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# Cogeneration: another way to increase energy efficiency of hybrid renewable energy hydrogen chain – A review of systems operating in cogeneration and of the energy efficiency assessment through exergy analysis

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## ABSTRACT

The intermittence of renewable sources requires an efficient and sustainable technology for storing energy. Hydrogen storage system (HSS), consist of electrolyzer, storage system and electricity generator, is a promising solution, due to the high energy content and the pollution-free nature of hydrogen. However, the high expense is a major obstacle for the practical utilization of HSS. Cogeneration can be a feasible way to handle this issue, since recovery and utilization of the produced heat improve the efficiency of the global system. Due to the different natures of energy flows (i.e., power, heat, hydrogen) in the cogeneration systems, an exergy analysis is essential to assess the overall efficiency. In this paper, a state of the art of the existing hybrid renewable energy – HSS system operating in cogeneration is proposed including their technical description, their cost, their efficiency and the operating experience. Moreover, a review of the different ways to carry out an exergy analysis for these systems is also presented. First, the entire value chain of hydrogen is briefly described from the production through electrolysis water trough to its storage, its regeneration by means of fuel cell, its transportation and its use. Secondly, a detailed description of the existing hybrid renewable energy – HSS system operating in cogeneration is provided. Systems were classified according to their connection configuration (grid connected, local grid and stand-alone building). A third part contains the optimization methods that have been applied to this kind of system. Finally, last part focuses on exergy analysis including a definition of exergy concept followed by a review of exergy analysis carried out on CHP-systems. This synthesis work highlighted the positive impact of cogeneration on the global efficiency of HSS and showed that the exergy analysis is essential to assess the system and to determine which steps of the system need to be improved. .

## HIGHLIGHTS

- The entire hydrogen value chain is described from production to utilization.
- The hybrid renewable source – hydrogen systems operating in cogeneration are reviewed.
- Optimization algorithms for the systems operating in cogeneration are compared.
- The exergy analyses carried out on hydrogen systems are reviewed.

*Keywords:* Renewable energy - Hydrogen chain – Energy storage – Combined heat and power – Hydrogen cogeneration – Exergy

## NOMENCLATURE

### *Abbreviations*

CHP: Combined Heat and Power  
PV: Photovoltaic  
CAPEX: Capital Expenditure  
OPEX: Operational Expenditure  
CCS: Carbon Capture and Storage  
RENE: renewable energy  
SMR: Steam Methane Reforming  
LTE: Low Temperature Electrolysis  
PEM: Proton Exchange Membrane  
AEM: Anion Exchange Membrane  
HTE: High Temperature Electrolysis  
SOE: Solid Oxide Electrolysis  
LOHC: Liquid Organic Hydrogen Carriers  
MOFs: Metal organic frameworks  
AFC: Alkaline Fuel Cell

PEMFC: Proton Exchange Membrane Fuel Cell  
 DMFC: Direct Methanol Fuel Cell  
 PAFC: Phosphoric Acid Fuel Cell  
 MCFC: Molten Carbonate Fuel Cell  
 SOFC: Solid Oxide Fuel Cell  
 FC: Fuel Cell  
 GHG: Greenhouses Gases  
 HRS: Hydrogen Refueling Station  
 LHV: Lower Heating Value  
 HICE: Hydrogen Interne Combustion Engine  
 ECS: Energy Complementary System  
 NEDO: New Energy and Industrial Technology Development Organization  
 HARI: Hydrogen and Renewable Integration  
 HHV: Hydrogen High Value  
 NTP: Normal Temperature and Pressure  
 MPC: Model based Predictive Control  
 PSO: Particle Swarm Optimization  
 HSS: Hydrogen Storage System  
 APC: Absorption Power Cycle  
 DHW: Domestic Hot Water  
 HRSG: Heat Recovery Steam Generator  
 PTSC: Parabolic Through Solar Collector  
 SPE: Solid Polymer Electrolyte  
 PEMFC HR: PEMFC with heat recovery  
 PEMFC EH: PEMFC coupled with an external electric heater

### *Symbols*

Ex: Exergy of some system (J)  
 En: Energy of some system (J)  
 $\dot{E}x_D$  : Exergy destruction (W)  
 T: Temperature (K)  
 S: Entropie (J/K)  
 P: Pressure (Pa)  
 V: Volume (m<sup>3</sup>)  
 N<sub>i</sub>: Number of mole (mole)  
 $\dot{Q}_{cv}$ : Heat flow (W)  
 $\dot{m}_i$ : Mass flow of some component i (kg/s)  
 $\dot{W}$ : Work (W)  
 $\dot{W}_{elec}$ : Electrical power (W)  
 $\dot{Q}_{heat}$ : Heat rate (W)  
 $s_i$ : Molar entropy of component i (J/(K.mol))  
 $h_i$ : Molar enthalpy of component i (J/mol)  
 $ex_i$ : Molar exergy rate of component i (J/mol)  
 $\dot{e}x_i$  : Mass exergy rate of component I (J/kg)  
 $\dot{n}_i$ : Molar flow rate of component i (mol/s)  
 SI: Sustainable Index

### *Greek letters*

$\mu$ : chemical potential (J/mol)  
 $\eta_{ex}$ : exergy efficiency (%)

### *Subscripts and exponents*

$i$ : related to some component  
 $o$ : related to the environment  
 $CHE$ : chemical  
 $PH$ : physical  
 $T$ : thermal  
 $P$ : mechanical  
 $W$ : work  
 $i_{in}$ : input flow  
 $o_{out}$ : output flow  
 $EN,AV$ : avoidable endogenous exergy  
 $EN,UN$ : unavoidable endogenous exergy  
 $EX,AV$ : avoidable exogenous exergy  
 $EX,UN$ : unavoidable exogenous exergy  
 $ex,ov$ : related to the exergy of the entire system

## I. Introduction

Over recent decades, energy consumption has been constantly increasing. Tremendous international and national organizations have set a number of objectives to build a more sustainable economy involving renewable energies (solar, wind, hydraulic, and biomass, etc.). The intermittence of these energy resources is a major obstacle for their further development; thus it is of critical importance to develop the highly-efficient energy storage technologies. Among the possible ways to store energy, hydrogen is a promising energy carrier, since it has a very high energy density and can be used in various ways. The energy produced by renewable sources is turned into hydrogen through an electrolysis water reaction, and then hydrogen is stored either in gaseous, solid or liquid form. It can be used directly as fuel or as feedstock for chemical industries. It can also be reconverted into power with fuel cells.

Wind energy was converted into hydrogen and electricity for the first time in 1981 in Denmark [1]. Solar energy was then used in 1983 at the Florida Solar Energy Center [2]. In 1991, the first Power to Gas plant was built using hydrogen as the renewable energy (RENE) storage means. [3] Built in 1995 in California, the first plant including a photovoltaic (PV) system and an electrolyzer produced about 50 – 70 Nm<sup>3</sup>/day of hydrogen [4]. Since then many hybrid RENE–hydrogen systems have been built around the world [5], but the efficiency of hydrogen systems is still low in comparison with other technologies such as batteries, which serves as the major obstacle for the extensive utilization of hydrogen technology in practice. Regarding this issue, the simultaneous power and heat production, i.e. cogeneration, allows to significantly improve the efficiency, which can be a very promising way to promote these types of systems [6] [7] [8].

Many studies have been carried out regarding the energy generation from renewable sources. Many authors modelled and optimized RENE systems with or without hydrogen energy systems, while at the same time many experimental plants were built from lab-scale to industrial scale. In 2009 Yilanci et al. published a review focused on solar/hydrogen/fuel cell systems for stationary applications. [9] They investigated the different means of hydrogen production (via solar electricity, via photoelectrolysis, photobiological hydrogen production as well as solar thermal hydrogen production). In this review only the projects which use solar energy were considered. In 2013, Gahleitner reviewed the Power to Gas pilot plants for stationary applications. This paper provides information about installed components and operational data. Abdalla et al. focused on the hydrogen storage and transportation. [10] They offer a detailed review on the studies of metal hydride and liquid organic hydrogen carriers as hydrogen storage medium. In 2018, Guo et al. reviewed the utilization of hybrid RENE systems for several applications (space heating, cooling, power production...). [11] They focused on the biomass hybrid systems. In 2019, Apostolou et al. published a review focused on the installations using wind energy. [12] They investigated how the energy is used as well as the possible hydrogen applications. They compared the efficiency, the carbon dioxide reduction, and the hydrogen cost, etc. of several plants. Parra et al. carried out a techno-economic review of hydrogen energy

systems for Power to Power, Power to Gas and Power to Mobility applications[13]. They investigated the efficiency of the key components and focused on their CAPEX and OPEX. They also examined the value creation of these systems such as selling prices of the products (gas, electricity, oxygen, heat). Maggio et al. published a review on the hydrogen production systems focused on socio, technical and economic aspects. [14] They investigated the forecasts, scenarios, visions, backcasts and roadmaps of hydrogen production systems by comparing electrolysis and SMR processes. They highlighted the drivers and obstacles for the development of hydrogen energy systems as well as its possible impact on the electricity and fuel markets. Recently, the cogeneration in hydrogen energy systems attracts more and more attention [15][16][17][18][19][20]. In fact, different processes in the HSS systems (e.g., electrolysis and fuel cell) generate heat which can be recovered and used for various applications. The cogeneration allows to significantly increase the whole efficiency of a specific plant, and can provide around 40% energy savings. [21]

Since 1980s, there have been 99 hydrogen projects identified, including lab-scale systems, demonstration, pilot and industrial plants, using different RENE sources and for different applications. The current paper will cover 22 projects of them involving cogeneration closely. Their configurations, operating states, economics and energy efficiencies will be analyzed and compared carefully to highlight the advantages and disadvantages of different designs of hydrogen CHP systems in practice, which may provide meaningful guidelines for the construction and operation of practical projects. Moreover, exergy analysis on those HSSs, which allows to compare different natures of flow energy and provides the information on both quantity and quality of energy [17] [19] [20], will be discussed here. Based on this, the exergy loss contributions from each component integrated within the hydrogen systems will be given, which can help researchers to identify the bottlenecks that limit the overall efficiencies of hydrogen systems and thus design the corresponding optimal schemes. Therefore, the present work can be helpful for both practical utilization and optimization of hydrogen with cogeneration, which will be an essential reference in this area.

## II. Description of Hydrogen value chain

Hydrogen value chain refers to the entire hydrogen lifecycle from production to utilization. Hydrogen economy concept emerged in the 1970s to designate the use of hydrogen as an energy storage and transportation medium [9]. This part describes the main steps of the hydrogen chain in order to contextualise the current situation of the hydrogen production and use and to ensure understanding of the following parts.

### 2.1. Hydrogen production

Hydrogen itself is a kind of clean and green energy source that generates no polluting particle nor carbon emission at the use end, but its production is not always as this. In fact, currently hydrogen is mainly produced from traditional fossil fuels: 96% of hydrogen production is from non-RENE [11] [22][23], while only 4% is from RENE [12], mostly through electrolysis. The different methods for hydrogen production are summarized and compared in Table 1. Generally, the approaches based on fossils fuels are more mature and of lower cost, when compared to those RENE-based ones. Although the RENE-based electrolysis has been well developed, its cost remains high. The other RENE-based methods, like bio-photolysis and dark fermentation, which hold the cost comparable to the traditional approaches, are still far away from maturity. Therefore, how to achieve the transition from the fossil-fuel hydrogen to zero-carbon hydrogen is still a critical challenge. Here, we will focus on analyzing the electrolysis technique in the following sections, since it is the most used one in practical RENE systems involving hydrogen.

**Table 1** Hydrogen production processes [13], [11], [4], [10] [24]

Hydrogen production process	Sustainable sources of raw material (Yes/No)	Carbon neutral (Yes/No)	Maturity	Efficiency	Cost (\$/kg)

Steam reforming	No (natural gas)	No	Very mature	74 - 85	2.27
Partial oxidation	No (natural gas)	No	Very mature	60 - 75	1.48
Auto thermal reforming	No	No	Very mature	60-75	1.48
Gasification from coal	No	No <i>except with CCS or sustainable biomass</i>	Mature	30 -40	1.77 - 2.05
Electrolysis	Yes (if use of RENE)	Yes (if use of RENE)	Mature	60 - 80	10.30
Bio-photolysis	Yes	Yes	Low	10-11	2.13
Dark fermentation	Yes	Yes	Low	60 -80	2.57
Photolysis	Yes	Yes	Low	0.06	8 -10

### 2.1.1. Principle of water electrolysis

Among the sustainable hydrogen production methods, water electrolysis is the most used since it is an environmentally friendly (carbon free) process and allows to store the surplus of RENE. Electrolysis is therefore the only possible way for the systems described in this paper. However, this process is two to three times more expensive than SMR [25] due to the use of noble metal catalyst. Electrolysis process is an electrochemical reaction which uses electric current to split water into hydrogen and oxygen, equation (1):

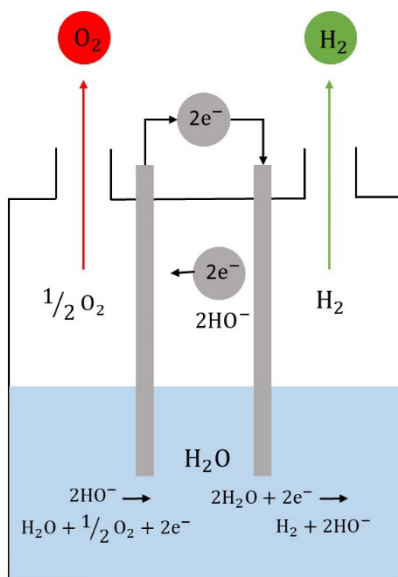
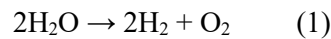


Fig. 1. Principle of electrolysis water in aqueous alkaline media.

The reaction occurs in a system called electrolyzer which consists of a DC source and two noble metal coated electrodes (Fig. 1). These two electrodes are separated by an ionic conductor electrolyte. Several electrolyzer types exist depending on the electrolyte material and the operating temperature, and available in a large size range for small to large scales. Water electrolysis consists of the water dissociation into hydrogen  $\text{H}_2$  and hydroxide ions  $\text{HO}^-$ . These hydroxides ions move in the electrolyte towards the positive pole (anode). At the anode, they absorb the electrons and are then oxidized to form water and oxygen. In the case of solid polymer, electrolyte (SPE) membrane, the hydrogen and oxygen

produced cannot be mixed, only hydroxide ions can pass through the membrane. The SPE serves also as an electrical insulator.

### 2.1.2. Different types of water electrolysis

Two types of electrolysis can be distinguished: (i) low temperature electrolysis (LTE) including alkaline (ALK) electrolysis, proton exchange membrane (PEM) electrolysis and anion exchange membrane (AEM) electrolysis; (ii) high temperature electrolysis (HTE) including solid oxide electrolysis (Fig. 2). This solid oxide electrolysis (SOE) is still in a development stage. A higher conversion efficiency as well as the production of syngas directly from steam and carbon dioxide are expected with this technology. Table 2 shows the main characteristics of ALK, PEM, AEM, and solid oxide electrolyzers. The water electrolyzer efficiency is calculated as the ratio between the amount of input electricity and the amount of produced hydrogen, and it is currently 60 – 80% based on the calorific value. The electrolyzer stack efficiency depends on several parameters, such as the configuration and components, the operating temperature and pressure. These parameters are also affected by the value of the load. The higher the temperature, the higher the efficiency. Hydrogen can be pressured internally, namely by increasing the pressure inside the electrolyzer, or externally namely by adding an additional compressor between the electrolyzer and the storage tank. The compression into the electrolyzer allows to have a better efficiency but increases the degradation rate of the stack.

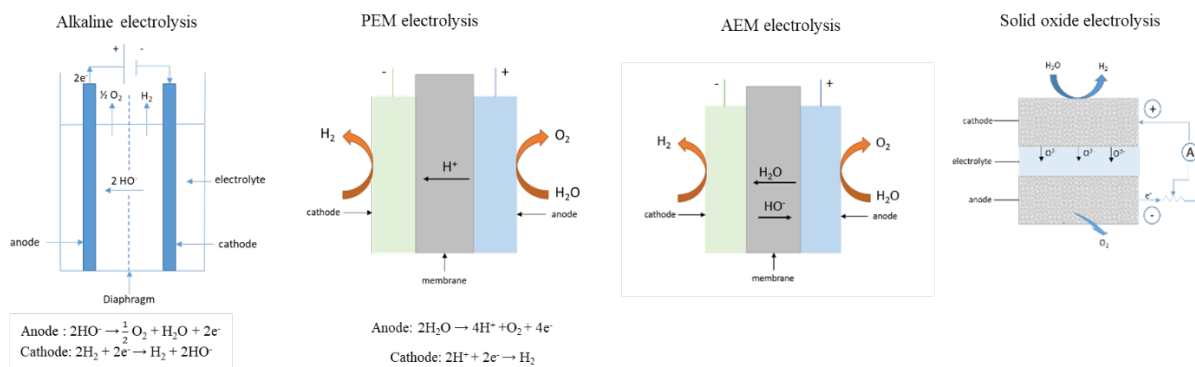


Fig. 1. Principle of the main electrolyzer technologies.

### 2.1.3. Alkaline and PEM electrolysis

Currently, ALK and PEM electrolyzers are the most used technologies. Until 2010, ALK electrolyzer was mainly adopted due to its maturity. Nevertheless, PEM electrolyzer has many advantages, such as a better starting behavior or a good dynamic operation with intermittent and fluctuating power sources, high pressure, high current and electrical power density. Therefore, there have been many pilot projects aimed to study it and to improve its performance.

ALK and PEM technologies are used in almost equal proportions for the power lower than 10 kW, including mainly the lab-scale and the demonstration plants. However, for the power between 10 and 100 kW, ALK technology is more used due to its maturity. The current researches concerning electrolyzer are focused on the improvement of the global efficiency of electrolyzer system, the lifetime, the operating power density and the stack size, the reduction of cost, the integration of pressurized system (to avoid the need of additional compression for the produced hydrogen), and finally the development of flexible systems compatible with intermittent and fluctuating power supply. Table 3 gives the advantages and disadvantages of both ALK and PEM electrolysis. Through the comparison in Table 3, the ALK is the more mature technique and suitable for large-scale applications, but mainly suffers from the problems of hydrogen purity and dynamic operation. By contrast, the



dynamic operation and hydrogen purity of PEM are improved, but it has not been a mature tech yet, which is not applicable for large-scale and long-term utilization in practice.

**Table 2** Main characteristics of ALK, PEM and Solid oxide electrolyzers

	Alkaline electrolysis	PEM electrolysis	Solid oxide electrolysis	Ref
Typical pressure (bar)	$P_{atm} - 30$ bars	$P_{atm} - 50$	$P_{atm} - 15$	[26]
Operating temperature (°C)	60 - 90	50 - 80	700 - 1000	[13], [26]
Current density (A/cm <sup>2</sup> )	0.2 – 0.6	1.0 – 2.0	0.3 – 1.0	[27]
Load flexibility (% of nominal load)	20 - 100	0 – 100	-100 / +100	[13]
Nominal stack efficiency (LHV)	63 – 71 %	60 – 68 %	100 %	[4]
Nonimal system efficiency (LHV)	51 – 60 %	46 – 60 %	76 – 81%	[4], [26]
Maximal nominal power per stack (MW)	6	2	0.01	[3]
Hydrogen production per stack (Nm <sup>3</sup> /h)	1400	400	10	[26]
Life time (kh)	55 – 120	60 -100	-	[13]
Degradation rates	1–2 $\mu$ V/h	up 3–8 $\mu$ V/h		[13]
Efficiency degradation per year	0.25 – 1.5 %	0.5 – 2.5 %	3 – 50 %	[13]
CAPEX (€/kWe)	Current: 750 – 1200 By 2030: 400-800	Current: 1200 – 2000 By 2030: 400-1700	-	[13]
OPEX of investment costs per year	<b>Small scale</b>	Current: 1.4 – 5.1 By 2030: 1.1- 11.9	Current: 1.6 – 5.5 By 2030: 0.9- 18.4	[13]
	<b>Large scale (1MWe)</b>	Current: 2.1 – 7.3 By 2030: 1.8-14.6	Current: 2.6 - 6.6 By 2030: 1.7-9.2	[13]

**Table 3** Comparison between ALK and PEM electrolysis [3], [13], [28]

	Alkaline electrolyzer	PEM electrolyzer
Advantages	Mature technology and widely experimented Suitable for large scale	Better starting behavior Wider operational range High hydrogen purity Higher pressure can be achieved Good dynamic operation with intermittent and fluctuating power sources Very promising for refueling stations
Disadvantages	Needs further improvement in dynamic operation Needs efficiency improvement Lower hydrogen purity Safety problems with the KOH electrolyte solution (tiredness and severe headaches among the personal operation) Problems with intermittent and fluctuating power sources (delayed reaction) and difficulties in starting the system after a shutdown	Not suitable for large scale Shorter lifetime than the manufacturers warranties Very rapid stack degradation Freezing of the membrane in winter

## 2.2. Hydrogen storage

Hydrogen can be stored in various ways which can be divided into two categories (physical and chemical) and kept several months. (Fig. 3). The detailed discussions about them will be given in following sub-sections:

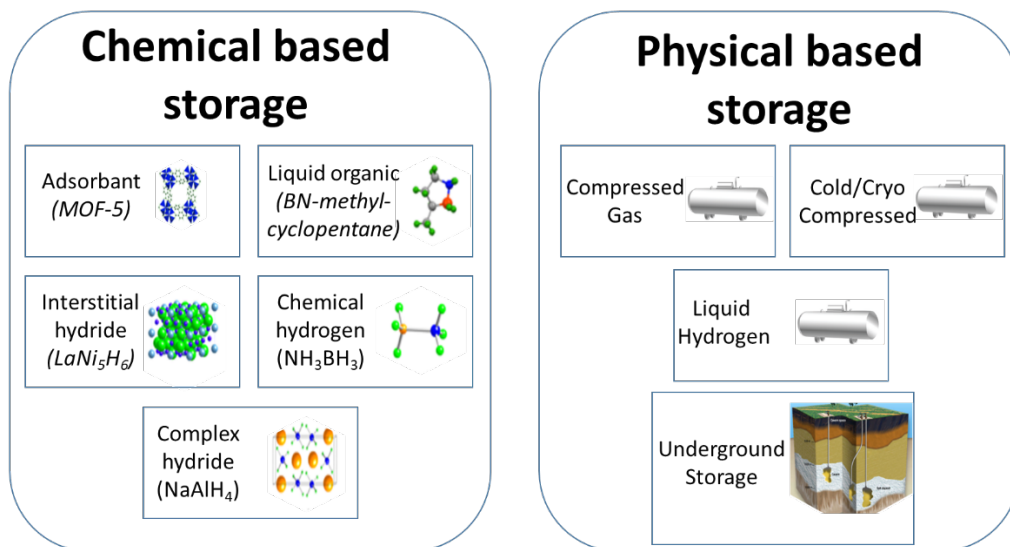


Fig. 2. Main technologies to store hydrogen.

### 2.2.1. Physical based storage

Hydrogen can be stored in tank through three techniques: liquid hydrogen, cold and cryo compressed hydrogen, and compressed hydrogen. Compressed hydrogen is the storage method mostly used. It kept the gas under high pressure in the tank in order to increase the storage density [29], since at 700 bar hydrogen density is 42 kg/m<sup>3</sup> while at 0°C and 1 atm its density is around 0.090 kg/m<sup>3</sup>. The operating pressure ranges from a few bars to several hundred bars. Furthermore, hydrogen can be liquefied by reducing its temperature to -252.87 °C at atmospheric pressure, with the density equal to 71 kg/m<sup>3</sup>. [29] The liquefied hydrogen has a higher energy density, but it requires a complex technical plant to prevent the possible evaporation. Therefore, this method is only utilized for the applications requiring a high purity of hydrogen. [30] Another way to store hydrogen is the combination of both

compression and cooling to obtain a higher energy density in comparison to the compressed gas. Hydrogen is cooled before being compressed. However, a higher energy input is required due to the cooling process. Figure 4 shows the principles of these three methods. The last means is the underground storage, including salt caverns, depleted oil or gas reservoirs and aquifers. However, this kind of storage method is expensive and cannot be applied everywhere.

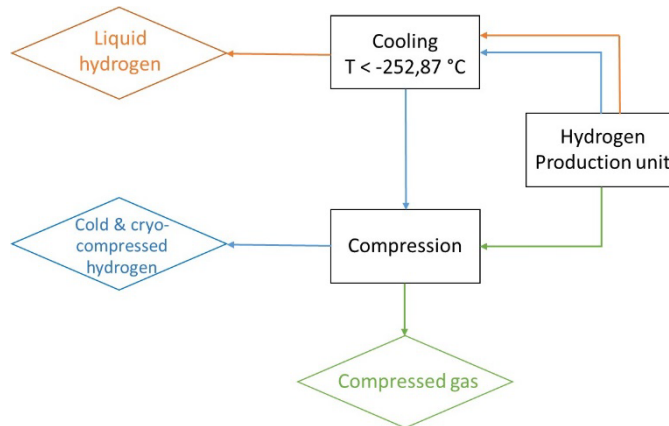


Fig. 3. Principles of liquid, cold and cryocompressed hydrogen storage technologies.

### 2.2.2. Chemical based storage

Hydrogen can also be stored by means of a reversible adsorption mechanism into another material. [29] Hydrogen can react with certain metals and thus formed interstitial compounds called metal hydride. Hydrogen is first adsorbed on the metal surface and then incorporated in element form into the metallic lattice. When there is a need of hydrogen, it can be desorbed from the metal. Most interesting materials are magnesium or alanate containing compounds. Another way is through use of unsaturated organic compounds such as N-ethylcarbazole and toluene. They can store a large amount of hydrogen through the absorption mechanisms. Liquid Organic Hydrogen Carriers (LOHC) are hydrogenated for storage. They are then dehydrogenated for reusing hydrogen. [31]

Hydrogen storage through adsorption requires the materials with high specific surface areas, such as metalorganic frameworks (MOFs), microporous crystalline aluminosilicates (zeolites), and microscopically small carbon nanotubes).[30] Note that the volumetric storage density increases by using the materials in powder form.

### 2.3. Hydrogen transportation

The state and storage means of hydrogen largely determine the ways of hydrogen transportation. [30] [32] [33]. Hydrogen in gaseous form is easy to transport in long distance and is currently transported mainly in lorries or pipelines. [30] It can also be transported in cryogenic liquid tankers or by blending it with natural gas. [33] The last option allows to use the already existing infrastructures and therefore can avoid the building of dedicated hydrogen pipelines. [30] Two options have been proposed: either use hydrogen natural gas mixture as it is or install the separation and purification units close to the end-use points to extract hydrogen.

### 2.4. Safety

Safety issues of hydrogen during production, transport and utilization are important factors that can affect practical applications of hydrogen energy. Hydrogen is highly flammable, and the safety issues are mainly related to its ignition and combustion features, including wide flammability range, low ignition energy, relatively high flame velocity, rapid diffusion and buoyancy.[30] [34]. Note that hydrogen ascends rapidly into the atmosphere and has less time to burn, since it is the

lightest element on Earth; additionally, in contrast to the carbon based fuels, burning hydrogen produces no hot ash and very little radiant heat. Compressed hydrogen, exactly as other flammable fuels, requires clear rules of usage, and in some cases hydrogen can be safer than the current fuels used to power vehicles. [35] As a crucial subject, the tremendous efforts have been done to develop various technologies to improve the hydrogen safety [34]. For instance, the International Association of Hydrogen Safety named HySafe focuses on the safety issues of hydrogen. [36] The detailed analysis on hydrogen safety issues and their possible solutions is beyond the scope of current paper. More information on this topic can be found in literature. [34] [35]

### III. Presentation of the various uses of Hydrogen

Hydrogen offers a wide range of applications in the energy, industry, and mobility sectors. In 2018, the world hydrogen consumption amounted to 56 million tones.[37] Asian is the main consumer with a consummation of one third of world production followed by north America and west Europe. The various applications of hydrogen are illustrated in Figure 5 and explained as follows.

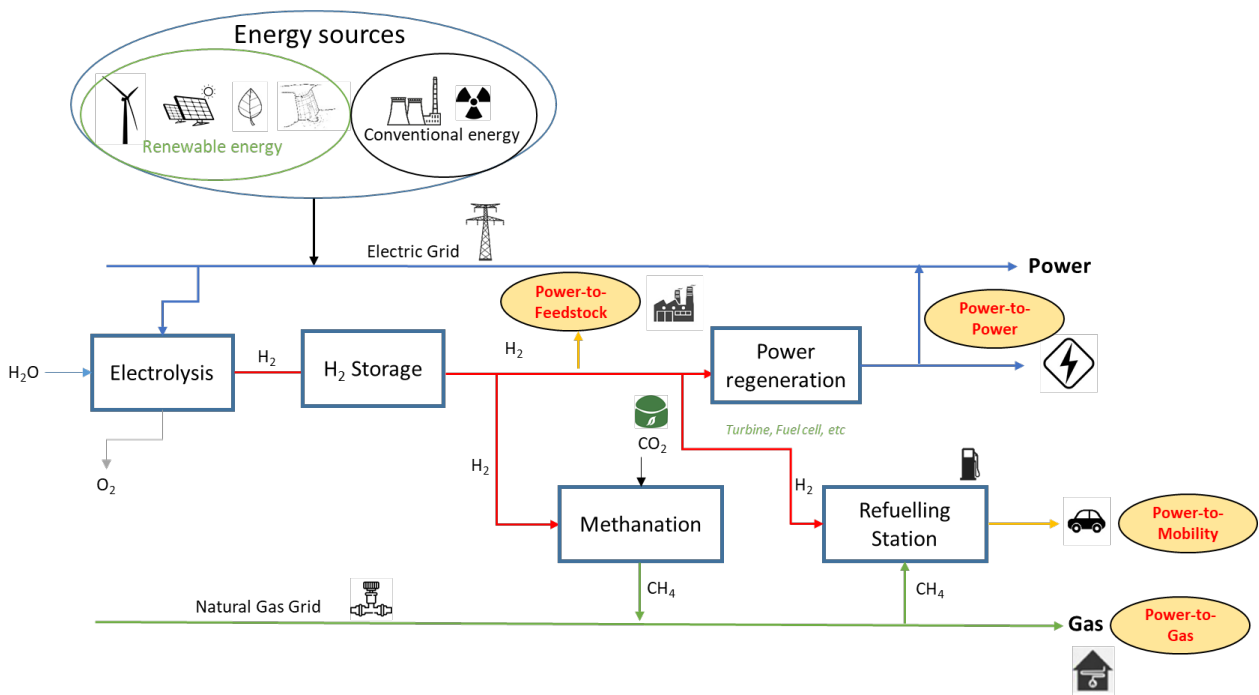


Fig. 4. Schematic of hydrogen value chain including Power to X applications.

#### 3.1. Hydrogen applications in the industries: Power-to-Feedstock

Power to Feedstock (also called Power to Industry) refers to the direct sale of produced hydrogen to industries. Hydrogen is then used as chemical feedstock and enables to decarbonize the industrial sectors. Currently, hydrogen is mainly employed as feedstock for ammonia and fertilizers production (55%), for fuel desulfurization in the refineries (25%), and for other chemicals production such as methanol or amine (10%). The remaining 10% are used in various sectors such as space, food, and glass industries. Overall, the chemical industries represent 63% of the global industrial hydrogen consumption.

#### 3.2. Applications of hydrogen in the energy sector

Hydrogen can be utilized in various ways in the energy sector: it can be injected into the natural gas grid after mixing with natural gas, and turned back into electricity in fuel cells as well as

hydrogen powered turbines. Both of them can be grid-connected or off-grid, allowing to supply remote communities for example.

### 3.2.1. *Power to Power*

Power-to-Power aims to balance the power grid using hydrogen as energy storage medium. In this case, the produced hydrogen through electrolysis is stored. When the electric grid load increases, hydrogen is reconverted into power by a FC (fuel cell) or a hydrogen-powered turbine, which enables the smooth production. The converters and inverters correspond to the greatest cost within the balance between the plants and the hydrogen energy systems.

FC is an environment friendly technique, which utilizes an electrochemical device that converts the chemical energy of the fuel into power through a simultaneous pair of redox reactions between a reducing fuel (such as hydrogen) and an oxidizing agent (such as oxygen). A large size range is available from small device producing a few watts of electricity (single cell) up to large power system producing megawatts (such as modular and scalable PEMFC stack system). Each component of a FC stack is composed of two electrodes which are separated by a solid or liquid electrolyte enabling the ionic charge transfer. [30] The electrodes are generally coated with a catalyst to accelerate the reaction. The overall reaction between hydrogen and oxygen generates electric power, water and heat. At the anode, a positive charge (proton) and a negative charge (electron) are generated due to the electro-oxidation reaction of hydrogen on catalyst. The proton is transferred to the cathode through the electrolyte while the electrons are blocked by the membrane and flow from the anode to the cathode through an external circuit, creating an electrical current. At the cathode, the electrochemical reaction between protons, electron and oxygen produces water and heat.

Several types of FC exist depending on the electrolyte nature, such as alkaline fuel cell (AFC), proton exchange fuel cell (PEMFC), direct methanol fuel cell (DMFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), and oxide fuel cell (SOFC). Table 4 shows the main characteristics of different types of FC. PEMFC is by far the mostly-used technology (90% of operational systems) and covers a large power range. Over the years, the portion of PEMFC is increasing due to their development and improvement. For example, until 2000 their power could not exceed 4 kW in the most cases; however, since 2000 their power has considerably increased and from 2015 the power ranges from 50 to more than 100 kW.

The choice of the FC technologies depends on the power required for the plant but also on the applications envisaged. AFC and PEMFC are very mature technologies, and both of them operate at low temperature. AFC is suitable for the stationary applications, while PEMFC is suitable for the mobile applications. However, PEMFC requires an expensive catalyst on the electrodes. As for AFM, it is the cheapest technology, without the need of precious metal, but it requires the pure hydrogen and oxygen. SOFC has the advantage of operating at high temperature. Moreover, SOFC is very stable, with low operating cost and maintenance, and can generate power constantly. MCFC can also operate at high temperature and be powered by various gases (like syngas, natural gas, biogas, etc.). Its efficiency is high, but its lifetime is short. DMFC operates at low temperature and also requires precious metal on the electrodes, but it is very suitable for portable power applications. Aside from AFC and PEMFC, the other technologies are still under development.

**Table 4** Characteristic of different types of fuel cell technology

Name	Electrolyte [38]	Operating temperature [13], [3], [38]	Catalyst [38]	Reductant fuel used [38]	Efficiency [3], [38]	Characteristics [3], [9], [13], [38]	Maturity of technology [38]
Alkaline (AFC)	Alkaline solution (such as aqueous potassium hydroxide solution)	Low temperature: $\approx 70\text{ }^{\circ}\text{C}$  (23 to 70 $^{\circ}\text{C}$ )	Various non precious metal (generally Nickel based catalyst)	Pure hydrogen	60 %	<ul style="list-style-type: none"> <li>- high electrical efficiencies</li> <li>- cheapest fuel cell</li> <li>- production of drinkable water</li> <li>- used mainly for stationary applications</li> <li>- very sensitive to poisoning by CO<sub>2</sub> =&gt; requires pure hydrogen and oxygen</li> <li>- tend to have large footprints</li> </ul>	Very mature (one of the first developed FC technology)
Proton Exchange Membrane (PEMFC)	Water based, acid polymer membrane	Low temperature: 80 $^{\circ}\text{C}$ (up to 100 $^{\circ}\text{C}$ )	Platinum based catalyst on the both electrodes	Hydrogen		<ul style="list-style-type: none"> <li>- high-power density</li> <li>- large range of electrical output</li> <li>- ideal for vehicle</li> <li>- use for stationary application</li> <li>- low weight and volume</li> <li>-no use of corrosive fluids</li> <li>- reach quickly the operation temperature</li> <li>- deterioration of the membrane at high temperature</li> <li>- expensive catalyst and very sensitive to CO poisoning</li> </ul>	Very mature
Phosphoric Acid (PAFC)	Liquid phosphoric acid in a bonded silicon carbide matrix	150 to 200 $^{\circ}\text{C}$	Dispersed platinum catalyst on carbon		Electrical: relatively low Up to 70% by CHP	<ul style="list-style-type: none"> <li>- quite resistant to poisoning by CO (CO concentration &lt; 1.5%)</li> <li>- for stationary power generation (100 to 400 kW)</li> <li>- suitable for CHP</li> <li>- instability, performance and cost issues</li> </ul>	Developed in the middle 1960s, tested since the 1970s
Solid Oxide (SOFC)	Solid ceramic (zirconium oxide)	Very high temperature : 800 to 1000 $^{\circ}\text{C}$	No precious metal requires	Hydro-carbon, Syngas (H <sub>2</sub> + CO)	50-60 %	<ul style="list-style-type: none"> <li>- Best run continuously due to the high temperature</li> <li>- Suitable for stationary power generation</li> <li>- Due to solid electrolyte, platelike configuration of cells not necessary</li> <li>- Not vulnerable to carbon monoxide catalyst poisoning</li> <li>- Vulnerable to sulfur</li> <li>- Various applications from auxiliary power units in vehicle to power plant</li> <li>- Very suitable for cogeneration (heat and power)</li> </ul>	
Molten Carbonate (MCFC)	Molten carbonate salt mixture suspended in a porous chemically inert ceramic oxide (LiAlO <sub>2</sub> ) matrix	Very high temperature: > 650 $^{\circ}\text{C}$	No precious metal required	Natural gas, biogas, syngas, methane and propane	Electrical: 60%  Up to 85% by CHP	<ul style="list-style-type: none"> <li>- developed for natural gas and coal-based power plants for electrical utility, industrial and military applications</li> <li>- more affordable (not use precious metal)</li> <li>- high efficiency</li> <li>- low power density</li> <li>- short lifetime</li> <li>- sensitive to corrosion</li> </ul>	
Direct Methanol (DMFC)	Polymer membrane	Low temperature: 60 to 130 $^{\circ}\text{C}$	Anode:platinum ruthenium Cathode: platinum	Methanol + steam		<ul style="list-style-type: none"> <li>- suitable for portable power applications (needed output &lt;W)</li> </ul>	

### 3.2.2. *Power to Gas*

Another hydrogen application is called Power to gas and consists of injecting hydrogen into the natural gas network for heat and power production after mixing with natural gas (for safety reasons). [14] [25] Hydrogen can also be transformed into methane through methanation process. Power to gas has many advantages: no additional infrastructure investment is necessary; it allows to stabilize the grid and to reduce GHG emissions.

### 3.3. *Hydrogen for the mobility sector: Power to Mobility*

In the transport sector, hydrogen can be used as fuel to power vehicles, called Power to Mobility. The vehicle is composed of a FC powered by hydrogen. Hydrogen tank improves the vehicle autonomy compared to battery and reduces the refueling time. This application requires the implementation of hydrogen refueling station (HRS). Power to Mobility is considered as the major reference market for hydrogen and offers a wide range of applications, such as passengers cars, buses, aviation, trains, maritime applications, and space applications. [30]

## **IV. Existing Hybrid Hydrogen RENE systems operating in CHP**

During their operation, the processes aimed for the energy storage by the means of hydrogen generate heat, which can be recovered and utilized for various applications. The simultaneous production and utilization of power and heat is called cogeneration or CHP. It allows to significantly increase the whole efficiency of a plant. Indeed, the efficiency of conventional plants is lower than 40%, while it is higher than 85% for the CHP plants. [39] Although the CHP combined with RENE has been extensively investigated in literature [15] [16] [17] [18] [19] [20], currently most of the plants producing power from RENE sources do not use the generated heat in practice. The heat generated in hydrogen storage process should be minor. Out of almost 100 projects using a hydrogen-RENE chain, only 22 of them are CHP plants. 4 of the 22 systems are no longer operating now and 2 have not operated yet (the summary is given in Table 5). These platforms operate in either the grid-connected mode or the standalone mode, and sometimes the both. Wind and solar energy are mostly used (83% wind energy and 50% solar energy), while hydraulic energy only accounts for 25% and is always in combination with another type of energy. The combination of several energy sources represents 33% of the platforms. The installed capacity of power stations ranges from a few kilowatts to several megawatts. Most of hydrogen RENE systems are located in Germany (58%), while 25% of them are in United Kingdom. Table 5 lists some RENE-CHP projects. These selected projects are made up of the same type of units, but the adopted technologies can be very different. Here, these projects are classified into three types: grid connected, local grid, and stand-alone cases, in terms of their working conditions. We will describe the selected projects and provides their technical specifications in the following section.

**Table 5** Renewable energy types used by CHP systems (listed in chronological order)

Name	Date	Design	Renewable energy			Ref
			Wind	Solar	Hydraulic	
<b>SWB (Germany)</b>	1989 – 1996	Grid connected		370 kWp		[40]
<b>Self-sufficient Solar House (Germany)</b>	1992 – 1995	Standalone		4,2 kWp		[9]
<b>Laboratory Plant Stralsund (Germany)</b>	1998 – in operation	Grid connected	100 kW	10 kW		[41]
<b>GlashusEtt (Sweden)</b>	1998 – in operation	Grid connected Stand alone		3 kW		[42]
<b>HARI (UK)</b>	2002 – in operation	Stand alone	50 kWp	13 kWp	3,2 kWp	[43]
<b>PURE (UK)</b>	2005 – in operation	Local grid	30 kW			[3], [44]
<b>Hydrogen Community Lolland (Denmark)</b>	2006 – in operation	Local grid	3,3 MW			[45]
<b>Clean Energy Center (Turkey)</b>	2007 – in operation	Standalone		5 kWp		[9]
<b>The Hydrogen Office (Scotland)</b>	2008 – 2014	Standalone	750 kW			[46]
<b>H2KT (Greenland)</b>	2010 – in operation	Grid connected Local grid	X		x	[47], [3]
<b>H2SUSBUILD (Greece)</b>	2010 – 2012	Local grid	X	X		[48]
<b>ENERTRAG (Germany)</b>	2011 – in operation	Grid connected	6000 kW			[3]
<b>RH2WKA (Germany)</b>	2013 – in operation	Grid connected	140 MW			[49]
<b>H2Herten (Germany)</b>	2013 – 2025	Stand alone	X			[3]
<b>H2Ber (Germany)</b>	2014 – in operation	Grid connected	X			[50], [51]
<b>H2orizon (Germany)</b>	2017 – in operation	Grid connected	3 MW			[52]
<b>Alzey, Exytron Null E (Germany)</b>	2017 – in operation	Local grid		125 kW		[53]
<b>BIG HIT (UK)</b>	2018 – in operation	Grid connected Local grid	1800 kW		x	[54]
<b>Haßfurt hydrogen storage plant (Germany)</b>	2019 – in operation	Grid connected	X			[40]
<b>NEDO Kofu City, Yamanashi Prefecture (Japan)</b>	2019 – in operation	Standalone		10 MW		[55]

**Table 5** (continued)



Name	Date	Design	Renewable energy			Ref
			Wind	Solar	Hydraulic	
<b>Bad Lauchstädt energy park (Germany)</b>	2022	Grid connected	40 MW			[56]
<b>HyPort (Belgium)</b>	2025	Grid connected	2.26 GW			[57]

#### 4.1. Description and Operating experience

These projects are classified into three categories according to their connection configurations (i.e., grid connected, local grid and standalone projects). Table 6 summarizes the main characteristics of the selected projects. The analysis on these projects will be conducted category by category.

**Table 6** Main characteristics of hybrid RENE Hydrogen systems (listed in chronological order)

Name	Electrolyzer	Hydrogen storage system	Hydrogen use				Ref
			Fuel Cell	CHP	Catalytic burner	Biogas burner	
SWB (Germany)	Alkaline 100 kW 22,3 Nm <sup>3</sup> /h HHV = 79 %	Pressurized tank 30 bar 5 000 Nm <sup>3</sup>	AFC 6,5 kW <sub>el</sub>				[40]
			PAFC 80 kW <sub>el</sub> 42 kW <sub>therm</sub>				
			PEM 100 kW				
Self sufficient Solar House (Germany)	PEM 2 kW 0,4 Nm <sup>3</sup> /h HHV = 63 %	Pressurized tank 28 bar 15 Nm <sup>3</sup>	PEM 3,5 kW <sub>el</sub>				[9]
Laboratory Plant Stralsund (Germany)	Alkaline 20 kW 4 Nm <sup>3</sup> /h HHV = 71 %	Pressurized tank 25 bar 200 Nm <sup>3</sup>	PEM 1,2 kW <sub>el</sub>	30 kW <sub>el</sub> 70 kW <sub>therm</sub>	20 kW		[41]
GlashusEtt (Sweden)	PEM 0,6 Nm <sup>3</sup> /h Efficiency = 48 %	Pressurized tank 13,8 bar 15 Nm <sup>3</sup>	PEM 4 kW			24 kW	[42]
HARI (UK)	Alkaline 36 kW 8 Nm <sup>3</sup> /h HHV = 83 %	Pressurized tank 137 bar 2856 Nm <sup>3</sup>	PEM 2 kW <sub>el</sub> 2 kW <sub>therm</sub>	15 kW <sub>el</sub> 38 kW <sub>therm</sub>			[43]
			PEM 5 kW <sub>el</sub>				
PURE (UK)	Alkaline 15 kW 3,55 Nm <sup>3</sup> /h HHV = 84 %	Pressurized tank 30 bar 44 Nm <sup>3</sup>	PEM 5 kW <sub>el</sub>				[3], [44]
Hydrogen Community Lolland (Denmark)	X	Not specified	PEM 1.5 kW				[45]
Clean Energy Center (Turkey)	PEM 3,35 kW 0,5 Nm <sup>3</sup> /h Efficiency = 56 %	Metal hydride 14 bar 5,4 Nm <sup>3</sup>	PEM 2,4 kW				[9]
The Hydrogen Office (Scotland)	30 kw 5.3 Nm <sup>3</sup> /h HHV = 70 %	Not specified	10 kW				[46]
H2KT (Greenland)	Alkaline 98 kW 19,4 Nm <sup>3</sup> /h HHV = 70 %	Pressurized tank 12 bar 185 Nm <sup>3</sup>	PEM 20 kW <sub>el</sub>				[47], [3]

H2SUSBUILD (Greece)	Alkaline	Not specified	X			X	[48]
ENERTRAG (Germany)	Alkaline 500 kW 120 Nm <sup>3</sup> /h HHV = 85 %	Pressurized tank 31 bar 15 Nm <sup>3</sup>		700 kW <sub>el</sub> 800 kW <sub>therm</sub>			[3], [58]
RH2 WKA (Germany)	Alkaline 1000 kW 200 Nm <sup>3</sup> /h HHV = 71 %	Pressurized tank 300 bar 3500 Nm <sup>3</sup>		250 kW <sub>el</sub> 400 kW <sub>therm</sub>			[49]
H2Herten (Germany)	Alkaline 152 kW 30 Nm <sup>3</sup> /h HHV = 70 %	Pressurized tank 50 bar 115 Nm <sup>3</sup>	PEM 50 kW <sub>el</sub>				[3]
H2Ber (Germany)	Alkaline 0.5 MW 250 kg/day H <sub>2</sub>	Solid state H <sub>2</sub> storage Capacity = 100 kg  Pressurized tank		x			[50], [51]
H2orizon (Germany)	PEM 880 kW 70 Nm <sup>3</sup> /h HHV = 70%			1,4 MW <sub>el</sub> 1.6 MW <sub>ther</sub>			[52]
Alzey, Exytron Null E (Germany)	Alkaline 40 kW 14 Nm <sup>3</sup> /h	Not specified		x			[53]
BIG HIT (UK)	PEM 500 kW 50 t/year	Not specified	Technology not specified 75 kW				[54]
	PEM 1 000 kW 50 t/year						
Hassfurt hydrogen storage plant (Germany)	PEM 1250 kW 225 Nm <sup>3</sup> /h	Not specified		170 kW <sub>el</sub> 183 kW <sub>therm</sub>			[40]
NEDO Kofu City, Yamanashi Prefecture  (Japan)	PEM 1.5 MW		5 kW (planned for 2021)				[55]
Bad Lauchstädt energy park (Germany)	35 MW 7777,8 Nm <sup>3</sup> /h	Underground storage Capacity = 50 Mio.m <sup>3</sup>					[56]
HyPort (Belgium)	50 MW 11111.11 Nm <sup>3</sup> /h	Not specified					[57]

#### 4.1.1. Grid connected cases

Solar Wasserstoff Bayern (SWB) in Germany was the first plant built composed of a hydrogen RENE chain using solar energy. In operation from 1986 to 1996, SWB aimed to assess the performances of a hydrogen system as storage medium in an industrial demonstration scale grid connected plant [40,59]. The plant was equipped with a hot and cold production systems including a 20 kW<sub>th</sub> air-powered gas boiler, a 20 kW<sub>th</sub> oxygen-powered gas boiler, and a 17 kW<sub>th</sub> catalytic- absorption chiller. Many operating problems occurred with the AFC: after about 2600 operation hours, the alkaline fuel cell output decreased of about 15 kW. Therefore, in 1994 the AFC was replaced by a PAFC. Three electrolyzer stacks had to be changed. The two firstly operated at a pressure of 1.5 bar, while the third was at a pressure of 32 bar. Between 1990 and 1996, a 100 kW PEM electrolyzer was tested. No problems occurred with hot and cold production systems, demonstrating that it is a very promising technology. Also in Germany, RH2WKA had been built between 2013 and 2015 [49], which uses 28 wind turbines (WTs) to generate the power of 140 MW, an alkaline electrolyzer, the pressurized tanks for hydrogen storage, and two CHP units with a total capacity of 250 kW<sub>el</sub> and 400 kW<sub>th</sub>. The generated power is fed into the national grid and supplied to 125 000 households, while the heat is sold to the local customers. The efficiencies of electrolyser, CHP-unit and whole system are 60.7%, 33.2% and 85%, respectively. Moreover, the industrial plant ENERTRAG was built in 2011 including WTs, 500 kW alkaline electrolyser, a HRS operated by Total (a biogas production system, 350 Nm<sup>3</sup> per hour) and two 350 kW<sub>el</sub> and 400 kW<sub>th</sub> CHP-

units powered by a hydrogen -biogas mix (70% hydrogen at maximum) [3]. It can heat 80 houses. ENERTRAG can operate in several modes: hydrogen production mode, basic charge mode (constant electrical power generation), forecast mode (predictable over 8 hours) and nominal charge mode (input power defines the electricity power injected to the grid). In November 2014, more than 100 MWh of wind energy has been converted into hydrogen and injected into the gas network. In 2019, a new hydrogen storage plant was built in Haßfurt in Germany [40]. The power is generated from wind energy and stored by a hydrogen storage system. The hydrogen, produced by a 1.25 MW PEM electrolyzer, is either used as fuel in the CHP unit or fed into the natural gas grid. The CHP unit capacity is 170 kW<sub>el</sub> and 183 kW<sub>therm</sub> with an efficiency of 80%. In Greenland, a hydrogen RENE chain, called H2KT, was built in 2010 using the wind and hydraulic energy [47]. 60% of the energy used for hydrogen production is obtained from the hydraulic energy. It consists of the WTs, an hydropower plant, an alkaline electrolyzer, the pressurized tank and two PEM fuel cells of 10 kW<sub>el</sub> each [3]. The generated power is fed into both the national grid and the local grid for the Nukissiorfiit building, while the heat is only employed to heat the Nukissiorfiit building.

Over the last few years, new projects have diversified the hydrogen applications. Installed in 2014 at Berlin Airport, H2Ber plant is composed of an RENE-HSS including a CHP-unit and a solid state H2 storage system with a 100 kg capacity [51]. The produced power is injected into the grid, while the hydrogen is into the natural gas grid or used as the fuel for mobility. In 2017, H2ORIZON has been built in Germany in which hydrogen is used to generate power and heat for supplying energy needs of the plant, but also used for the mobility [52]. The plant is composed of 18 wind turbines of 3 MW each, a 880 kW PEM electrolyzer, two CHP units representing a total capacity of 1,6 MW thermal and 1,4 MW electrical and a boiler with a maximum combustion output of 1,4 MW. In Belgium hydrogen produced at HyPort plant is used for mobility, for power and heat generation and as raw material for the industry [57]. By the end of 2020, 399 wind turbines will be installed with a combined installed capacity of 2,26 GW. Green hydrogen production plant is scheduled to be in operation by 2025. Several hundred more wind turbines generating an extra 1,75 GW are planned in the future. The demonstration plant will produce hydrogen through an innovative 50 MW electrolyzer producing 11111.11 Nm<sup>3</sup>/h. Also planned is the Energiepark Bad Lauchstädt located in Germany [56]. In operation by 2022 this plant will produce energy from wind energy and feed it into the national grid. Hydrogen will be used as fuel for industry and mobility as well for power and heat generation. The plant particularity is the means used to store hydrogen: it will use an underground storage. This Energiepark will be composed of a 40 MW wind park, 35 MW electrolyzer producing 7777,8 Nm<sup>3</sup>/h hydrogen, underground storage in caverns with a capacity of 50 Mio.m<sup>3</sup> and will build pipelines for hydrogen transport (100 000 m<sup>3</sup>/h). Lately the projects have been more diverse: various hydrogen storage technologies are used and hydrogen is no longer used only as energy storage means but also for other applications, which could allow to decarbonize several sectors.

#### *4.1.2. Local grid cases*

Cogeneration is particularly essential in local grid or in rural community. Over the past two decades projects have emerged in which hydrogen RENE chains are used to supply energy needs of neighborhood. Started in 2005, the Promoting Unst Renewable Energy (PURE) project in UK aims to demonstrate that a hybrid wind hydrogen system can supply energy needs to a remote rural community [3]. Electricity is used to provide heat, power and transport and is supplied by the method “on demand”. The system is composed of traditional equipment but also of a wind to heat system for heating the five business properties, two storage heaters of which one is a wet system (standard radiators are used to heat up a building) and one is a dry system (bricks are used to heat up the building). Wet heater provides lasting heating energy (4 days) while the dry system only provides a heat storage option of 12 hours. The project also includes a hydrogen fuel cell car and a hydrogen dispensing facility. In 2016, the potential for developing hydrogen, oxygen and nitrogen energy storage at Unst has been investigated for 4 areas of applications: transport, farming and aquaculture, oil and gas and public sector buildings [44]. It was concluded that both hydrogen fueling station and hydrogen buses are viable and it would make sense to combine these two projects together. Although the implementation of hydrogen powered ferry would be good for the community, this project needs further technical and financial appraisals. Concerning farming applications, the requirements for fertilizers are growing in Unst and this project is viable. Due to the absence of market, the use of renewable oxygen and nitrogen for supplying the Aquaculture or for supplying oil and gas terminals is not viable. Renewable energy produced could be used in the public buildings (heat, electrical...): this project is viable. In 2006 the first step of the Hydrogen Community Lolland project started, which consisted of testing the system in a demonstration plant in a recycling depot [45]. 3,3 MW Windmill park produces energy, which is stored in form of hydrogen through electrolysis. Fuel cells generate power which is used by the waste water plant and the recovered heat is used for heating. The oxygen produced during the electrolysis distributed to the waste water plant for the waste

water cleaning (aerobic cleaning process by use of pure oxygen as opposed to ambient air). During the second phase five households were equipped with fuel cells. Hydrogen was produced in a central electrolysis plant and supplied by pipeline. Fuel cells were finally installed in 35 households. A similar system has been established in 2017 in Alzey (Germany), but this time using solar energy [53]. The system is composed of 125 kW PV area, a 40kW alkaline electrolyzer, a CHP unit, a boiler and a hot water tank. The system also includes a methanation unit. Energy costs per resident calculated with this system amounts around 0.22 €/kWh (or 1 – 1,3 €/m<sup>2</sup>/month). This zero emission technology allows to reduce CO<sub>2</sub> emission of 99,3 % in comparison with a conventional housing scheme as well as NO<sub>x</sub> emission (< 250 g / year). Started in 2018 in the islands of Eday and Shapinsay BIG HIT project uses hydrogen either in the local building or transported by sea ferry in 5 hydrogen tube-trailers to mainland Orkney in order to be converted back into heat and power for buildings and vessels as well as to be used as fuel in hydrogen powered vehicles [54]. A grid connected 900 kW wind turbine has been installed in Shapinsay while a 900 kW wind turbine and a grid connected tidal test site with 14 grid connected test berths has been installed in Eday. Two PEM electrolyzer producing 50 tons of hydrogen each year. The 75 kW fuel cell system located in Kirkwall contains 3 Proton Motor PM 400 fuel cell stacks. Each of the 3 PM 400 stacks has a nominal electrical power output range from 4 to 30 kW.

#### 4.1.3. Stand-alone cases

The commercial buildings and houses that are energetically self-sufficient have been developed for several years. Already in 1992, the Fraunhofer Institute for Solar Energy Systems developed a self-sufficient solar house in order to study the feasibility of a stand-alone system which could supply all the energy needs of a household (Table 7) [9]. The house, with an area of 145 m<sup>2</sup>, is composed of a photovoltaic array, an electrolyzer, a pressurized tank of hydrogen and oxygen, and a fuel cell connected to the system with a DC/DC to match the 48 V system of the house. From 1992 to 1995 the entire energy needs for heating, domestic hot water, electricity and cooking were supplied by solar energy. Due to the problems of alkaline electrolyzer, the Fraunhofer institute developed its own polymer exchange membrane electrolyzer. Another observation was the loss of battery capacity over three years of operation, which underscores the need for an advanced state of charge control algorithm. Table 8 shows the efficiencies of key components. Except for the PV arrays, most of major components in the system had high efficiencies, which guaranteed its smooth operation at the first three years.

**Table 7** Estimated energy needs for a four person household (Fraunhofer Institute Project) [9]

Space heating demand (SHD)	≈ 300 kWh/year
Domestic hot water (DHW)	≈ 300 kWh/year
Cooking	≈ 700 kWh/year
Electricity	≈ 700 kWh/year
System operation	≈ 1000 kWh/year
Seasonal storage volume	≈ 500 kWh and an additional 500 kWh is needed for the low temperature energy demand

**Table 8** Efficiencies of key components of Fraunhofer Institute's system [9]

COMPONENT	Efficiency
Heat recovery in the ventilation system	80 %
TI Wall	50%
Bifacial illuminated thermal collector	50%
PV array	10%
Electrolyser	75%
Fuel Cell	55%
Inverter	87%

An alternative energy system was established in GlashusEtt, an information center [42]. The system (Table 9) is composed of 3 kW PV array, an PEM electrolyzer, a hydrogen storage system, a PEM fuel cell system and a biogas system, the façade is made of glass which has a low thermal conductivity and thus allows to reduce energy losses by half. The system was designed to supply all the energy needs of the building with a part of the generated power fed into the national power grids. The PEM fuel cell system is composed of a fuel processor (reformer), including a desulphurization unit and a CO cleanup unit, a polymer electrolyte fuel cell stack and an electrical compartment. It can run with a reformed biogas or with hydrogen. The biogas burner delivers a thermal output of 24 kW and can be turned on or off only: no partial loads are possible. The fuel cell produces heat and power: the coolant loop directly connected to a 500 liters accumulator tank absorbs thermal energy. Water in the accumulator tank is used as a heat exchanger. Basis on the lower heating value (LHV) of electrolyzer has an efficiency of 43%, while the fuel cell has an electrical efficiency of 13% and a thermal efficiency of 56%.

**Table 7** Fuel cell data of GlashussEtt [42]

Working pressure	Biogas powered: 0.9 barg Hydrogen powered: 0.35 – 0.7 barg
Rated unit power output	4 kW net 10 kW peak demand for 15 min
Rated efficiency	18% electrical 40% total efficiency
Rated thermal output	6.5 Kw

**Table 8** Energy and exergy efficiencies of Clean Energy Center [42]

Component	Energy efficiency	Exergy efficiency
Photovoltaics	11,2 – 12,4 %	9,8 – 11,5 %
PEM electrolyzer	56%	52 %
Fuel Cell (one module)	30 - 44%	24,5 – 38 %
Overall system	0.88 – 9.7 %	0.77 – 9.3 %

Still using solar energy another self-sufficient building with a hydrogen RENE system was designed in 2007 to provide all energy demands at the Clean Energy Center (CEC) on the campus of Pammukkale University in Turkey. [9] The tilted double glass windows and bricks constituting Trombewalls are used for passive heating, and solar collectors are located on the top of the house for active heating. The floor, roof and wall are insulated. The system is composed of fixed PV arrays (2,5 kWp), PV arrays mounted on two passive solar trackers (2,5 kWp), a lead acid battery set composed of 16 pieces, a PEM electrolyzer producing 0.53 m<sup>3</sup>/h hydrogen, a 5,4 Nm<sup>3</sup> metal hydride tank and a 2 PEM fuel cell:2 units of 1.2 kW. In addition to the energy analysis, an exergy analysis was also carried out which showed an overall system exergy efficiency ranges between 0.77 and 9.3% (Table 10).

From 2008 to 2014, a hybrid renewable hydrogen system using the timely wind energy was installed in the Hydrogen Office in Scotland to supply the entire energy demands of the building [46]. It is composed of a 750 kW wind turbine, a 30 kW electrolyzer producing 5,3 Nm<sup>3</sup>/h hydrogen at 12 bar, a 10 kW hydrogen fuel cell, a geothermal source heat pump and 5 kW hydrogen boiler to provide space heating in the nearby Fife Renewables Innovation Centre. The project was a success which demonstrated the potential of hydrogen energy system to store the surplus of energy and that it is possible to uses this hybrid system to supply all energy needs.

From the wind energy, H<sub>2</sub>Herten pilot plant produces power, heat and fuel in order to supply a local grid (a commercial building) independent of the national grid [3]. H<sub>2</sub>Herten generated 250 MWh of electricity and 6500 kg of hydrogen. The heat generated in all of the different processes is reused for energy purposes [58]. Wind turbines are located close to H<sub>2</sub>Herten plant, but during the simulation no direct connection between them existed. The connection was made virtually via socalled wind turbine simulator. The system is composed of a lithium ion battery bank for short-term storage with a capacity of 30 kWh and an output peak of 50 kW. When the batteries are full, the electrolyzer is used to store the surplus of energy. They act also as buffer for the conditioning of the wind power. A 152 kW alkaline electrolyzer generates up to 30 Nm<sup>3</sup>/h of hydrogen at an outlet pressure of 10 bar. Pressurized tanks are used for medium and long term storage allowing to store around 5300 Nm<sup>3</sup> of hydrogen. Hydrogen is then used to power a 50 kW PEM fuel cell or a hydrogen internal combustion engine (HICE) or to supply a hydrogen refueling station. It was planned to add photovoltaics system to the plant. Basis on simulation the plant achieved an overall efficiency between 58 and

70 %, depending on the use of heat generated during the processes. During the construction and commissioning of the project it was noted that the use of hydrogen systems requires the definition of technical safety procedures. Some components had to be adjusted to the specific requirements of the Energy Complementary System (ECS) of the plant. For example, a bidirectional inverter had to be developed because it was not previously available on the market.

The hydrogen RENE system installed in the building of the New Energy and Industrial Technology Development Organization (NEDO) in Kofu City in Japan in 2019 used as energy sources a 10 MW photovoltaic park, solar modules located on the roof of the visitor center, and a hydropower generator [55]. The hydrogen energy system is composed of a 1,5 MW PEM electrolyzer and pressurized tanks for hydrogen storage. By 2021 a 5 kW Panasonic Fuel Cell was installed to generate power and heat. This system allows to supply energy needs of the building.

At the West Beacon Farm (Leicestershire, UK) a stand-alone hydrogen RENE system has been installed in 2002 to the existing RENE system [43]. This project, called the Hydrogen and Renewable Integration (HARI), aims to test the feasibility of a stand-alone RE system. Some devices were already installed at West Beacon Farm such as two 25 kW Carter wind turbine generator, a 13 kWp PV array, two micro hydroelectric turbines with combined output of 3 kW, a 10 kW<sub>thermal</sub> heat pump, a CHP unit (15 kW<sub>electrical</sub> and 38 kW<sub>thermal</sub>), a conservatory used for passive solar space heating, a biomass space heating, a battery powered car, a battery petrol hybrid car and a rainwater collector. For the HARI project, the energy storage systems have been installed such as a hydrogen system and a Sodium/Nickel chloride (NaNiCl) battery with a capacity of 20 kWh to replace the old 120 kWh lead acid battery. The hydrogen system is composed of a 36 kW alkaline electrolyzer composed of 46 cells stack, a pressurized hydrogen storage system composed of 48 cylinders at 137 bar of a total capacity of 2856 Nm<sup>3</sup> of hydrogen, equivalent to a storage capacity of 3,8 MWh and two systems for power regeneration including a 2 kW PEM fuel cell which operates as a CHP and a 5 kW Gencore unit. Thermal management system has been defined as such when the fuel cell is operating, the Gencore unit is turned off and the other way around. It is planned to use the heat extracted from the electrolyzer by its cooling system. The thermal outputs will be fed into a phase-change heat store to be used for space heating within the home. The hybrid storage system uses thus batteries for short-term (low volume energy storage) and hydrogen system for longer term. After some operating time, hydrogen leaks were observed at various joint in the piping infrastructure. KOH crystals accumulate on a valve seat causing hydrogen leaks. Grain of the drier's desiccant obstructs the valve that also causes hydrogen leaks. The misalignment of components during transit and a manufacturing fault result in electrolyte leakages. AC-DC conversion causes the most significant parasitic losses. Indeed, the rectifier required in the electrolyzer causes a loss of about 2,5 kW at low power inputs, and up to about 5 kW at its rated power, that amounts to 28 % and 11 % of the total power input respectively. AC-DC conversion efficiency decreases significantly at part load. Electrolyzer efficiency amounts to 75,2% using HVV at NTP. Whole electrolysis process efficiency of 48,8 % using HVV at NTP. The switching cycles caused a degradation of electrolyzer stacks after 2 years' operation reducing the electrolyzer efficiency. Electrolyzer oversizing in the order of 39% for its task: it needs to be redesigned in order to improve its efficiency and its reliability. The ideal match between the battery capacity and the number of cells in the electrolyzer module allows to ensure the best hydrogen production and the most efficient conversion energy. Roundtrip efficiency of the hydrogen energy system (cycle from electricity to hydrogen and back to electricity again) is 16% while the overall electrical plus hydrogen energy system efficiency is 44%. As far as possible, electricity should remain as electricity in the system until its point of end use. Energy audit is required to increase the whole efficiency of the plant since it allows to show where inefficiencies arise and thus where improvements can be made.

From 2010 to 2012 in Lavrion in Greece H2SUSBUILD aimed to develop a trigeneration system to supply power, heating and cooling loads of residential or commercial buildings [48]. Wind turbines and PV panels were used to supply the electrical load and the excess was converted to hydrogen to be used as energy storage material and then used as green fuel to cover the buildings heating needs through direct combustion in a hydrogen natural gas burning system or to produce combined heating and electricity by means of fuel cells.

During the phase test, the systems covered the power requirements of the building. A full scale installation designed to satisfy both electrical and thermal energy demands of a 600 m<sup>2</sup> office was carried out.

#### 4.2. Investment cost

**Table 9** Investment nature and cost

Project name	Total investment cost	Type of funding	Ref
SWB	75 000 000 €	Public (50%) and private (50%)	[59]
RH2-WKA	4 500 000 €	Public	[60]
ENERTRAG	21 000 000 €	Public and private	[61]
H2Ber	>10 00 000 €	Public and private	[62]
PURE	560 000 €	n.a	[63]
Hydrogen community Lolland	n.a	Public	[45]
BIG HIT	7 246 103 € [64]	n.a	[64]
Self-sufficient solar House Fraunhofer Institute	5,8 million €	Public	[65]
H2SUSBUILD	9 889 566, 47 €	Public	[66]
H2Herten	3 million €	Public and private	[58]

Table 11 shows the investment nature and the cost of existing CHP systems. SWB project had been divided into two parts: phase 1 from 1986 to 1991 and phase 2 from 1992 to 1996 [59]. The total cost reached 145 million Deutsche Mark (around € 75 000 000), of which 64 million Deutsche Mark (around € 33 000 000) for the phase 1, including 50% equipment, 20% design and engineering, 15% operation, evaluation and 15% infrastructure and other. RH2WKA was funded by the German Federal Ministry of Transport and Digital Infrastructure. The total investment cost amounts to 21 million euros [60] and was financed by European Union, Deutsche Bahn, the French Oil & Gas company Total, and the Swedish power company Vattenfall. The total cost of the self-sufficient solar house built by the Fraunhofer institute amounts to 11,4 million Deutsche Mark (€ 5,8 million), including all scientific part (planning, simulation, measurements and evaluation) amounting to 2,9 million €; a part for the development of the hydrogen and oxygen storage system of 2 million euros; and the cost of the building construction of 0,8 million € of which 0,7 million 0.37 million€ for all the technical components (Electrolyzer prototypes, fuel cell and solar collector) [65]. Basis on the GlashusEtt simulation, the investment cost of an alternative system must be lower than a conventional system in the order of 300,000 SEK (around 30 000 €) to be competitive [42]. H2SUSBUILD project cost amounts to 9 889 566, 47 € of which 6 699 755 € was funded by European Union.[66]. Concerning H2Herten project, 90% of the funding resources has been covered by the Land of North Rhine Westphalia (Germany) [58]. The pilot plant has an expected life of 15 years (until 2025).

## V. CHP system optimizations and enhanced value provided by cogeneration

According to the descriptions of the selected projects, it is obvious that cogeneration can bring many advantages: the simultaneous production of power and heat allows to increase the efficiency of the system. As a reminder, the efficiency of conventional plant is generally lower than 40%, while it is higher than 85% for the CHP plants [39]. Bornapour et al. simulated a hydrogen RENE system with and without cogeneration. [67] They showed that by using point estimate method that when cogeneration is used the energy generation and the profit increase. CHP system also allows to enhance independence of a microgrid. To make this possible, the use of each energy flows must be optimized. Many methods exist to manage these flows such as metaheuristic algorithms or mixed integer linear method (Table 12). [68]

**Table 10** Algorithm list for CHP system optimization

Metaheuristic algorithm	Authors	Ref
Harmony search algorithm	Vasebi et al.	[69]

Genetic algorithm	Sinha et al.	[70]
Particle swarm optimization (PSO) method	Mohammadi-Ivatloo et al.	[71]
Modified PSO	Maleki et al.	[72]
Firefly algorithm	Yazdani et al.	[73]
Real coded genetic algorithm	Haghrah et al.	[74]
Whale optimization method	Nazari-Heris et al.	[75]
Invasive weed optimization algorithm	Jayabarathi et al.	[76]
Exchange market algorithm	Ghorbani et al.	[77]

Another method is to use mixed integer linear/nonlinear programming method [78,79]. Nazari-Heris et al. have optimized a CHP plant for a microgrid composed of fuel cells, heat only, and power only units using  $\epsilon$  constraint method [80]. Three cases are investigated: off grid mode, grid connected mode and the impact of the time of the use demand response program on microgrid scheduling. Didani et al. [81] have used the demand response program to study a microgrid composed of a fuel cell and CHP unit in grid connected mode. Without taking into account the demand response the total production cost and pollutant emission per day are higher than when the demand response is considered. Giannakoudis et al. are modeled a RENE Hydrogen system under uncertainty (wind speed, energy price and load) using a stochastic Annealing optimization algorithm [82]. Zhang et al. have optimized a microgrid including wind turbines, PV generators, fuel cell, batteries and gas fired boilers using a stochastic model predictive control [83]. It consists of a mixed integer linear programming based energy management model in which the uncertainty was taken into consideration. They show that this method is more efficient than an open loop based stochastic day ahead programming strategy and a MPC strategy. Romero-Quete et al. have developed a model predictive control program in which an Affine Arithmetic based Economic Dispatch is integrated for a CHP system composed of PV array, a gas boiler a CHP unit, a battery and a thermal tank [84]. This method allows to reduce the forecasting errors. Considering economic, environmental and reliability aspects Pourghasem et al. have developed a multistage stochastic method which combines an exchange market algorithm and a weighted sum method [85]. Cao et al. have optimized a PV Hydrogen chain using the downside risk constraints method in order to measure imposed risks [86]. It allows to model the financial risks imposed from the uncertainties (thermal and electrical loads, electricity market price and solar irradiation). Xiao et al. have developed a mixed integer linear programming for a wind energy – hydrogen chain including solid oxide electrolyzer, hydrogen tanks and PEM fuel cell [87]. Stochastic method describes the uncertainties of wind power and electricity price while the financial risk is estimated using conditional value at risk.

## VI. Exergy: a key parameter to optimize cogeneration systems

In such complex systems, the assessment of the overall efficiency is harder than it may look due to the variety of nature of energy flows (electricity, heat and hydrogen). Based on the first law of thermodynamics, which states that during a transformation the total energy is constant (energy can be transformed from one form to another but can be neither created or destroyed), energy analysis is insufficient to assess a real system efficiency since the irreversibility and therefore the entropy are not considered. It is only by taking the second law of thermodynamics into account that different types of energy can be compared and that the overall efficiency can be assessed: this is the exergy concept. First law focuses on quantity while second law on quantity but also on quality. The following section introduces the exergy concept and reviews the different methods to carry out an exergy analysis.

### 6.1. Definition

Exergy is defined as the useful potential of a certain amount of energy at a specified state [21]. In other words, exergy is the available energy. Exergy is also defined as the maximum amount of work that can bring a stream (matter, heat or work) into equilibrium with a reference environment. The exergy of a system in equilibrium with the environment is zero. Exergy analysis provides information such as where, why and how



much energy is wasted and thus allows to quantify the rate of irreversibility due to the entropy generation of each component. Exergy of a system, denoted by  $E_x$ , is defined by the following equation (2) where the subscript  $_0$  refers to the environment and  $_i$  refers to some component of the system:

$$E_x = E_n + P_0 \cdot V - T_0 S - \sum_i \mu_{i0} N_i \quad (2)$$

Equation (2) is composed of two parts: (i) one related to the system with  $E_n$  the energy of some system (J),  $S$  the entropy (J/K),  $V$  the volume and  $N_i$  the number of mole of each system components; (ii) the other related to the environment with  $T_0$  the ambient temperature,  $P_0$  the ambient pressure and  $\mu_{i0}$  the chemical potential of components (J/mol).

Gouy-Stodola formulated an exergy balance equation (3), which is applicable to all component of thermal systems, including the four parts of exergy, namely chemical, physical, potential and kinetic [88]: (CHE for chemical, T for thermal, P for mechanical and W for work)

$$E_x^W = E_x^{CHE} + (\sum_{inlet} E_x^T - \sum_{outlet} E_x^T) + (\sum_{inlet} E_x^P - \sum_{outlet} E_x^P) + T_0 \left( \sum_{inlet} \dot{S}_i - \sum_{outlet} \dot{S}_i + \frac{\dot{Q}_{cv}}{T_0} \right) \quad (3)$$

$E_x^{CHE}$  represents the rate of exergy flow of the fuel. Entropy generation is expressed by the fourth term, in which  $\dot{Q}_{cv}$  corresponds to the heat transfer interaction between a component and the environment.

## 6.2. Exergy analysis of electrolyzer and fuel cell

Exergy analysis aims to understand where occur the exergy losses and the irreversibility and to quantify them as well as to assess the exergy efficiency of a system. Exergy efficiency is defined as the ration between the total output exergy flow of the system and its input exergy flow.

Recently some studies have been carried out to assess the performance of some specific equipment of HSS. Nafchi et al. have developed a one dimensional mathematical model (more accurate than thermodynamic models) for assessment of exergy efficiency of PEM electrolyzer and for study the effect of different parameters. They took into account the water transport phenomena for the anode, membrane and cathode as well as the effects of the electro osmotic drag, hydraulic pressure and diffusion in the membrane [89]. They defined exergy efficiency as (equation 4):

$$\psi_{ex} = \frac{\dot{N}_{H_2, out} * LHV_{H_2}}{\dot{W}_{elec} + \dot{Q}_{heat}} \quad (4)$$

where  $\dot{N}_{H_2, out}$  is the mass flow rate (mol/s),  $LHV_{H_2}$  is the lower heating value (J/mol),  $\dot{W}_{elec}$  is the electrical power (W) and  $\dot{Q}_{heat}$  is the heat rate (W). Among others, the increase of membrane thickness, current density, height and width of channel leads to lower exergy efficiency (Table 13).

**Table 11** Effect of different parameters on exergy efficiency of PEM electrolyzer [89]

Parameter	Action	Effect on efficiency	Cause
Working temperature	Increase	Increase	- Reduces the open voltage. - At higher cathode pressure, required power to store hydrogen reduces and purity of hydrogen increases.
Cathode pressure	Decrease		
Anode and cathode exchange current density	Increase	Decrease	Creates higher voltage drop in the electrolyzer
Membrane thickness	Increase	Decrease	Increase of membrane thickness causes increase of ohmic losses
Current density	Increase	Decrease	Over voltages of the electrolyzer increase and leads to decrease of energy and exergy efficiencies.
Height and width of the channel	Increase	Decrease	Causes higher ohmic overvoltage

Özgür et al. reviewed the exergy analysis of PEMFC and PEMFC operated in cogeneration [21]. Researches are focused on studying of operating temperature and pressure, but also on effects of air stoichiometry, relative humidity, voltage, membrane thickness, current density. Higher exergy efficiency and better performance involves higher operating temperature and pressure, lower membrane thickness,

effectively adjusted air stoichiometry and current density and relative humidity (Table 14).

**Table 12** Effects of different parameters on exergy efficiency of PEM fuel cell [21]

Parameter	Action	Effect on efficiency	Cause
Operating Temperature	Increase	Increase	When temperature raises, system over potentials (activation, ohmic, concentration losses) reduce
Operating Pressure	Increase	Increase	Pressure difference between anode and cathode creates electroosmotic drag. High pressure increase this drag and means increased system exergy efficiency.
Air stoichiometry	Increase	Increase	Ration must be range between 2 and 4 for better performance but effect is not remarkable
Current density	Increase	Increase up to 1.0 A/cm <sup>2</sup> Then decrease	When current density is too increased, the difference between the gross stack power and net system power increases because of parasitic loads But too much increment causes performance decrement
Humidification	Increase	Increase	Humidity is very important for the membrane. Lower humidity causes drying out of membrane and higher humidity can cause blockage. Humidity must be neither too low nor too high.
Membrane thickness	Increase	Decrease	Increase of membrane thickness causes increase of ohmic losses and therefore decrease the performance of PEMFC.

Barelli et al. compared theoretically two PEMFC- and SOFC-based micro CHPs for residential application [90]. Systems are fueled with natural gas. As result, PEMFC-based micro CHP operating at atmospheric pressure and low temperature is the most efficient one. Again for residential applications, Baniasadi et al. designed a micro CHP composed on a PEMFC integrated with an absorption chiller in order to supply the electrical energy, hot water and space cooling [91]. Increasing the operating pressure from 1 to 5 bar led to a rise of exergy efficiency from 41% to 49%. Kwan and Yao modelled a PEMFC combined with a thermoelectric module for residential air cooling and heating demands [92]. Fuel cell efficiency varied from 53% to 68%. Liu et al. [93] developed a thermodynamic model of a PEMFC system and carried out energy, exergy and detailed ecological analysis. They defined the ecological function as the difference between the power output and exergy loss due to entropy generation. They showed that the fuel stack and heat exchanger cause the most exergy loss. The system was tested under various stack inlet temperature and current density. Best performance (net power, energy and exergy efficiency higher) was obtained for an inlet temperature of 348.15K while the higher level of the ecological function is obtained for an inlet temperature of 338.15K.

Baniasadi and Dincer modeled the performance of a CHP SOFC for which the system exergy efficiency was calculated to be 60-90% as a function of current density [94]. They observed that the entropy generation rate decrease of 25% every 100 °C increase in average operating temperature. Wang et al. developed a dynamic model of a flammable FC operating in cogeneration for residential applications [95]. The heat exchanger represented the largest exergy destruction. An additional heat storage was required in this kind of system in view of the slow thermal response under a transient electrical demand. Ahmadi et al. investigated a CHP system including a SOFC, an absorption power cycle (APC) and domestic hot water (DHW) unit [96]. Preheater represented one quarter of total exergy destruction rate while SOFC stack represented 17% of the total exergy destruction. Reducing the current density of the SOFC system, compressor pressure ratio, steam to carbon ratio, and absorber temperature should improve the total exergy efficiency of the system. Gholmanian et al. Evaluated a biomass fueled combined cooling, heating and power system composed of a biomass gasifier, a SOFC, a double effect absorption refrigeration cycle and a Heat Recovery Steam Generator (HRSG) [97]. They obtained a maximum exergy efficiency of the entire system of 37.92% representing an increase of 49.88% compared to the SOFC system without CCHP. Irreversibility occurs mainly in heat exchanger and gasifier. Hosseinpour et al. studied a system producing heat and power from biogas and SOFC and also concluded that gasifier is the main source of entropy generation [98]. To conclude, most of the exergy destruction in SOFC occurs in the heat exchangers and fuel rich combustion. [99]

### 6.3. Exergy analysis carried out for CHP system

A lot of studies have carried out the exergy analysis of different systems, many of which focus on the use of generated heat by a fuel cell. The PEMFC efficiency is up to 60% in electrical energy and up to 80% in

CHP [21]. Table 15 summarizes the existing exergy analyses of CHP systems with the exergy efficiency values calculated. Exergy analysis involves calculating the rate of exergy balance, which is defined as [100]:

$$\sum_{in}(1 - \frac{T_0}{T_i}) \dot{Q}_i + \dot{W}_{in} + \sum_{in} \dot{m}_i \dot{e}x_i = \sum_{out}(1 - \frac{T_0}{T_i}) \dot{Q}_i + \dot{W}_{out} + \sum_{out} \dot{m}_i \dot{e}x_i + \dot{E}x_D \quad (5)$$

where  $\dot{E}x_D$  (W) is the exergy destruction,  $\sum \dot{m}_i \dot{e}x_i$  (W) the sum of input or output exergy rates,  $\frac{T_0}{T_i}$  the ratio of the ambient temperature to the flow temperature. Shaygan et al. carried out the first energy, exergy and economic analysis is for this type of system. The system consists of a PV – HSS system including an electrolyzer and a 5.5 kW PEMFC [101]. Average annual exergy efficiencies obtained for the compressor, the electrolyzer, the fuel cell and the PV cell amount to 75.9%, 11.2%, 32.8% and 10.8%, respectively. Average annual values of overall system energy efficiencies: energy efficiency was 20.4% while this value amounted to 21.8% for the exergy efficiency. They defined exergy efficiency of electrolyzer as in equation (6):

$$\eta_{ex,electrolyser} = \frac{\dot{E}x_{out,electrolyser}}{\dot{E}x_{out,solar} + \dot{E}x_{out,H_2O}} \quad (6)$$

where  $\dot{E}x_{out,electrolyser}$  is the rate of exergy (W) of electrolyzer,  $\dot{E}x_{out,solar}$  is the rate of exergy (W) of PV array and  $\dot{E}x_{out,H_2O}$  is the rate of exergy (W) of water tank. The exergy efficiency value obtained for electrolyzer is significantly lower than the value obtained in other papers in the literature. Indeed, in the other papers, exergy efficiency of electrolyzer is calculated as in equation (7) where  $\dot{m}_{H_2}$  is the mass flow rate (kg/s) of hydrogen,  $ex_{H_2}$  is the specific exergy rate (kJ/kg) of hydrogen and  $\dot{W}_{electrolyser}$  is the power input in electrolyzer (kW) [102].

$$\eta_{ex,electrolyser} = \frac{\dot{m}_{H_2} \cdot ex_{H_2}}{\dot{W}_{electrolyser}} \quad (7)$$

Shaygan et al. realized also an advanced exergy analysis, in which exergy destruction is divided into two parts: endogenous exergy destruction (due to the irreversibility) and the exogenous exergy destruction (due to the ineffectiveness of other component of the system that affecting this component) [101]. In addition to dividing exergy into endogenous and exogenous, each of these divisions are classified into two avoidable and unavoidable terms. Bagheri et al. summarized these terms as in equation (8) [103]:

$$\dot{E}x_{D,i} = \dot{E}x_{D,i}^{EN,UN} + \dot{E}x_{D,i}^{EN,AV} + \dot{E}x_{D,i}^{EX,UN} + \dot{E}x_{D,i}^{EX,AV} \quad (8)$$

in which  $\dot{E}x_{D,i}$  is the total exergy destruction,  $\dot{E}x_{D,i}^{EN,UN}$  is the unavoidable endogenous exergy destruction,  $\dot{E}x_{D,i}^{EN,AV}$  is the avoidable endogenous exergy destruction,  $\dot{E}x_{D,i}^{EX,UN}$  is unavoidable exogenous exergy destruction, and  $\dot{E}x_{D,i}^{EX,AV}$  is avoidable exogenous exergy destruction. As a result of the advanced exergy analysis, Shaygan et al. have also concluded that the PV cells represents the most exergy destruction due to unavoidable endogenous exergy destruction [101]. In electrolyzer, the exergy destruction is due to exogenous unavoidable (due to the PV cells) as well as in the compressor. In the PEMFC avoidable endogenous and exogenous exergy destruction amount to 10.8% and 3.1% of the total exergy destruction, respectively. The chemical reaction occurring in electrolyzer and fuel cell is the main cause of exergy destruction. Calderón et al. investigated a test-bed hybrid solar/wind generator including a HSS composed of an electrolyzer, a metal hydride system for hydrogen storage and a fuel cell [104]. As a result, the electrolyzer exergy efficiency is acceptable (68.75%), PV modules exergy efficiency is low (8.39%). Fuel cell exergy efficiency amounts to 35.9%. Exergy efficiency of the electrolyzer and fuel cell depend more on the used/produced hydrogen flow and on the electrical power than on the ambient temperature and pressure. The influence of hydrogen temperature and pressure on these components is neglected. Gill EZ et al. carried out an energy, exergy and exergo economic and exergo environmental analysis of a multi-generation system including of parabolic through solar collector (PTSC), regenerative power plant, double-effect absorption chiller system, PEM electrolyzer and multi-stage flash desalination plant in order to generate electricity, cooling, heating, hot water, freshwater and hydrogen fuel [105]. Due to the variety of the energy flows the exergy analysis is very pertinent in this case. They concluded that “the greater amount of heat generated by the system at a uniform rate of electrical power corresponds to the lesser efficiencies and more will be exergy destruction occurred” [105]. Hosseini et al. modeled a PV-HSS system operating in cogeneration for residential applications [106]. The system was composed of a solar PV system, an PEM electrolyzer, hydrogen storage tank, a SOFC and a HRSG. The maximum total energy and

exergy efficiencies amounted to 55.7% and 49.0%, respectively, which were obtained when the fuel cell was in operation. Khosravi et al. analyzed an off-grid hybrid RENE (PV-array and wind turbine) – HSS including an electrolyzer, an hydrogen tank and a fuel cell [107]. They focused on the economic analysis by calculating the life cycle cost (LCC) defined as the sum of the annual capital cost, the annual maintenance cost, the cost of installation and the cost of replacement of the components. The main part of input exergy was caused by PV-array (80%) that impacts the entire system since it represents 65% of the maximum exergy destruction of the system. The amount of the exergy destruction for the wind turbine, the electrolyzer, the fuel cell and the converter reached 13.52%, 2.3%, 3.5% and 1.4%, respectively. Khalid et al. designed a hybrid RENE (solar-wind) – HSS system for a building in order to supply it with power, fresh water and heat [102]. They defined exergy efficiency for each component where  $\dot{E}x$  is the exergy rate (kW),  $\dot{m}_{H_2}$  is the mass flow rate (kg/s),  $\dot{W}_{FC}$  is the work rate or power (kW),  $ex_{H_2}$  is the specific exergy (kJ/kg) (Table 16). They concluded that PV collector followed by the wind turbine represented the largest exergy destructions. The exergy efficiency of the overall system amounted to 26.8% while the energy efficiency amounted to 26%.

**Table 13** Exergy analysis of RENE-HSS system carried out and their efficiencies

Authors	CHP	Efficiencies of equipment			Overall system efficiency		Ref
		Component	Energy Efficiency	Exergy Efficiency	Energy	Exergy	
Shaygan et al.		PV-array		10.8%	20.4 %	21.8%	[101]
		Electrolyzer		11.2%			
		Compressor	n.a	75.9%			
		Fuel Cell (PEM, 5 kW)		32.8 %			
Calderon et al.		PV-array	n.a	8.39%	n.a	n.a	[104]
		Electrolyzer	68%	68.75%			
		Fuel Cell	29.5 - 35.6%	35.9%			
Gill EZ et al.	X	Parabolic trough solar collector	66.84%	40.07 %	n.a	n.a	[105]
		Regenerative Power Plant	41.08%	23.26 %			
		Double effect Absorption System	1.2%	0.22 %			
		Multistage Flash Desalination Plant	66.02%	8.151 %			
Hosseini et al.	X	PV-array	17%	18.3%	55.7%	49%	[106]
		Electrolyzer	65%	n.a			
Khosravi et al.		PV-array	12%	16%	n.a	14.204%	[107]
Khalid and al.	X	Electrolyzer (PEM)	76%	62.7%	26%	26.8%	[102]
		Fuel Cell (PEM)	83.8%	63.3%			
Kalinci et al.		PV-array	13.31%	14.26%	n.a	n.a	[108]
		Wind turbines	46%	50.1%			
		Electrolyzer	59.68%	60.26%			
Hacatoglu et al.	X	PV-array	70%	14%	n.a	11%	[109]
		Inverter	n.a	96%			
		Battery	n.a	81%			
		Electrolyzer	75%	62%			
		Hydrogen cooling	n.a	97%			
		Fuel Cell (PEM)	53%	69%			
Nguyen et al.	X	Fuel Cell (PEM) with heat recovery	n.a	45%	n.a	n.a	[110]
Caliskan et al.		for a dead state temperature = 20°C :			3.44%	5.856%	[111]

		PV-array	9.06%	9.72 %			
		Wind turbine	26.15%	71.70 %			
		Electrolyzer	53.55%	53.58 %			
		PEMFC	33.06%	32.99%			
Nouri and al.	X	PV-array	n.a	32%			
		Electrolyzer	n.a	67%	n.a	94.87%	[112]
		Hydrogen Liquefaction Cycle	n.a	93.24%			
Khosravi et al.		PV-array	12.86%	15.97%			
		OTEC system (depending on the working fluid)	2.75%	19.42 % to 20.91%	3.32%	18.35 %	[113]

**Table 14** Exergy efficiency of different component of RENE-HSS system [102]

Component	Exergy efficiency
PV collector	$\eta_{ex,PV} = \frac{\dot{W}_{PV}}{\dot{E}x_{sol,PV}^{PV}}$
Electrolyzer	$\eta_{ex,electrolyser} = \frac{\dot{m}_{H_2} \cdot ex_{H_2}}{\dot{W}_{electrolyser}}$
Fuel cell	$\eta_{ex,FC} = \frac{\dot{W}_{FC}}{\dot{m}_{H_2} \cdot ex_{H_2}}$
Wind turbine	$\eta_{ex,WT} = \frac{\dot{W}_{WT,out}}{\dot{W}_{WT,in}}$
Overall system	$\eta_{ex,ov} = \frac{(\dot{E}x_{heat}^Q + \dot{W}_{WT,out} + \dot{W}_{PV} + \dot{W}_{FC} - \dot{W}_{electrolyser})}{\dot{W}_{WT,in} + \dot{E}x_{sol,PV}^{PV}}$

Kalinci et al. examined a stand-alone RENE-HSS system including a PV array, wind turbines, 200 kW PEM electrolyzer, PEMFC, hydrogen tank and converter [108]. As a result, the average exergy efficiencies of the PV array, the wind turbines and the electrolyzer amounted to 14.26%, 50.12% and 60.26%, respectively. Hacatoglu et al. carried out an exergy analysis of a RENE-HSS system including an activated carbon storage to generate power, hot and cold thermal energy flows [109]. The system is composed of a PV or PV-thermal cells, SPE electrolyzer, tanks containing activated carbon, PEMFC and VRLA battery. The storage through activated carbon involved an adsorption reaction that could generate cold energy. The systems were examined for four modes of operation: (1) battery charging, (2), hydrogen charging, (3) battery discharging and (4) hydrogen discharging. Two cases are studied: (i) base case which evaluates the performance of the system (only power production) and (ii) modified case which considerate in the analysis the possibility of multiple products outputs. They considered the total exergy of a material stream as the sum of its physical, equation (9) and chemical equation (10) exergy while kinetic and potential energy components are ignored:

$$\dot{E}x_i^{PH} = \dot{n}_i [(h_i - h_{i,0}) - T_0(s_i - s_{i,0})] \quad (9)$$

$$\dot{E}x_i^{CH} = \dot{n}_i ex_i^{CH} \quad (10)$$

where  $\dot{E}x_i^{PH}$  and  $\dot{E}x_i^{CH}$  are the physical and the chemical exergy of the species  $i$  respectively,  $\dot{n}_i$  is the molar flow rate of species  $i$ ,  $h_i$ ,  $s_i$  and  $e_i^{CH}$  are the molar enthalpy, entropy and chemical exergy of the species  $i$ , respectively.  $T_0$ ,  $h_{i,0}$  and  $s_{i,0}$  are the temperature, enthalpy, and entropy of species  $i$  at the reference environment, respectively. As result, the benchmark system's exergy efficiency amounted to 4,0% including the PV sub-system while the modified system's exergy efficiency amounted to 11% including the PV sub-system (82% if the PV subsystem is excluded). Nguyen et al. modeled a PEMFC with heat recovery (PEMFC-HR) for preheating its inlet air in the context of a stand-alone hybrid-solar hydrogen system for a remote telecommunication application in extreme cold climate conditions [110]. The study was focuses on the PEMFC. 2kW-PEMFC-HR performance was compared with a PEMFC coupled with an external electric heater (PEMFC-EH). The aim was to understand the impacts of various ambient temperature and power parameters on the performance of the PEMFC-HR. The specific exergy of the fuel cell included the specific

physical exergy which depends on the temperature and pressure of reactants and products, and the specific chemical exergy which depends on the chemical reactions, mixing and phase change processes that occur in the system. As a result, 30% of the electrical energy generated by the PEMFC could be saved by replacing the PEMFC-EH by PEMFC-HR system. The exergy destruction of the fuel cell stack is dominant in PEMFC-HR system. Moreover, the exergy efficiency of PEMFC-HR did not depend on the ambient temperature: for the range of -50°C to 30°C they observed a variation of exergy efficiency around 0.5%. Caliskan et al. developed a thermodynamic model using three hybrids renewable energy (geothermal – wind – solar) with an HSS followed by a case study of a hybrid (solar – wind) renewable energy – HSS [111]. They considered the exergy input for the wind turbine only kinetic exergy changing of the air, for the electrolyzer only electrical power input and for the PEMFC only exergy of hydrogen as exergy input. They defined the sustainable index (SI) that indicates the impact of exergy efficiency on the sustainability of the resources or systems. The higher the SI, the more sustainable the process/unit. SI is defined as equation (11):

$$SI = \frac{1}{1-\eta_{ex,ov}} \quad (11)$$

They showed that for the renewable energy resources, the wind turbine system has the highest exergy efficiency. Dead state temperature has an impact on the exergy loss rate of the solar PV panel as well as on electrolyzer and fuel cell. When dead state temperature increases, exergy efficiency of electrolyzer increases while exergy efficiency of fuel cell decreases. But the overall exergy efficiency of the system is not so much impacted by the dead state. Nouri et. al. investigated a hybrid plant for production of liquid hydrogen and carbon dioxide using photovoltaic and electrolyzer systems [112]. The plant was composed of five subsystems: power generation using grid-connected solar PV, hydrogen and oxygen gas production using an alkaline electrolyzer, oxyfuel power plant for power and heat generation, carbon dioxide liquefaction using an absorption-compression refrigeration subsystem and a hydrogen liquefaction unit. As a result, PV system and heat exchangers were the major sources of irreversibility. The proposed plant achieved a high exergy efficiency of 94.87% while the exergy efficiency of the hydrogen liquefaction cycle was 93.24%. Khosravi et al. proposed a new hybrid ocean thermal energy conversion (OTEC)/PV with HSS [107]. The system was composed of turbine, generator, evaporator condenser, pumps, PV panels, electrolyzer, hydrogen tanks, fuel cell and converter. The exergy efficiency of this system was 18.35%. The average energy and exergy efficiencies for the PV panels amounted to 12.86% and 15.97% respectively. The exergy destruction for the system outlet, the PV system, turbine, condenser, evaporator was 46.31%, 24.13%, 4.35%, 3.85% and 1.43%, respectively.

Table 17 summarizes the existing publication about exergy analysis carried out for RENE-HSS systems. Nowadays, all of them are theoretical systems or test beds. Moreover, most of them are off-grid and almost half do not operate in cogeneration. The grid-connected platform MYRTE (Figure 6) located in Ajaccio (France) is an innovative solar-HSS system composed of PV-array of 560 kWp, tanks for oxygen and hydrogen storage, a heat system management system and two sections, each including PEM electrolyzer and PEMFC (Table 18)[114]. Power produced from PV-array is fed into the grid and the surplus is stored by means of hydrogen. When power is needed and solar energy is not available, fuel cell regenerate power. Heat system management recovers heat generated during these processes. A third section is planned and will include an electrolyzer, a fuel cell, a lithium battery, an adsorption chiller and an HRS. Next step for us is to carry out the thermodynamic modeling of this new section and to realize the exergy analysis of the entire platform in order to identify the localization of the irreversibility.

According to the literature review above, the overall energy efficiencies can vary within in a large range from the lower bound less than 5% to the upper bound equal to about 50%, and their overall exergy efficiencies can even range from about 5% to 95%. The considerable difference of efficiencies can be attributed to the different designs and techniques integrated in the systems, especially whether to use cogeneration techs. Moreover, high energy efficiency generally corresponds to high exergy efficiency. Exergy loss is mainly due to the PV panel and wind turbines, followed by the heat exchangers. However, high exergy efficiency of PV arrays alone cannot necessarily result in the good overall efficiencies. Apparently, the performance of RENE-HSS systems depends on the synergy of all the components and operations. In this sense, their optimization should not only be limited to some specify component but also be extended to the system level.

# MYRTE PLATFORM

MYRTE: MISSION HYDROGÈNE RENOUVELABLE POUR INTÉGRATION AU RÉSEAU ELECTRIQUE

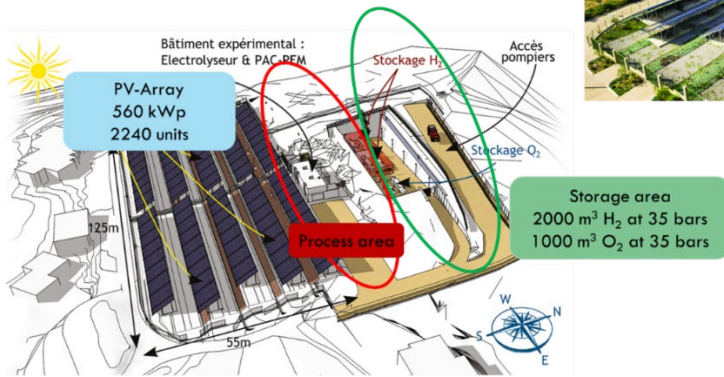


Fig. 5. MYRTE Platform diagram.

Table 15 Publication about exergy analysis of RENE-HSS system

Authors	Year	Type of system	Source	On- / Off-grid	Electrolyzer (type)	H2 storage (type)	Fuel cell (type)	Other equipment	CHP Yes/No	Products	Ref
Hacatoglu et al.	2010	Theoretical	Solar (PV and/or thermal cells)	Off-grid	SPE	Activated carbon storage	PEM	VRLA battery	Yes	Power Hot Cold	[109]
Calderón et al.	2010	Test-bed	Solar (PV) Wind	Off-grid	Type n.a	Metal hydride tank	Type n.a	Battery	No	Power	[104]
Caliskan et al.	2012	Theoretical	Solar (PV) Wind Geothermal	Off-grid	Type n.a	Metal hydride tank	PEM	Battery O <sub>2</sub> storage system	No	Power	[111]
Hosseini et al.	2012	Theoretical	Solar (PV)	Off-grid	PEM	Gaseous form tank	SOFC	HRSG Absorption chiller	Yes	Power Heat	[106]
Nguyen et al.	2015	Theoretical	Solar (PV)	Off-grid	Type n.a	Gaseous form tank	PEM 2 kW	Battery	Yes	Power Heat	[110]
Khalid and al.	2016	Theoretical	Solar (PV collector) Wind	Off-grid	PEM	Gaseous form tank	Type n.a	-	Yes	Power Heat Fresh water	[102]
Kalinci et al.	2016	Theoretical	Solar (PV) Wind	Off-grid	PEM 200 kW	Gaseous form tank	PEM 100 kW	-	No	Power	[108]
Khosravi et al.	2017	Theoretical	Solar (PV) Wind	Off-grid	Type n.a	Gaseous form tank	Type n.a	-	No	Power	[107]
Shaygan et al.	2019	Theoretical	Solar (PV)	On-grid	Type n.a	Gaseous form tank	PEM 5,5kW	-	No	Power	[101]
Khosravi et al.	2019	Theoretical	Ocean thermal energy Solar (PV)	On-grid	Type n.a	Gaseous form tank	Type n.a	OTEC system	No	Power	[107]
Nouri and al.	2020	Theoretical	Solar (PV)	On-grid	Alkaline	Liquid form tank	No	Battery H <sub>2</sub> liquefaction unit Absorption - compression	Yes	Power Heat Liquid H <sub>2</sub> and CO <sub>2</sub>	[112]

								refrigeration system Oxyfuel power plant CO <sub>2</sub> liquefaction unit			
Gill EZ et al.	2020	Theoretical	Solar (PTSC)	n.a	PEM	Liquid form tank		Absorption chiller Desalination unit	Yes	Power Heat Cold Hot water Freshwater Hydrogen as fuel	[105]
MYRTE Platform		Existing	Solar (PV)	On-grid	PEM	Gaseous form tank	PEM 100 kW and 60 kW	Adsorption chiller (in 2021) Battery (in 2021) H <sub>2</sub> refueling station (in 2021)	Yes	Power Heat Cold (in 2021)	-

**Table 16** Characteristics of Section 1 and 2 of MYRTE Platform

	Section 1	Section 2
Electrolyzer	PEM 50 kW (10 Nm <sup>3</sup> /h H <sub>2</sub> - 5 Nm <sup>3</sup> /h O <sub>2</sub> )	PEM 57 kW (13 Nm <sup>3</sup> /h H <sub>2</sub> - 5 Nm <sup>3</sup> /h O <sub>2</sub> )
Fuel Cell	PEM 100 kW	PEM 50 kW

## VII. Conclusions

Due to its high energy content and pollution-free nature, hydrogen can be used for transportation, heating and power generation in industries. Utilization of renewable hydrogen in these sectors will considerably reduce the GHG emissions and help the achievement of energy transition. However, the performance of hydrogen systems still need to be improved and the global cost has to be reduced to promote the use of hybrid RENE-hydrogen systems. In this regard, cogeneration that generates power and heat simultaneously allows to make these systems much more profitable, increase the efficiency, and help to develop micro grids. In fact, due to the various possible applications of hydrogen, the hybrid RENE-hydrogen systems can be utilized to produce different energy flows, including power, heat, hydrogen as fuels for mobility or for industries, etc. in order to become more competitive.

In order to further improve the performance of RENE-hydrogen systems, exergy analysis is therefore essential for the system characterization and assessment. Thanks to exergy analysis, the localization where takes place the greatest exergy losses have been identified. Advanced exergy analysis allows to identify if the exergy destruction is avoidable or unavoidable and thus, by reducing the latter, to increase the exergy efficiency. In this review, we analyzed and compared the mostly-recent publications that study the energy and exergy efficiencies of various RENE-hydrogen systems. As for each component in the systems, the typical energy efficiency is 9 – 15% for PV arrays, 54 – 68% for electrolyzers, and 29 – 35 % for PEM fuel cells, while the typical exergy efficiency is about 8 – 18 % for PV arrays, 53 – 68 % for electrolyzers, and 33 – 36% for fuel cells. Importantly, when the system operates in cogeneration, energy and exergy efficiency of electrolyzer increases to 76% and 67% respectively, while energy and exergy efficiency of fuel cell increases to 53 – 83.8 % and 63.8 – 69 %, respectively. Likewise, the overall energy and exergy efficiencies of the entire system significantly increase up to 90% as heat is recovered. Nevertheless, at present, few systems operating in cogeneration have been implemented and no exergy analysis has been carried out for those practical systems, either. In fact, the performance assessment through exergy concept has only been conducted to systems in simulations. Therefore, extending the exergy analysis on simulating systems to practical systems can be an important research direction. Our future work will concern the exergy analysis of the MYRTE Platform located in Ajaccio in order to assess its overall efficiency, to identify the sources of irreversibility



and then to improve its performance. Besides the technical improvements, it is also required to define a policy and to establish a legal framework to promote these systems since green hydrogen needs to be clearly defined.

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