COBEM 2023 27TH INTERNATIONAL CONGRESS OF MECHANICAL ENGENEERING

ABCM Brazilian Society of Mechanical Sciences and Engineering

27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-1299
ENERGY AUTONOMY IN SUSTAINABLE COMMUNITIES USING HYBRID SOLAR PV-BATTERY-HYDROGEN: A REVIEW

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Abstract. *The concepts of achieving carbon neutrality and sustainable energy generation are inherently interconnected. While renewable energy sources have gained traction, their intermittency remains a major hurdle. To ensure carbon-neutral energy supply meets demand, an effective energy storage system is essential. The utilization of photovoltaic (PV) energy systems is increasing, with electricity transmission networks now encompassing diverse sizes. Ranging from small modules for individual households to mini-PV plants in communities and large-scale solar fields powering multiple cities, PV systems are revolutionizing energy generation. However, determining the optimal energy storage strategy remains an ongoing quest. This article presents a comprehensive review of technological advancements in power generation, local and medium-scale storage, and distribution systems. It explores the utilization of surplus electricity generated by PV systems to produce hydrogen (H_2) as part of the energy transition in small towns, assessing their potential for achieving carbon neutrality in electricity generation. Additionally, the review includes in-depth analysis of a case study conducted since 2020, examining tested strategies for managing electricity production and storage using batteries and H_2. Furthermore, the application of the produced H_2 to meet the energy demands of the community is also discussed.*

Keywords: *Carbon Neutrality, Energy Autonomy, Sustainable Communities, Hybrid Systems, Hydrogen Production.*

1. INTRODUCTION

The energy transition, in broad terms, is a process that aims to change the energy matrix, to replace the use of fossil fuels with renewable sources. This had been happening slowly a few decades ago, but after the damage done to the environment began to be evident and almost reaching the point of becoming irreversible, the global industry and the main authorities are joining forces, resources, and knowledge to find the best solutions for a future free of global contamination and sustainable.

In the report "Net Zero by 2050: A road map for the Global Energy Sector" published in 2021 by International Energy Agency (2021), data from the year 2020 with estimates until 2050 were presented, Figure 1, showing that the electricity generation sector is responsible for more than 50% of CO_2 emissions followed by the industrial and transport sectors, this behavior is observed both in countries with advanced economies and in countries and markets of emerging economies.

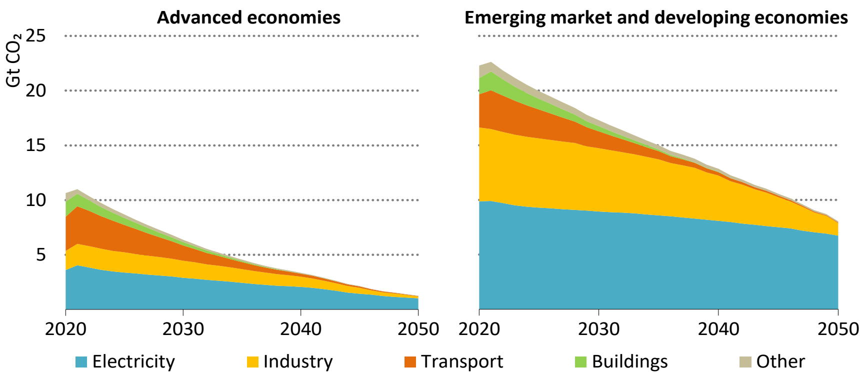

Figure 1. CO_2 emissions from existing global infrastructure by sector and region.

Among the main challenges in the energy transition process is the fact that renewable sources are variable in nature, with generation surpluses or deficits, as well as geographical limitations, requiring auxiliary systems or storage systems to be able to meet energy demand at peak load times of the year.

Figure 2 shows the forecast until the year 2050 of the scenario that is estimated to have a global energy supply if emissions are reduced by 50% according to the model developed by the International Energy Agency (2021), the use of fossil fuels is not completely eliminated due to those that are used in the manufacture of some products such as chemical raw materials, lubricants, asphalt among others and in some industrial processes where their use is indispensable such as aviation fuel.

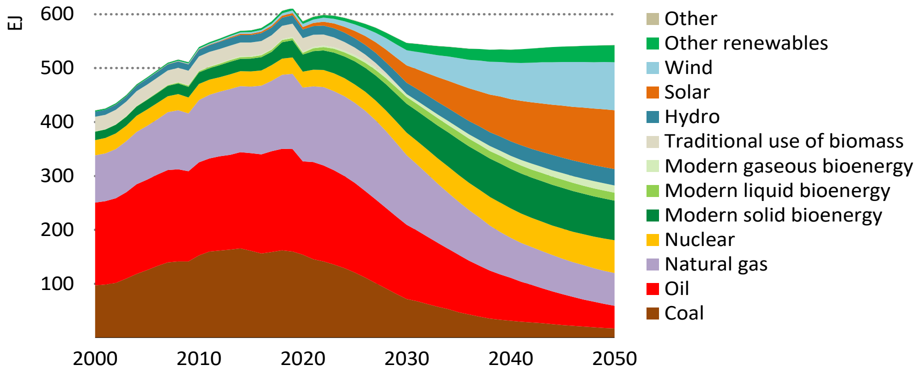

Figure 2. Total energy supply by sources, Zero Emissions scenario for 2050

It is also observed that from the year 2020 there is a greater development of renewable sources, highlighting solar photovoltaic and wind, so it is crucial to optimize both generation and energy storage systems to provide the stability that the energy matrix needs. Maximizing life-cycle energy efficiency is also one of the key parameters in determining how sustainable an energy generation system or process is (Scholczova, 2023).

In order to achieve the emission reduction targets, different types of projects or electricity generation and storage systems are being developed that use entirely renewable sources. As previously mentioned, the long-term potential of photovoltaic solar energy is evident, but the main problem with this source is that it is intermittent and therefore of low reliability, requiring it to work together with some type of auxiliary system or accumulator that stores the excess energy produced in periods of low demand and delivers it in periods when demand is higher (Michaelides, 2022; Zsiborács et al., 2019).

It is proposed in the literature to implement a system that takes advantage of the excess energy produced by a photovoltaic system in periods of low demand to produce hydrogen that can be stored in tanks and when necessary, during periods of higher demand, use fuel cells to produce energy that helps supply the load (Marocco et al., 2021; Erdemir; Dincer, 2022; Fan et al., 2022).

The main objective of this work is to present the advances that have been made in the area of hybrid systems that use solar photovoltaic energy, battery and hydrogen in their composition, and the different configurations that have already been tested as well as those that are in the development phase.

2. LITERATURE REVIEW

The components that make up the hybrid system are photovoltaic modules, battery bank, electrolyser, pressurized reservoir and fuel cell, Figure 3, the technology of these components can vary, and an optimal configuration needs to be analyzed according to the location where the system is installed (Marocco et al., 2021).

Groppi et al. (2018) developed an economic and environmental sustainability analysis of energy storage using batteries and hydrogen for the case of Favignana island on the west coast of Sicily, demonstrating that hybrid systems using batteries and electrolyser are the best option to harness surplus electricity with a view to decreasing carbon emissions, 10.87%, compared to the other configurations analyzed.

Hydrogen production increases proportionally to the increase of injected solar energy, according to the study done by Erdemir e Dincer (2022), where they developed a system to supply the energy demand of 1500 residential buildings in southern Ontario by compensating with a hydrogen energy storage system. The highest amount of hydrogen production they obtained was during the month of June, 5564 kg, with an area of 300000 m2 of the solar photovoltaic system.

According to the study carried out by Vargas-Ferrer et al. (2023), where they analyzed the integration of electrolytic hydrogen production into the national energy grid, they obtained that the on-grid hydrogen production scenarios presented better cost-benefit than the off-grid scenarios, with a reduction in costs between 2-3 US $ Billion for the complete system.

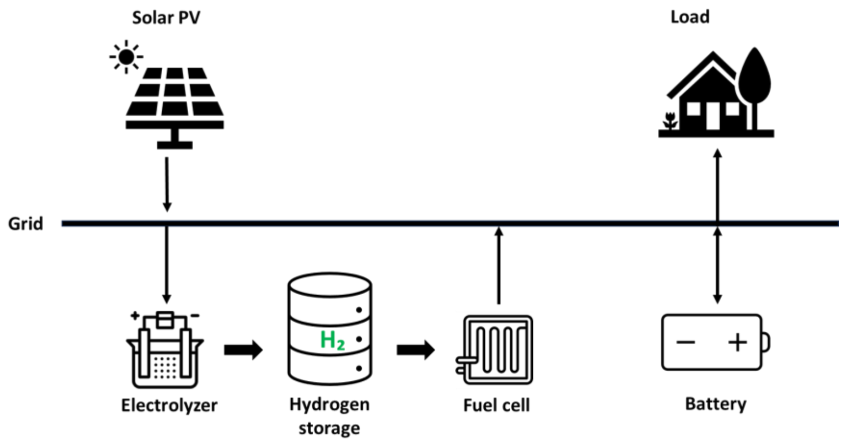

Figure 3. Schematic of the hybrid system configuration.

2.1 Types of electrolysers

The electrolyser is an electrochemical device that uses electrical energy to decompose water into hydrogen and oxygen, it may be composed of a set of electrolyser cells connected in series (Berrada & Laasmi, 2021).

Depending on the electrolyte used and the operating temperature, according to Vincent & Bessarabov (2018), Li & Baek (2021), (K. Li et al., 2021), International Energy Agency (2021a), Ishaq; Dincer; Crawford (2022) and International Energy Agency (2023). they are divided into: polymer electrolyte membrane (PEM), solid oxide electrolyser (SOE), alkaline electrolyser (AE) and anion exchange membrane (AEM), Table 1 shows some characteristics of these electrolysers:

Table 1. Types of electrolysers used for hydrogen production.

Type	Efficiency (LHV)(1) (%)	Efficiency (kWh per Kh of H_2)	Stack life (Operating hours)	Typical output pressure (bar)
PEM	57	58	40000	30
SOE(2)	79 - 84	–	–	>25
AE	65	51	80000	Atmospheric
AEM(2)	>70	57 – 69	>5000	<35

(1) LHV = Lower Heating Values
(2) Technologies still in prototype phase

The most commercialized are the AE type, as well as the PEM type that unlike other technologies performs better with variable renewable energy sources, its design takes up less space than AE, but due to the materials it uses for its manufacture (platinum, iridium and titanium) it is much more expensive, USD 1750/ kW, however the costs of AE are between USD 1000 - 1400/kW (International Energy Agency, 2021a). SOE and AEM type electrolysers are in demonstration phase and close to being commercialized (International Energy Agency, 2023).

Some of the main advantages of SOE are its ability to work at high temperatures (600 - 850 °C), which allows it to achieve higher thermodynamic efficiencies than the AE and PEM types, it uses a ceramic electrolyte that can conduct the oxide ions and the materials used for its manufacture are cheap (nickel, zirconia and steel), unlike the PEM type, which requires precious materials such as platinum (Hauch et al., 2020).

However, the AEM electrolyzer is a combination of the advantages of the AE and PEM types, achieving higher efficiencies (> 70%). One of the main characteristics is that its polymer membrane has no porosity and has intrinsic anionic conductivity, the materials used in the membrane and electrodes can be steel and nickel respectively, which reduces manufacturing costs (Henkensmeier et al., 2021; Santoro et al., 2022). As shown in Figure 4, according to Wappler et al. (2022), by 2025 electrolyzer manufacturing capacity is expected to increase by more than 10 GW compared to 2023, reaching a total capacity of approximately 23 GW.

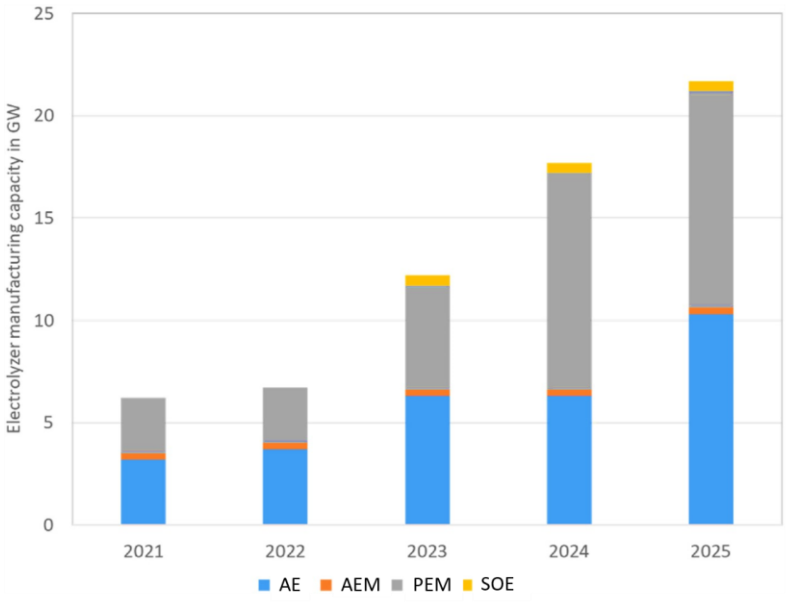

Figure 4. Cumulative manufacturing capacities of types of electrolysers from 2021 to 2025

2.2 Hydrogen storages technologies

One of the most important characteristics of hydrogen is its ability to store energy both in quantity and in periods over the long term, so depending on supply or demand, storage technology can vary in volumetric scale, type of reservoir, construction material, determining where storage points could be located, close to the centers of production or the centers of energy demand (International Renewable Energy Agency, 2022).

The classification of hydrogen storage types can be extensive but can be divided into two major groups: surface storage, which comprises the utilization of the different physical states and molecular interactions of hydrogen, Figure 5, underground storage, which makes use of reservoirs that already exist either naturally or artificially, Figure 6 (Amirthan & Perera, 2022).

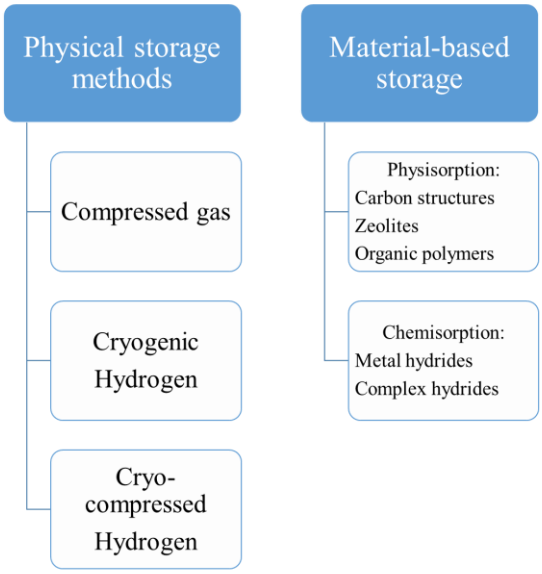

Figure 5. Hydrogen storage at the surface.

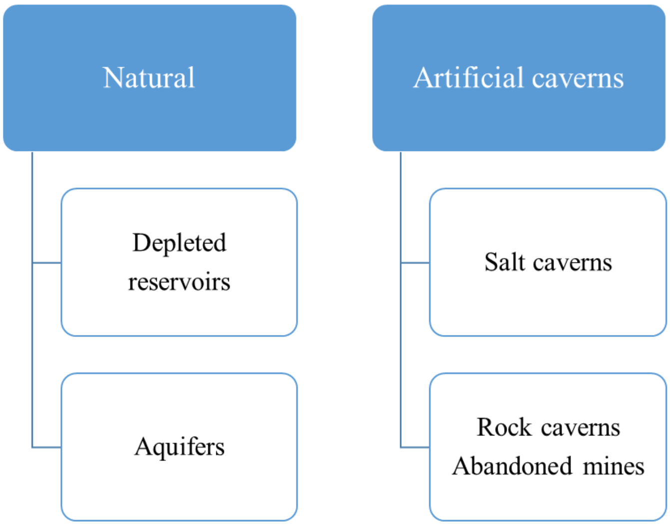

Figure 6. Underground storage of hydrogen.

2.3 Type of fuel cells

A fuel cell is a device that works in reverse of an electrolyser, generating electricity and heat through an electrochemical process using hydrogen and air as a source, with no CO_2 emissions and also water vapor as a by-product (International Renewable Energy Agency, 2022).

Fuel cells can achieve electrical efficiencies of 60% or more even when running at partial load, one of the key features that can be leveraged to complement variable load systems (International Energy Agency, 2021a).

Based on the characteristic of the electrolyte, there is the alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) which use liquid electrolytes, as well as the proton exchange membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) working with solid electrolytes (Ali & Pasha, 2018; İnci, 2022). Table 2 shows some characteristics of these types of fuel cells:

Table 2. Types of fuel cells which use hydrogen.

Type	Electrolyte	Voltage (V)	Efficiency (%)	Power rating
AFC	Potassium hydroxide	~ 1	60 – 70	10 – 200 kW
PAFC	Phosphoric acid	~ 1.1	~ 40 – 55	200 kW – 50MW
MCFC	Molten carbonate	0.7 – 1	~ 50 – 70	10 kW – 200 MW
PEMFC	Polymeric membrane	~ 1.1	40 – 60	10 W – 500 kW
SOFC	Ceramic	0.8 – 1	50 – 70	1 kW – 2 MW

2.4 Case studies and applications.

In this section some applications of different configurations of hybrid systems are presented both modeling study cases and cases that have already been applied in cities or islands, Table 3. The systems used are based on the configuration: PV, electrolyser, hydrogen storage and fuel cell, depending on the application other components have been added to the system from wind turbines in the generation part, batteries in the storage part and even heating pumps powered by renewable sources to satisfy the heating demand. It is also important to highlight the amount of CO_2 emissions that each project manages to reduce, serving as a benchmark for applications that are being developed with the long-term goal of carbon neutrality.

Table 3. Case studies and applications of hybrid systems.

Author (Year)	**Hybrid system configuration**	**Energy demand covered**	**Hydrogen Production**	**Carbon avoidance**	**Location**
Groppi et al.(2018)	PV + Battery + Electrolyser + Hydrogen tank	13915 MWh/year	868 kg/year	1063.36 $tonCO_2$/year	Favignana, Sicily, Italy.
Marocco et al.(2021)	PV + Battery (Li-ion) + Electrolyser (AE) + Hydrogen tank + Fuel cell (PEMFC)	172 MWh/year	–	286 $tonCO_2$/year	Ginostra, Sicily, Italy.
Al-Buraiki & Al-Sharafi (2022)	PV + Wind Turbine + Battery (Lead-Acid) + Electrolyser + Hydrogen tank	12.14 MWh/year	260 kg/year (demand)	9.6 $tonCO_2$/year	Dhahram, Kingdom of Saudi Arabia.
Michaelides(2022)	PV + Wind Turbine + Electrolyser + Hydrogen tank + Fuel cell + Heat pump (RES)	103523 MWh/year (Electricity) + 998000 GJ/year (Heating)	–	87414 $tonCO_2$/year	North Texas, USA.
Mohammed(2023)	PV + Electrolyser (AE) + Hydrogen tank + Fuel cell	1763.1 MWh/year	–	882 $tonCO_2$/year	Eastern Saudi Arabia
Mohammed et al. (2023)	PV + Electrolyser (AE) + Hydrogen tank + Fuel cell (PEMFC)	409 MWh/year	–	214.88 $tonCO_2$/year	Eastern Saudi Arabia
Shahverdian et al. (2023)	PV + Wind Turbine + Electrolyser (PEM) + Hydrogen tank + Fuel cell (PEMFC)	–	33353 mol/year	86.94 $tonCO_2$/year	Tehran, Iran.

3. CONCLUSION AND FUTURE DIRECTIONS OF RESEARCH

This paper has presented some of the hydrogen-based energy production and storage technologies that are in use or still under development, types of electrolyzers, forms of storage and types of fuel cells, which are the fundamental part of solar PV - Battery - Hydrogen hybrid systems. Technological advances in each of these components are decisive and determine the future potential to make a breakthrough in changing the world's energy matrix and thus also help to reduce CO2 emissions. Among the main challenges to be overcome are:

- Improve the durability and reduce the costs of SOE and AEM electrolyzer and fuel cell technologies by increasing investment in development and research that shows great potential.

- Enhancing both the forms and the materials used for storing and transporting hydrogen, since this is the part of the system that most limits its full potential and determines its infrastructure and the end use that hydrogen could have.

- Investigate the possibility of implementing this type of system in more communities and small towns around the world so that they can serve as pilot projects that would help bring electricity to remote locations or places where this resource may be limited.

4. ACKNOWLEDGEMENTS

This study was financed in part by the Minas Gerais State Research Support Foundation, FAPEMIG – Brazil, and the National Council for Scientific and Technological Development (CNPq), Brazilian governmental agencies.

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