban areas connected through the same feeder) can be seen as loads from the grids' perspective. Ultimately, the end goal of any power system is to supply all of its load adequately over time. In the context of microgrids, it is common to categorize them regarding three main features: consumption, importance, and response.

Consumption refers to the size, rates and the demand profiles over time, including residential, commercial, and industrial facilities (Kanakadhurga and Prabaharan, 2022). In turn, importance indicates if a given load is meant to be treated as critical (e.g., hospitals, essential services, gas and fuels) or non-critical (e.g., residences, commercial air-conditioning) (ANEEL, 2020), with the latter being preferentially curtailed in the case of contingencies. In addition, the responsiveness of a load is related to whether it is a merely passive load or a 'smart' one, which allows for control over the demand requested, modulating is operation as if it was a dispatchable asset; this feature usually depends on embedded integration with power converter interfaces. On the other hand, traditional or non-responsive loads have a fixed or uncontrollable demand requirement, with no communication feedback between the energy supplier and the consumer (Kanakadhurga and Prabaharan, 2022).

2.2.3 Energy Storage Systems (ESS)

The increasing integration of renewable and distributed generation has significantly impacted power systems' operational profiles, in great part, because those resources tend to be characterized by their intermittency, which makes the network operation more unpredictable and complex (Kroposki et al., 2017). Another major issue is that the interconnected grid was originally designed to be regulated through dynamic modulation of high-inertia synchronous machines. However, alternative energy sources often depend on power electronic-based converter interfaces to connect with the network. Converters provide low to no inertia, as well as limitations on short-circuit current and reactive power, and can introduce harmonics, which could compromise the systems' stability, protection schemes and energy quality (Ciotta, 2023). One of the main approaches to mitigate these issues is the incorporation of energy storage systems, whether based on hydrogen storage, batteries, supercapacitors, or pumped hydroelectric plants, for example (Ciotta, 2023; Hu et al., 2017; Greener, 2021). Each storage technology can be more or less adequate for resolving either of both the generation-consumption periods mismatches or the provision of controllable and fast responses needed to ensure system stability. Note that these functions are particularly important in the context of a microgrid, which often deploy some form of Battery Energy Storage System (BESS), due to their operational flexibility and ease of implementation.

A BESS consists of a battery bank, fire extinguishers and sensors couple with battery monitoring, power conversion, and energy management systems (Saadat, 2011), being often used as a primary energy source to provide short-term energy supply. In isolated microgrids, it overcomes the barriers posed by intermittent resources, such as solar and wind, by charging when there is excess generation and discharging otherwise (Peyghami et al., 2019; Liu et al., 2022). Additional applications, such as ancillary services provision, frequency support, or voltage regulation are also relevant and presented in more detail in (Greener, 2021; Liu et al., 2022; Jena and Rajanarayan Prusty, 2014; Conejo and Baringo, 2018). Alternatively, BESS-related functions can be provided by a Hydrogen Energy Storage System (HESS), which stores electricity in the form of hydrogen gas, instead of electrochemical potential. For such, the system must be composed of three stages: hydrogen production (electrolyzer); storage (compressor and tank); and recovery stage, typically a fuel cell (i.e., the hydrogen could also be turned back into electricity if used as a fuel in a generator). Analogous to the BESS, HESS also depends on power conversion systems, energy management systems, and auxiliary components (Diaz, 2020; Hossain et al., 2023; Smolinka et al., 2015). The following section discusses basic hydrogen-related technologies in more detail.

Other examples of relevant energy storage technologies are supercapacitors, which encompass some features of both batteries and capacitors. Those are electrochemical devices composed of two electrodes separated by a dielectric medium, storing energy in the form of an electrostatic field. Although presenting low energy density, they can handle high currents for short periods of time (Das et al., 2022; Banerjee et al., 2020; Mitali et al., 2022; Li et al., 2024). In turn, reversible hydroelectric plants reuse turbines' water outflow to replenish a hydroelectric power plant's reservoir by pumping the used water back upstream, preferably by pumps powered by excess renewable energy. (Mensah, 2020; Souza Cruz et al., 2022).

2.2.4 Converters

Power electronic-based interfaces are utilized in various power system applications, such as static compensators, high-frequency transformers, high-voltage DC links, inverters, rectifiers, static disconnection switches, among others (Hart, 2011; Hirsch et al., 2018). The controlled conversion of any electrical quantity (DC or AC) into another desired waveform is their most fundamental function and the one with the greatest impact, as it relates to application of one or more DC ↔ DC, DC ↔ AC, or AC ↔ AC transformation stages to couple different primary sources or loads to a synchronized interconnected system. Note that, regardless of application, all these converters rely on the same technological principle, that is, fast-switching semiconductor devices in which the toggling between conduction and cutoff states is controlled by external logic signals, as in thyristors, IGBTs, MOSFETs. In the context of microgrids, converters are ubiquitously used due to widespread application of converter-interfaced resources (e.g., alternative energy generation, BESS/HESS, controllable loads), and also as coupling elements deployed to link DC and AC sections of a microgrid, realize soft-open points, or promote PCC connections that allow for greater power flow controllability (Souza Junior and Freitas, 2022).

2.2.5 Operation and planning

A microgrid can operate either in connected (on-grid) or isolated (off-grid) modes (Berry, 2022). The on-grid mode is preferred when the microgrid composition leads to highly uncertain generation profiles. When in off-grid mode, operational management becomes essential to meet the planning needs (Jirdehi et al., 2020). Is this regard, energy management is crucial, as it relates to forecasting, scheduling and availability constraints of the assets deployed.

Furthermore, selection of an adequate control framework to regulate dynamic operation, given different scenarios and contingencies, is necessary, especially with respect to the control and coordination paradigm enabled throughout the converter interfaces in the system. For example, when on-grid mode, the voltage and frequency references are typically maintained by the external network at the PCC and all converter-interfaced resources can operate as Grid Following (Gao et al., 2022). However, when off-grid mode, Grid Forming devices (i.e., which could be grid forming generators) must regulate and coordinate the microgrid to guarantee the internal frequency and voltage are stable, and that the total supply and demand are balanced (Lima, 2022).

The planning of a microgrid involves determining a feasible and preferably optimized selection of active elements and their respective dispatch levels, considering more extensive future horizons, before their practical implementation (Guoping et al., 2018; Arcia-Garibaldi et al., 2018). Planning can be addressed from three perspectives: actors in the energy distribution system (government and regulation); resources and assets (energy sources, infrastructure, control, protection, and human resources); and distribution network procedures (order, organizational and budgetary aspects). Robust microgrid planning utilizes optimization techniques, considering technical and economic aspects to minimize the total cost of configuration and sizing (Mina-Casaran et al., 2021).

2.2.6 Managing and control

Energy management systems are fundamental in microgrids with multiple sources and/or energy storage systems, enabling optimized energy sharing for efficient, reliable, and cost-effective operation (Hanna et al., 2022). Energy management involves optimizing distribution considering various objective functions and constraints, such as operational cost, emissions, and revenues. The management system can use hierarchical control structures to optimize resources, applying setpoints calculated by real-time forecasting algorithms (Jirdehi et al., 2020; Ahmad et al., 2023). The forecasting horizon is classified into different timeframes, ranging from very short to long, to meet specific control and scheduling needs (Saadat, 2011).

As discussed, voltage and frequency stability are crucial features in microgrids, and their provision can modulate both active and reactive power dynamics. Abrupt load variations or generating losses, along with high transmission losses, harmonics or poor power factors can compromise the system operation. To maintain stability, it is essential to apply control feedbacks that regulate and coordinate different resources in the microgrid, particularly in the case of converters, so that they respond with the necessary compensations when deviations form desired operational zones are observed. There are different control techniques for each microgrid operational mode (Nithara and Anand, 2021), whereas control hierarchies can be divided into three types: primary, secondary, and tertiary, each playing distinct roles in energy stability and quality (Ahmethodzic and Mustafa Music, 2021; Uddin et al., 2023; Ahmed et al., 2020).

2.2.7 Communication

Effective application of a microgrid's integrated controls schemes depends on communication infrastructure for data and commands transfer between its various components. This is commonly implemented to ensure monitoring of critical variables and statuses through supervisory systems, the coordination of distributed resources local controllers, and the connected loads and meters.

Reliable and sufficiently low latency data links are required for both proper functioning of devices and the rapid restoration after failures, as well as for improving stability during islanding incidents (Ahmad et al., 2023; Kundur and Malik, 2022). The communication physical layer relates to the transmission medium and associated protocols (e.g., twisted pair cable, optic fiber, coaxial cable, radio waves, microwaves, Ethernet, Wireless), which are responsible for sending/receiving the signals encapsulating information exchanged between controllers and different management systems (Kundur and Malik, 2022; Kumar, 2019; Hanna et al., 2022). Hence, over this communication network, different communication architectures and protocol stacks can be applied, defining a set of reference rules and standards so that the interconnected devices can exchange useful, timely and auditable information (Abbasi et al., 2023; Aghmadi et al., 2023; Kumar, 2019; Jha, 2021). Common standards used in the electric sector include IEC 61850, IEC 60870, Modbus, among others.

2.2.8 Protection

The protection of a microgrid is highly case-specific, since it is sensitive to the type of architecture (DC, AC, or AC/DC) and the topology (radial or ring) implemented. Additionally, the operating modes should also be considered, among several other aspects that must be addressed when conceiving and implementing a protection scheme. Comprehensive discussions regarding the challenges of microgrid protection, tailored to each specific system, along with their respective boundary proposals, can be found in the following: Dagar et al. (2021), Altaf et al. (2022), Kumar (2024), Patnaik (2020), Muhammed et al. (2023), Saadat (2011), Kundur and Malik (2022), and Peyghami et al. (2019).

2.3 Hydrogen technologies highlights

Hydrogen is a gas with a higher energy density than conventional fuels (per mass), making it a valuable raw material and a potential energy source to be integrated into the power system. For example, it can serve as a vector for storing excess renewable energy production, promoting the low-carbon energy transition. The main technologies needed for its integration with the power system include fuel cells, electrolyzers, and different storage techniques, such as high-pressure cylinders, cryogenic tankes and hydrogen carrier materials (Muhammed et al., 20233). In this sense, as clean hydrogen production technologies develop, widespread connection of fuel cells and/or electrolyzers into the power grid are gaining prominence in several countries, as part of their long-term energy and network expansion strategies (ANEEL, 2020).

Fuel cells convert chemical energy directly into electrical energy and are described as galvanic devices, consisting of a cathode, an anode, and an electrolyte material between them, with a membrane to guarantee free electrons can't flow through the electrolyte. Fundamentally, power is generated through the induction of an external terminal current between cathode and anode, as H_2 fuel is fed into the cell and internal chemical reactions lead to a corresponding flow of hydrogen ions through the membrane, as illustrated in Figure 3. Because of the direct conversion of chemical energy into electrical energy without intermediate thermal processes, fuel cells are not subject to thermodynamic cycles (Da Rosa, 2012). They are distinguished by the type of material used in the construction of their cell's elements, which determines its operating proprieties and limits. Note that the fuel cell principle can be applied with other fuels, such as ethanol, or methanol, whereas there are more or less appropriate construction set ups for each application (Abdelkareem et al., 2021).

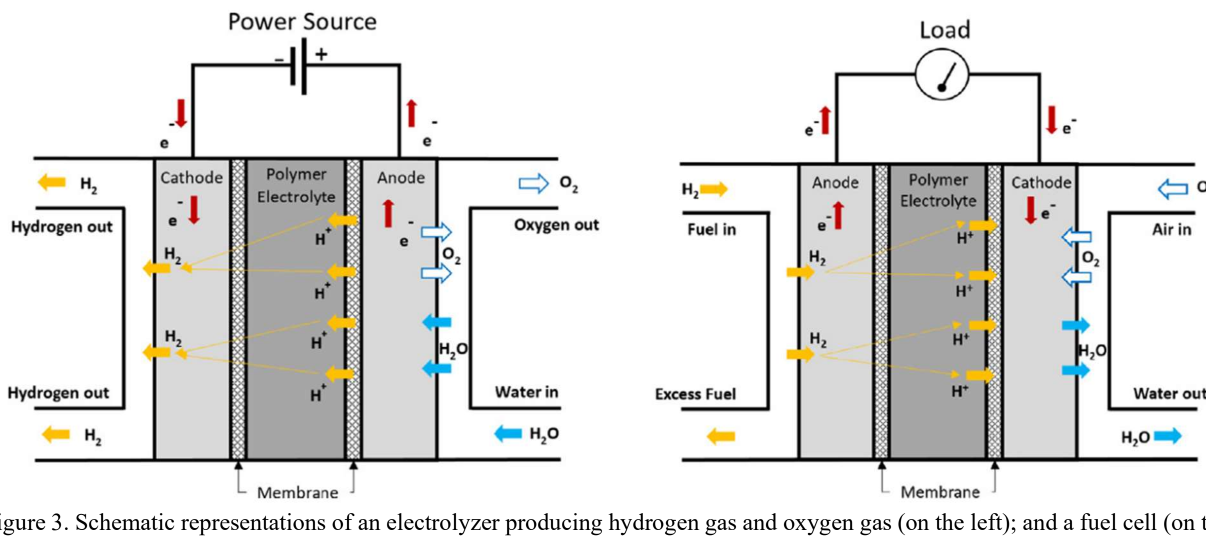

Figure 3. Schematic representations of an electrolyzer producing hydrogen gas and oxygen gas (on the left); and a fuel cell (on the right) consuming hydrogen and oxygen to produce electricity. Source: Alshehri et al. (2019).

Fundamentally, the operating principle of an electrolyzer is also based on an element analogous to a fuel cell. However, in this case, the input is a current induced by a source, which leads to internal chemical reactions causing water molecules to break down (for a water electrolyzer), which, in turn, releases H_2 as a byproduct. That is, when there is application of a sufficiently high DC voltage across the terminals of the cell stack (i.e., capable of overcoming the voltages induced by the reversible and irreversible chemical processes associated with water decomposition) (Khalid Ratib et al., 2024), a forced current circulates leading to reactions that release H_2 and O_2, matched up with hydrogen ions flowing within the cell (He et al., 2024; Lebbal and Lecœuche, 2009). Figure 3 also illustrates an electrolyzer working principle.

In the context of microgrids, hydrogen production through water electrolysis has emerged as a promising alternative to mitigate intermittency, with surplus energy generation being stored in a hydrogen tanks (Agbossou et al., 2004; Monforti Ferrario et al., 2020). However, the recovery through fuel cells faces economic challenges, especially when compared to batteries (Diaz, 2020). While hydrogen is more efficient in providing energy over medium and long periods, batteries excel in short-term supply (Hossain et al., 2023; Smolinka et al., 2015). Therefore, aiming to identify existing strategies for integrating hydrogen as an energy storage medium, it is worthwhile to explore authors who present strategies for the production, storage, and final use of hydrogen for re-electrification. As examples, Hossain et al. (2023) compares energy management strategies in microgrids with batteries and hydrogen as energy storage mediums, prioritizing supply based on duration. Surplus energy is directed to the electrolyzer for hydrogen storage, while shortages are supplemented by fuel cells. Smolinka et al. (2015) analyze HESS, its control strategies, and performance, focusing on the architecture for hydrogen production, compression, and electricity generation. An energy management system integrates the HESS and other systems, ensuring the stability of the microgrid. Aspects of hydrogen production and specificities on different hydrogen storage technologies are discussed in Da Rosa (2012), Monforti Ferrario et al. (2020), Smolinka et al. (2015), and Arsad et al. (2022).

3 Hydrogen production in power systems

Most fundamentally, H_2 can be integrated to the power system by importing hydrogen from other sector and using it as an energy source for electricity generation; by producing H_2 through the consumption of electrical energy, meant to be exported; or by the introduction of closed H_2 production-consumption cycles within the system, aimed at improving its operation. In this sense, H_2 produced from electrolysis using renewable sources can be used for various purposes, which, in the literature, are typically referred to in accordance with the following categories (Hassan et al., 2023): *Energy-to-energy*, when hydrogen is produced, stored and subsequently re-electrified by a fuel cell; *Energy-to-gas*, when the produced hydrogen is directly mixed into the natural gas system or converted into synthetic methane; *Energy-to-fuel*, when the produced hydrogen is used by fuel cell electric vehicles, as well as being converted into ammonia for ship fueling; and *Energy-to-feedstock*, when the hydrogen produced from renewable sources is used as a raw material for the production of chemical compounds and synthetic fuels.

Note that non-renewable sources can be used in the production of hydrogen (whether by electrolysis powered through non-renewable energy or chemical reformation of another product, such as coal). To differentiate between H_2 obtained from each alternative, certification methods have been developed. Different classifications are being implemented, considering the carbon content emitted and the presence of technologies for carbon emission elimination, among other factors (Ferreira et al., 2021). Although no universally accepted standard regarding hydrogen classification was identified in the literature, a color code system based on the origin and production methods has been widely used, whereas detailed descriptions of widespread hydrogen color types can be found in EPE (2021). What is typically referred to as green hydrogen, can be generally understood as H_2 produced by water electrolysis directly or indirectly powered by renewable sources, with no direct carbon dioxide emissions (Ferreira et al., 2021).

In the Brazilian context, electric sector's regulatory agencies established specific definitions, such as 'hydrogen from partially renewable sources' or 'hydrogen from renewable sources' (CCEE, 2022). The first corresponds to any hydrogen quota produced by water electrolysis in which the electrolyzers consume power directly from the National Interconnected System (NIS), without proof of a Power Purchase Agreement (PPA[1]) or self-production. The proportion of renewables is considered equal to the system's generation sources composition when the hydrogen is produced. Complementary, 'hydrogen from renewable sources' corresponds to any hydrogen quota produced with proof of a PPA or renewable self-production to cover for the energy consumed by the electrolyzer during production hours. Note that renewable energy is defined as energy derived from non-fossil sources, which include wind, solar, geothermal, tidal energy, wave energy, and other oceanic forms, in addition to hydropower, biomass,

[1]PPA is a long-term energy trading contract. Thus, it is a document made between an energy producer and a consumer. The goal is to establish all the guidelines for the purchase and sale of this resource.

landfill gases, wastewater treatment, and biogas (CCEE, 2022). Furthermore, law 14.948/2024 established the National Policy for Low Carbon Hydrogen, formalizing some hydrogen-related definitions in the Brazilian context (Brazil, 2024), such as: *renewable hydrogen*, which is characterized as low carbon emission hydrogen, collected naturally or generated from renewable sources (i.e., this includes reformed biomass, ethanol, and other biofuels, as well as renewable energy-powered water electrolysis, as previously discussed); and *green hydrogen*, which specifically refers to hydrogen produced exclusively by renewable energy-powered water electrolysis.

Regardless of classifications, there is an increasing pressure for countries to modify their respective hydrogen production chains to prioritize renewable methods, so that hydrogen becomes an integrating agent in sectors that need to be decarbonized (Li et al., 2022; Muhammed et al., 2023), whereas, in Brazil, the main objective is to meet Paris Agreement's Nationally Determined Contributions[2] targets (GOV, 2020; Lagioia et al., 2023). Further, the current paradigm of large-scale renewable hydrogen production to meet both local and external demands should be contrasted with centralized and distributed electrolyzer insertion into the power system as a large-scale green hydrogen production pathway. In this sense, some authors present studies on microgrids for hydrogen production, where electrolyzers are assessed as essential loads in the system, being characterizing as industrial, critical, and responsive (Cozzolino and Bella, 2024; Allidières et al., 2019). Moreover, considering that the electrolysis process is viewed as an additional load by the network, which can alter its operational and electrical profiles (e.g., feeder loading, short-circuit levels, bus voltages) (Majeed Butt et al., 2021), studies have been conducted to evaluate and facilitate the integration of electrolyzers into the grid.

In the following, Table 2 presents a non-exhaustive list of publications that address hydrogen in the context of hybrid microgrids, including the operating mode and the constituent elements of each case studied.

Table 2. List of publications about microgrids for hydrogen production through water electrolysis.

Theme	Arrangement	Operation	H_2	Related Publication
Ancillary Services.	Grid/EL	Ongrid	Load	(Cozzolino and Bella, 2024)
Ancillary Services.	Grid/EL	Ongrid	Load	(Allidières et al., 2019)
Dispatch to minimize curtailment; Control strategies; Design optimization.	PV/EL	Ongrid	Load	(Yang et al., 2021)
Dispatch optimization.	WT/DG[3]/EL	Ongrid	Load	(Wu et.al, 2019)
Power-to-hydrogen optimization framework.	PV/WT/BESS/EL	Ongrid	Load	(Khan et al., 2023)
Decentralized control framework.	PV/BESS/ EL	Offgrid	Load	(Zhang e Wei., 2020)
Energy management system; Design optimization.	PV/WT/EL	Ongrid	Load	(Alluraiah and Vijayapriya, 2023)
Maximum Power Point Tracking (MPPT) strategy.	PV/EL/HT	Ongrid	Load	(Bayoumi et al., 2023)
Optimization of energy management system.	PV/WT/BESS/EL/HT	Ongrid	Load	(Wang et al., 2022)
Design of BESS and HESS association.	PV/BESS/ EL/FC	Offgrid	Load / Source	(Li et al., 2023)
Whale optimization technique applied to converter control.	PV/WT/BESS/EL/FC	Ongrid	Load / Source	(Balu et al., 2023)
Operational planning.	PV/BESS/EL/HT/FC	Ongrid	Load / Source	(Noro and Uchiyama, 2021)
Predictive model of distributed control; Optimization of energy management system.	PV/BESS/EL/HT/FC	Offgrid	Load / Source	(K/bidi et al., 2021)

[2]The Brazilian government is committed to reducing greenhouse gas emissions by 48% by 2025 and by 53% by 2030, compared to the year 2005. Therefore, efforts are being made to achieve net-zero emissions by 2050 (GOV, 2020).
[3]Diesel Generator.

Operational control strategies.	PV/WT/BESS/EL/HT/ FC	Ongrid	Load / Source	(Pei et al., 2021)
Design optimization.	PV/EL/HT/ FC	Ongrid	Source	(Hassan et al., 2022)
Energy management system.	PV/FC/SC	Offgrid	Source	(Ferahtia et al., 2020)
Mixed-integer linear optimization of design.	PV/EL/HT/ FC	Ongrid	ESS	(Diaz, 2020)
Energy management strategy for battery vs hydrogen prioritization.	PV/WT/BESS/EL/HT/ FC	Ongrid	ESS	(Monforti Ferrario et al., 2020)

4 Examples of related initiatives

This section highlights initiatives involving microgrids for green hydrogen production via water electrolysis. A global overview of these projects is provided to highlight the primary technologies employed in microgrids of varying hydrogen production capacities. Furthermore, the diverse microgrid configurations incorporating H_2 production are detailed in the contexts outlined in Table 2, where hydrogen can be viewed as a load, an ESS, or primary energy source.

- **Catalonia, Spain:** The Polytechnic University of Catalonia has initiated activities for a Hydrogen Laboratory and a pilot plant to produce Hydrogen. The pilot plant initially produces 6 kg of hydrogen per day and stores 17 kg, using 24 solar panels with a maximum power of 13 kW and a microgrid of 5 kW. In the future, the capacity will be expanded to 40 kg of hydrogen per day, with storage of 34 kg, over 40 kW of solar power, and 10 kW in the microgrid (UPC, 2023).
- **Puertollano, Spain**: Iberdrola has commissioned its green hydrogen production plant for industrial use, consisting of a 100 MW solar photovoltaic park, a lithium-ion battery energy storage system with a capacity of 20 MWh, and a 20 MW electrolysis system powered by renewable sources. The plant will produce GH_2 for Fertiberia's ammonia factory, enabling the production of green fertilizers and reducing the need for natural gas by more than 10%. The plant has the capacity to produce over 200,000 tons of ammonia per year (Iberdrola, 2022).
- **Itaipu Binacional**: The Itaipu Technological Park has a Hydrogen Experimental Plant, in operation since 2014, resulting from an agreement between Eletrobras, Itaipu Binacional, the National Hydrogen Energy Reference Center, and the Itaipu Technological Park Foundation Brazil. The plant has an alkaline electrolyzer with a production capacity of 1 kg H2/h and can be supplied by electricity from the Itaipu Power Plant and by solar photovoltaic energy. There is also a 6 kW PEM fuel cell for hydrogen use (Ferracin et al., 2019).
- **Porto de Pecém:** The Green Hydrogen Hub at the Port of Pecém, located in the state of Ceará, has an operational hydrogen production plant since 2021. It consists of a 3 MW solar generation system and an electrolyzer module capable of producing 250 m^3/h of Hydrogen (Gontijo, 2023). Additionally, from 2025 onwards, the Pecém H2V Hub is expected to produce 1.3 million tons of hydrogen by 2030 (Cigolotti, Genovese and Fragiacomo, 2021).
- **Eletrobrás Furnas**: Located between Araporã (MG) and Itumbiara (GO), the green hydrogen plant at Eletrobras Furnas' Itumbiara Hydroelectric Power Plant boasts a 200 kW alkaline electrolyzer, producing 50 Nm^3/h of hydrogen from locally treated water. With a daily production capacity of 100 kg, the hydrogen is stored in an 1,956 kg tank. A 300 kW PEMFC enables the conversion of the stored hydrogen back into energy (Gomes, 2020).

5 Conclusions

Overall, this article demonstrated that the electric sector has undergone significant transformations driven by the growth of distributed generation and the adoption of intermittent energy sources. This scenario has considerably increased the complexity of Power Systems, demanding innovative solutions for planning, operation, and control. Among these solutions, microgrids were highlighted for their ability to enhance system flexibility and resilience. Complementarily, hydrogen has also emerged as a promising resource for the energy sector, offering versatility in production, storage, and re-electrification of energy.

An innovative approach involves the distributed integration of microgrids incorporating hydrogen technologies, such as fuel cells, electrolyzers, and hydrogen energy storage systems. It was demonstrated that these microgrids can be classified based on their devices, configurations, control modes, and applications, allowing them to adapt to various demands and objectives.

Additionally, the design of hydrogen-producing microgrids requires a comprehensive analysis of physical components and the stages of planning, operation, control, communication, and protection. These interconnected concepts are essential to the technical and economic viability of the proposed solutions.

Recent strategies were identified, emphasizing the use of renewable energy in electrolysis for hydrogen production. This hydrogen can be utilized in various applications, including energy generation, fuels, and raw materials.

Finally, microgrids showcasing different configurations for hydrogen production and utilization were presented.

These initiatives illustrate the potential of hydrogen to meet energy demands and support resource management strategies aligned with Brazil's hydrogen production certification policies.

Acknowledgment

The authors wish to appreciate the Galp and SENAI CIMATEC for supporting this research, as well as the funding agencies ANP and EMBRAPII, which were fundamental to the development of this work.

References

Abbasi, M. et al. (2023) “Review on the microgrid concept, structures, components, communication systems, and control methods”, Energies, 16(1), p. 484. Available at: https://doi.org/10.3390/en16010484.

Abdelkareem, M.A. et al. (2021) “Environmental aspects of fuel cells: A review”, The Science of the total environment, 752(141803), p. 141803. Available at: https://doi.org/10.1016/j.scitotenv.2020.141803.

Agbadaola, O. et al. (2024) “Hydrogen technologies and policies for sustainable future: a

Agbossou, K. et al. (2004) “Performance of a stand-alone renewable energy system based on energy storage as hydrogen”, IEEE transactions on energy conversion, 19(3), p. 633–640. Available at: https://doi.org/10.1109/tec.2004.827719.

Aghmadi, A. et al. (2023) “A comprehensive review of architecture, communication, and cybersecurity in networked microgrid systems”, Inventions, 8(4), p. 84. Available at: https://doi.org/10.3390/inventions8040084.

Ahmad, S. et al. (2023) “A review of microgrid energy management and control strategies”, IEEE access: practical innovations, open solutions, 11, p. 21729–21757. Available at: https://doi.org/10.1109/access.2023.3248511.

Ahmed, M. et al. (2020) “Stability and control aspects of microgrid architectures–A comprehensive review”, IEEE access: practical innovations, open solutions, 8, p. 144730–144766. Available at: https://doi.org/10.1109/access.2020.3014977.

Ahmethodzic, L. and Mustafa Music (2021) “Comprehensive review of trends in microgrid control”, Renewable energy focus, 38, p. 84–96. Available at: https://doi.org/10.1016/j.ref.2021.07.003.

Ali, N. and Kumar, D. (2021) “State-of-the-art review on microgrid control strategies and power management with distributed energy resources”, em Lecture Notes in Electrical Engineering. Singapore: Springer Singapore, p. 749–756.

Allidières, L. et al. (2019) “On the ability of pem water electrolysers to provide power grid services”, International journal of hydrogen energy, 44(20), p. 9690–9700. Available at: https://doi.org/10.1016/j.ijhydene.2018.11.186.

Alluraiah, N.C. and Vijayapriya, P. (2023) “Optimization, design, and feasibility analysis of a grid-integrated hybrid AC/DC microgrid system for rural electrification”, IEEE access: practical innovations, open solutions, 11, p. 67013–67029. Available at: https://doi.org/10.1109/access.2023.3291010.

Alshehri, F. et al. (2019) “Modelling and evaluation of PEM hydrogen technologies for frequency ancillary services in future multi-energy sustainable power systems”, Heliyon, 5(4), p. e01396. Available at: https://doi.org/10.1016/j.heliyon.2019.e01396.

Altaf, M.W. et al. (2022) “Microgrid protection challenges and mitigation approaches–A comprehensive review”, IEEE access: practical innovations, open solutions, 10, p. 38895–38922. Available at: https://doi.org/10.1109/access.2022.3165011.

ANEEL (2020) RESOLUÇÃO NORMATIVA ANEEL No 1.000, DE 7 DE DEZEMBRO DE 2021. Available at: https://www2.aneel.gov.br/cedoc/ren20211000.html. (accessed 04 March 2024).

Arcia-Garibaldi, G. et al. (2018) “Future power transmission: Visions, technologies and challenges”, Renewable and Sustainable Energy Reviews, 94, p. 285–301. Available at: https://doi.org/10.1016/j.rser.2018.06.004.

Arsad, A.Z. et al. (2022) “simolstorage integrated hybrid renewable energy systems: A review analysis for future research directions”, International journal of hydrogen energy, 47(39), p. 17285–17312. Available at: https://doi.org/10.1016/j.ijhydene.2022.03.208.

Azad, A.K. and Khan, M.M.K. (2021) “Bioenergy resources and technologies”. Elsevier. Available at: https://doi.org/10.1016/c2019-0-05000-5.

Babayomi, O. et al. (2023) “Smart grid evolution: Predictive control of distributed energy resources—A review”, International journal of electrical power & energy systems, 147(108812), p. 108812. Available at: https://doi.org/10.1016/j.ijepes.2022.108812.

Balu, V. et al. (2023) “Improving the power quality and hydrogen production from renewable energy sources based microgrid”, Engineering Research Express, 5(3), p. 035037. Available at: https://doi.org/10.1088/2631-8695/acecdb.

Banerjee, S. et al. (2020) Applications of Supercapacitors. Em Handbook of Nanocomposite Supercapacitor Materials I. Springer International Publishing. (accessed 21 June 2024).

Bayoumi, M.A. et al. (2023) “Investigation of green hydrogen production and storage from PV arrays connected to an AC microgrid system”, em 2023 International Telecommunications Conference (ITC-Egypt). IEEE, p. 157–164.

Berry, T. (2022) “IEC 61850 for Microgrids and Load Shedding”. Available at: https://www.pacw.org/iec-tc-57-wg-17-update-7. (accessed 18 May 2024).

Bezerra, F. D. (2023). HIDROGÊNIO VERDE: OPORTUNIDADE PARA O NORDESTE: v. 8 n. 320 (2023). Caderno Setorial ETENE, 8.

Bihari, S.P. et al. (2021) “A comprehensive review of microgrid control mechanism and impact assessment for hybrid renewable energy integration”, IEEE access: practical innovations, open solutions, 9, p. 88942–88958. Available at: https://doi.org/10.1109/access.2021.3090266.

BloombergNEF (2020) Hydrogen Economy Outlook - Key messages. Available at: https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30- Mar-2020.pdf. (accessed 10 August 2024).

Brazil (2024) Lei N° 14.948, de 2 de agosto de 2024. Available at: https://www.planalto.gov.br/ccivil_03/_Ato2023-2026/2024/Lei/L14948.htm. (accessed 10 August 2024).

CCEE (2022). Manual para Certificação de Hidrogênio. (accessed 10 August 2024).

Chiappini, G. (2023) Hidrogênio verde: conheça 10 projetos promissores em desenvolvimento no Brasil, Eixos. Available at: https://eixos.com.br/hidrogenio/hidrogenio-verde-conheca-16-projetos-promissores-em-desenvolvimento-no-brasil/ (Accessed: August 5, 2024).

Ciotta, M. (2023) Anais do II Seminário Interdisciplinar de Energia: SINERG - Usinas hidroelétricas reversíveis e sua relação com a eficiência energética na hidroeletricidade. Organizado por S.I.-U. São Paulo. (accessed 15 May 2024).

Conejo, A.J. and Baringo, L. (2018) Power System Operations. Cham: Springer International Publishing.

Cozzolino, R. and Bella, G. (2024) "A review of electrolyzer-based systems providing grid ancillary services: current status, market, challenges and future directions", Frontiers in energy research, 12. Available at: https://doi.org/10.3389/fenrg.2024.1358333.

Da Rosa, A.V. (2012) Fundamentals of renewable energy processes. 3rd ed. San Diego, CA, USA: Academic Press. (accessed 10 August 2024).

Dagar, A. et al. (2021) "Microgrid protection: A comprehensive review", Renewable and Sustainable Energy Reviews, 149(111401), p. 111401. Available at: https://doi.org/10.1016/j.rser.2021.111401.

Das, H.S. et al. (2022) "A comprehensive review on power conditioning units and control techniques in fuel cell hybrid systems", Energy reports, 8, p. 14236–14258. Available at: https://doi.org/10.1016/j.egyr.2022.10.407. (accessed 15 May 2024).

Dashti, R. and Rouhandeh, M. (2023) "Power distribution system planning framework (A comprehensive review)", Energy strategy reviews, 50(101256), p. 101256. Available at: https://doi.org/10.1016/j.esr.2023.101256.

De Barros, B.F. et al. (2014) Geração, transmissão, distribuição e consumo de energia elétrica. (accessed 13 June 2024).

Diaz, I. U. (2020) Hidrogênio Como Sistema de Armazenamento Energético de Fontes Renováveis Intermitentes no Contexto De Uma Microrrede. (accessed 05 August 2024).

EPE (2021) *Bases para a Consolidação da Estratégia Brasileira do Hidrogênio*. Available at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-569/Hidroge%CC%82nio_23Fev2021NT%20%282%29.pdf.

Espina, E. et al. (2020) "Distributed control strategies for microgrids: An overview", IEEE access: practical innovations, open solutions, 8, p. 193412–193448. Available at: https://doi.org/10.1109/access.2020.3032378.

Ferahtia, S. et al. (2020) "A hybrid power system based on fuel cell, photovoltaic source and supercapacitor", SN applied sciences, 2(5). Available at: https://doi.org/10.1007/s42452-020-2709-0.

Ferracin, R.J. et al. (2019) "Avaliação Do Potencial De Produção De Hidrogênio Para Armazenamento De Energia Hidrelétrica Utilizando Dados Experimentais Obtidos Na Planta De Produção De Hidrogênio Com Eletrolisador Alcalino De Água Instalado No Parque Tecnológico Itaipu", Xxv Snptee Seminário Nacional De Produção E Transmissão De Energia Elétrica. Available at: http://www.bvr.com.br/snptee/xxvsnptee/public/GES/3615.pdf.

Ferreira, T.V.B. et al. (2021) Bases para a Consolidação da Estratégia Brasileira do Hidrogênio. Available at: http://www.epe.gov.br/.

Gao, X. et al. (2022) "Stability analysis of grid-following and grid-forming converters based on state-space model", em 2022 International Power Electronics Conference (IPEC-Himeji 2022- ECCE Asia). IEEE.

Göksel, B.F. (2022) "A literature survey on exergy analyses of marine diesel engine and power systems", Seatific Engineering Research Journal [Preprint]. Available at: https://doi.org/10.14744/seatific.2022.0008.

Gomes, M.M. et al. (2020) "Operação de um sistema de eletrólise acionado por fotovoltaicos", Anais do Congresso Brasileiro de Energia Solar. Available at: https://anaiscbens.emnuvens.com.br (Accessed: 31 October 2024).

Gontijo, J. (2023) *1ª planta de hidrogênio verde do País entra em operação*, *Diário do Comércio*. Available at: https://diariodocomercio.com.br/economia/primeira-planta-hidrogenio-verde-brasil-entra-operacao/#gref. (Accessed: October 7, 2024).

GOV (2020) NDC - a ambição climática do Brasil. Available at: https://www.gov.br/mma/pt-br/assuntos/mudanca-do-clima/NDC (accessed 11 August 2024).

Greener (2021) "Estudo Estratégico Mercado de Armazenamento". Available at: https://www.greener.com.br/produto/estudo-estrategico-do-mercado-de-armazenamento-de-energia-no-brasil2021/. (accessed 15 May 2024).

Guoping, Z. et al. (2018) "An overview of microgrid planning and design method", em 2018 IEEE 3rd Advanced Information Technology, Electronic and Automation Control Conference (IAEAC). IEEE.

Hanna, S. et al. (2022) "Supporting the requirements-based selection of suitable communication protocols in smart grids", em 2022 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe). IEEE, p. 1–5.

Hart, D.W. (2011) Eletrônica de Potência: Análise e Projetos de Circuitos. (accessed 20 May 2024).

Hassan, Q. et al. (2022) "Optimizing a microgrid photovoltaic-fuel cell energy system at the highest renewable fraction", International journal of hydrogen energy, 47(28), p. 13710–13731. Available at: https://doi.org/10.1016/j.ijhydene.2022.02.108.

Hassan, Q. *et al.* (2023) "Renewable energy-to-green hydrogen: A review of main resources routes, processes and evaluation", *International journal of hydrogen energy*, 48(46), p. 17383–17408. Available at: https://doi.org/10.1016/j.ijhydene.2023.01.175.

Hassan, Q. et al. (2023) "Renewable energy-to-green hydrogen: A review of main resources routes, processes and evaluation", International journal of hydrogen energy, 48(46), p. 17383–17408. Available at: https://doi.org/10.1016/j.ijhydene.2023.01.175.

He, M. et al. (2024) "A generic equivalent circuit model for PEM electrolyzer with multi-timescale and stages under multi-mode control", Applied energy, 359(122728), p. 122728. Available at: https://doi.org/10.1016/j.apenergy.2024.122728.

Hirsch, A. et al. (2018) "Microgrids: A review of technologies, key drivers, and outstanding issues", Renewable and Sustainable Energy Reviews, 90, p. 402–411. Available at: https://doi.org/10.1016/j.rser.2018.03.040.

Hossain, M.A. et al. (2019) "Evolution of microgrids with converter-interfaced generations: Challenges and opportunities", International journal of electrical power & energy systems, 109, p. 160–186. Available at: https://doi.org/10.1016/j.ijepes.2019.01.038.

Hossain, Md Arafat et al. (2023) "Control strategy review for hydrogen-renewable energy power system", Journal of energy storage, 72(108170), p. 108170. Available at: https://doi.org/10.1016/j.est.2023.108170.

Hu, X. et al. (2017) "Technological developments in batteries: A survey of principal roles, types, and management needs", IEEE power & energy magazine, 15(5), p. 20–31. Available at: https://doi.org/10.1109/mpe.2017.2708812.

Iberdrola (2022) His Majesty the King inaugurates Iberdrola's green hydrogen plant in Puertollano, the largest for industrial use in Europe, Iberdrola. Available at: https://www.iberdrola.com/press-room/news/detail/his-majesty-the-king-inaugurates-green-hydrogen-plant-puertollano. (accessed 23 August 2024).

IRENA (2015) "Battery Storage For Renewables: Market Status And Technology Outlook".

Jena, D. and Rajanarayan Prusty, B. (2014) Power System Analysis Operation and Control. 2o ed. New Delhi, India: I K International Publishing House. (accessed 21 August 2024).

Jha, A.V. et al. (2021) "Smart grid cyber-physical systems: communication technologies, standards and challenges", Wireless networks, 27(4), p. 2595–2613. Available at: https://doi.org/10.1007/s11276-021-02579-1.

Jirdehi, M.A. et al. (2020) "Different aspects of microgrid management: A comprehensive review", Journal of energy storage, 30(101457), p. 101457. Available at: https://doi.org/10.1016/j.est.2020.101457.

K/bidi, F. et al. (2021) "Power management of a hybrid micro-grid with photovoltaic production and hydrogen storage", Energies, 14(6), p. 1628. Available at: https://doi.org/10.3390/en14061628.

Kanakadhurga, D. and Prabaharan, N. (2022) "Demand side management in microgrid: A critical review of key issues and recent trends", Renewable and Sustainable Energy Reviews, 156(111915), p. 111915. Available at: https://doi.org/10.1016/j.rser.2021.111915.

Khalid Ratib, M. et al. (2024) “Electrical circuit modeling of proton exchange membrane electrolyzer: The state-of-the-art, current challenges, and recommendations”, International journal of hydrogen energy, 49, p. 625–645. Available at: https://doi.org/10.1016/j.ijhydene.2023.08.319. (accessed 22 August 2024).

Khan, M.A. et al. (2023) “Techno-economic analysis and predictive operation of a power-to-hydrogen for renewable microgrids”, Energy conversion and management, 298(117762), p. 117762. Available at: https://doi.org/10.1016/j.enconman.2023.117762.

Kroposki, B. et al. (2017) “Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy”, IEEE power & energy magazine, 15(2), p. 61–73. Available at: https://doi.org/10.1109/mpe.2016.2637122.

Kumar, K. et al. (2024) “A review of microgrid protection for addressing challenges and solutions”, Renewable energy focus, 49(100572), p. 100572. Available at: https://doi.org/10.1016/j.ref.2024.100572.

Kumar, S. et al. (2019) “Microgrid communications - protocols and standards”, em Variability, Scalability and Stability of Microgrids. Institution of Engineering and Technology, p. 291–326.

Kundur, P.S. and Malik, O.P. (2022) Power system stability and control, second edition. 2º ed. McGraw-Hill Companies.

Lagioia, G. et al. (2023) “Blue and green hydrogen energy to meet European Union decarbonisation objectives. An overview of perspectives and the current state of affairs”, International journal of hydrogen energy, 48(4), p. 1304–1322. Available at: https://doi.org/10.1016/j.ijhydene.2022.10.044.

Lebbal, M.E. and Lecœuche, S. (2009) “Identification and monitoring of a PEM electrolyser based on dynamical modelling”, International journal of hydrogen energy, 34(14), p. 5992–5999. Available at: https://doi.org/10.1016/j.ijhydene.2009.02.003.

Li, H. et al. (2022) “Safety of hydrogen storage and transportation: An overview on mechanisms, techniques, and challenges”, Energy reports, 8, p. 6258–6269. Available at: https://doi.org/10.1016/j.egyr.2022.04.067.

Li, N. et al. (2023) “An approach for sizing a PV–battery–electrolyzer–fuel cell energy system: A case study at a field lab”, Renewable and Sustainable Energy Reviews, 181(113308), p. 113308. Available at: https://doi.org/10.1016/j.rser.2023.113308.

Li, Y. et al. (2024) “Recent progress in hydrogen: From solar to solar cell”, Journal of materials science & technology, 176, p. 236–257. Available at: https://doi.org/10.1016/j.jmst.2023.08.030.

Lima, J. (2022) GERAÇÃO DE ENERGIA FOTOVOLTAICA ON-GRID E OFF-GRID. UNIVERSIDADE FEDERAL RURAL DO SEMIÁRIDO. Available at: https://repositorio.ufersa.edu.br/handle/prefix/9058.

Liu, T. et al. (2022) “Stability and control of power grids”, Annual review of control, robotics, and autonomous systems, 5(1), p. 689–716. Available at: https://doi.org/10.1146/annurev-control-042820-011148.

Majeed Butt et al. (2021) “Recent advancement in smart grid technology: Future prospects in the electrical power network”, Ain Shams Engineering Journal, 12(1), p. 687–695. Available at: https://doi.org/10.1016/j.asej.2020.05.004.

Marques, W. et al. (2022) O sol nasce para todos: sustentabilidade mediante telhas fotovoltaicas de concreto. Revista de Engenharia e Tecnologia, 14(1). (accessed 13 June 2024).

Mensah, J.H.R. (2020) Procedimento de armazenamento de energia com usinas hidrelétricas reversíveis como mecanismo sustentável para recuperação de nível de água em reservatórios de centrais hidrelétricas de regularização: estudo de caso da UHE Furnas. Universidade Federal de Itajubá.

Mina-Casaran, J.D. et al. (2021) “Demand response integration in microgrid planning as a strategy for energy transition in power systems”, IET renewable power generation, 15(4), p. 889–902. Available at: https://doi.org/10.1049/rpg2.12080.

Mitali, J. et al. (2022) “Energy storage systems: a review”, Energy Storage and Saving, 1(3), p. 166–216. Available at: https://doi.org/10.1016/j.enss.2022.07.002.

Monforti Ferrario, A. et al. (2020) "Hydrogen vs. Battery in the long-term operation. A comparative between energy management strategies for hybrid renewable microgrids", Electronics, 9(4), p. 698. Available at: https://doi.org/10.3390/electronics9040698.

Muhammad, Y. et al. (2020) "Solution of optimal reactive power dispatch with FACTS devices: A survey", Energy reports, 6, p. 2211–2229. Available at: https://doi.org/10.1016/j.egyr.2020.07.030.

Muhammed, N.S. et al. (2023) "Hydrogen production, transportation, utilization, and storage: Recent advances towards sustainable energy", Journal of energy storage, 73(109207), p. 109207. Available at: https://doi.org/10.1016/j.est.2023.109207.

Nithara and Anand (2021) "Comparative analysis of different control strategies in Microgrid", International journal of green energy, 18(12), p. 1249–1262. Available at: https://doi.org/10.1080/15435075.2021.1897830.

Noro, Y. and Uchiyama, S. (2021) "Use of hydrogen storage in an off-grid system for implementing a renewable-energy system", Clean energy, 5(4), p. 704–712. Available at: https://doi.org/10.1093/ce/zkab043.

Otmani, F.E. et al. (2020) "MPPT based sliding mode control for fuel cell connected grid system", IFAC-PapersOnLine, 53(2), p. 13322–13327. Available at: https://doi.org/10.1016/j.ifacol.2020.12.165.

Patnaik, B. et al. (2020) "AC microgrid protection – A review: Current and future prospective", Applied energy, 271(115210), p. 115210. Available at: https://doi.org/10.1016/j.apenergy.2020.115210.

Pei, W. et al. (2022) "Review of Operational Control Strategy for DC Microgrids with Electric-hydrogen Hybrid Storage Systems", CSEE Journal of Power and Energy Systems, 8, p. 329–346. Available at: https://doi.org/10.17775/CSEEJPES.2021.06960.

Perez, F. (2020) Control of AC/DC microgrids with renewables in the context of smart grids including ancillary services and electric mobility. Universidade Federal de Itajubá. Available at: https://repositorio.unifei.edu.br/jspui/handle/123456789/2235.

Peyghami, S. et al. (2019) "Standard Test Systems for Modern Power System Analysis: An Overview", IEEE industrial electronics magazine, 13(4), p. 86–105. Available at: https://doi.org/10.1109/mie.2019.2942376.

Pinto, M. (2014) Energia elétrica: geração, transmissão e sistemas interligados. (accessed 13 June 2024).

Rangel, N. et al. (2023) "An optimisation tool for minimising fuel consumption, costs and emissions from Diesel-PV-Battery hybrid microgrids", Applied energy, 335(120748), p. 120748. Available at: https://doi.org/10.1016/j.apenergy.2023.120748.

Rasul, M.G. et al. (2022) "The future of hydrogen: Challenges on production, storage and applications", Energy conversion and management, 272(116326), p. 116326. Available at: https://doi.org/10.1016/j.enconman.2022.116326.

Saadat, H. (2011) Power System Analysis. 3º ed. Psa Pub. (accessed 21 August 2024).

Saeed, M.H. et al. (2021) "A Review on Microgrids' Challenges & Perspectives", IEEE access: practical innovations, open solutions, 9, p. 166502–166517. Available at: https://doi.org/10.1109/access.2021.3135083.

Sepasi, S. et al. (2023) "Power quality in microgrids: A critical review of fundamentals, standards, and case studies", IEEE access: practical innovations, open solutions, 11, p. 108493–108531. Available at: https://doi.org/10.1109/access.2023.3321301.

Shahgholian, G. (2021) "A brief review on microgrids: Operation, applications, modeling, and control", International transactions on electrical energy systems, 31(6). Available at: https://doi.org/10.1002/2050-7038.12885.

Shahzad, S. et al. (2023) "Possibilities, challenges, and future opportunities of microgrids: A review", Sustainability, 15(8), p. 6366. Available at: https://doi.org/10.3390/su15086366.

Shukla, S. and Pandit, M. (2021) "Renewable microgrids with economic and environmental benefits: A review", em 2021 IEEE 2nd International Conference On Electrical Power and Energy Systems (ICEPES). IEEE.

Smolinka, T. et al. (2015) “Hydrogen production from renewable energies—electrolyzer technologies”, em Electrochemical Energy Storage for Renewable Sources and Grid Balancing. Elsevier, p. 103–128.

Souza Cruz, I. et al. (2022) “Renewable Hybrid Systems for water pumping: a review”, IEEE Latin America Transactions, 20(10), p. 2263–2274. Available at: https://doi.org/10.1109/tla.2022.9885164.

Souza Junior, M.E.T. and Freitas, L.C.G. (2022) “Power electronics for modern sustainable power systems: Distributed generation, microgrids and smart grids—A review”, Sustainability, 14(6), p. 3597. Available at: https://doi.org/10.3390/su14063597.

Ton, D.T. and Smith, M.A. (2012) “The U.s. department of energy’s microgrid initiative”, Electricity Journal, 25(8), p. 84–94. Available at: https://doi.org/10.1016/j.tej.2012.09.013.

Twaisan, K. and Barışçı, N. (2022) “Integrated distributed energy resources (DER) and microgrids: Modeling and optimization of DERs”, Electronics, 11(18), p. 2816. Available at: https://doi.org/10.3390/electronics11182816.

Uddin, M. et al. (2023) “Microgrids: A review, outstanding issues and future trends”, Energy strategy reviews, 49(101127), p. 101127. Available at: https://doi.org/10.1016/j.esr.2023.101127.

Upadhyay, R. (2021) “A review on power electronics in renewable source of energy”, International journal of science and research (Raipur, India), 10(8), p. 427–432. Available at: https://doi.org/10.21275/mr21810143943.

UPC (2023) The UPC opens the Hydrogen Laboratory and the green hydrogen pilot plant, UPC. Available at: https://www.upc.edu/en/press-room/news/the-upc-opens-the-hydrogen-laboratory-and-the-green-hydrogen-pilot-plant#. (accessed 23 August 2024).

Vian, Â. et al. (2021) Energia Eólica Fundamentos Tecnologia e Aplicações. Editora Blucher. (accessed 21 June 2024).

Von Schuckmann, K. et al. (2020) “Heat stored in the Earth system: where does the energy go?”, Earth system science data, 12(3), p. 2013–2041. Available at: https://doi.org/10.5194/essd-12-2013-2020.

Wang, J. et al. (2022) “Two-stage energy management strategies of sustainable wind-PV-hydrogen-storage microgrid based on receding horizon optimization”, Energies, 15(8), p. 2861. Available at: https://doi.org/10.3390/en15082861.

Williams, B. et al. (2023) “Demand Side Management in industrial, commercial, and residential sectors: A review of constraints and considerations”, Energies, 16(13), p. 5155. Available at: https://doi.org/10.3390/en16135155.

Wu, X. et al. (2019) “Optimal scheduling for microgrids with hydrogen fueling stations considering uncertainty using data-driven approach”, Applied energy, 253(113568), p. 113568. Available at: https://doi.org/10.1016/j.apenergy.2019.113568.

Yang, Y. et al. (2021) “Optimal power reallocation of large-scale grid-connected photovoltaic power station integrated with hydrogen production”, Journal of cleaner production, 298(126830), p. 126830. Available at: https://doi.org/10.1016/j.jclepro.2021.126830.

Zhang, Y. and Wei, W. (2020) “Decentralised coordination control strategy of the PV generator, storage battery and hydrogen production unit in islanded AC microgrid”, IET renewable power generation, 14(6), p. 1053–1062. Available at: https://doi.org/10.1049/iet-rpg.2019.0842.

Zhou, X. et al. (2015) “An overview on microgrid technology”, em 2015 IEEE International Conference on Mechatronics and Automation (ICMA). IEEE.