Ref. Ares(2026)5337300 - 27/05/2026

THESEUS

Hub4Circularity

A First of a kind Hub for circularity demonstrator for Attica and peripheral regions

Grant Agreement No 101178059

DELIVERABLE 6.5:

CHP fuel cell system v1

Work Package: 6

LEAD BENEFICIARY:

Centre for Research and Technology, Hellas (CERTH)

Delivery Date: 31.05.2026

Document Sheet

Project acronym	**Theseus**
Project full title	A First of a kind Hub for circularity demonstrator for Attica and peripheral regions
Programme	Horizon Europe
Topic	HORIZON-CL4-2024-TWIN-TRANSITION-01-38
Type of Action	HORIZON Innovation Actions
Grant Agreement	101178059
Start day	1 December 2024
Duration	60 months

LEGAL NOTICE
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Health and Digital Executive Agency (HADEA). Neither the European Union nor the granting authority can be held responsible for them.

©Theseus Consortium, 2026
Reproduction is authorised provided the source is acknowledged.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

Document Information

Deliverable number	D6.5
Deliverable name	CHP fuel cell system v1
Lead beneficiary	CERTH
WP	6
Related task(s)	6.3
Type	R
Reviewers	Nikolaos Petridis (DHCP), Babis Manousiadis (ICCS)
Delivery date	31.05.2026
Main author(s)	Christos Evaggelou (CERTH), Nikolaos Margaritis (CLEAN)
Contributor(s)	Panagiotis Grammelis (CERTH), Dionisios Giannakopoulos (CERTH), Dimitrios Kourkoumpas(CERTH)

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

Dissemination level

PU	Public	X
SEN	Sensitive, limited under the conditions of the Grant Agreement	
Classified R-UE/EU-R	EU RESTRICTED under the Commission Decision No2015/444	
Classified C-UE/EU-C	EU CONFIDENTIAL under the Commission Decision No2015/444	
Classified S-UE/EU-S	EU SECRET under the Commission Decision No2015/444	

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

Document history

Version	Date	Changes	Reviewer/Contributor
V0.1	01.05.2026	First Draft	Christos Evaggelou (CERTH), Nikolaos Margaritis (CLEAN)
V0.2	13.05.2026	Minor changes from review	Panagiotis Grammelis (CERTH), Dionisios Giannakopoulos (CERTH), Dimitrios Kourkoumpas (CERTH) Nikolaos Petridis (DHCP)
V0.3	18.05.2026	Final Draft	Christos Evaggelou (CERTH)
V1.0	26.05.2026	Final Version	Babis Manousiadis (ICCS)

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

Publishable summary

Deliverable D6.5, entitled “CHP Fuel Cell System v1”, has been developed within the framework of Work Package 6 (WP6) “Energy Symbiotic Flows”. It constitutes the first deliverable in a three-part series addressing the potential deployment of fuel cell technologies for green hydrogen utilization. The overarching objective of this series is to evaluate pathways for energy production and utilization, with particular emphasis on electricity generation systems and combined heat and power (CHP) applications.

This deliverable primarily addresses the theoretical background of the technology, starting with an introduction to hydrogen as an energy carrier, including its classification based on production pathways. In addition, it reviews key sectors and industrial processes in which hydrogen can be effectively utilized. Subsequently, the focus shifts to green hydrogen, with a detailed examination of water electrolysis as the principal production mechanism. Various electrolysis technologies are analysed, highlighting their operational principles and comparative characteristics. The document further explores hydrogen storage methods, considering both physical and material-based approaches. Additionally, the deliverable presents the main technological routes through which, green hydrogen can be converted into usable electrical and thermal energy, particularly within fuel cell and CHP systems. Finally, a concise technical overview is provided for the specific green hydrogen system installed at the CERTH/CPERI facilities in Ptolemaida. This system is currently operational and will subsequently be examined as a pilot-scale demonstration application, serving as a practical case study for evaluating the performance, functionality, and applicability of the technology.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

Contents

1 Abstract 11
2 Introduction 12
3 H_2 Technology 13
3.1 Colours of Hydrogen 13
3.2 Hydrogen Use 16
3.3 Electrolysis 18
3.4 Storage 28
3.5 Fuel cell 35
4 Specific Technology 40
5 Conclusions 43
References 44

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

List of Figures

Figure 1. Alkaline water electrolysis working principle 20
Figure 2. AEM water electrolysis working principle 22
Figure 3. PEM water electrolysis working principle 24
Figure 4. SOEC water electrolysis working principle 26
Figure 5. Typical operation of a fuel cell 35
Figure 6. Energy Pack's design 40
Figure 7. Graphical description of EP interfaces and system components 41
Figure 8. Installed Energy Pack 42

List of Tables

Table 1. Definition of hydrogen colour spectrum 15
Table 2. Comparative overview of water electrolysis technologies 27
Table 3. Different types of compressed hydrogen storage vessels 29
Table 4. Brief comparison between the different types of Fuel Cells 38

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

Abbreviations

Abbreviations	Full name
AEM	Anion Exchange Membrane
AFC	Alkaline Fuel Cell
CAPEX	Capital Expenditure
CCUS	Carbon Capture Utilization and Storage
CFRP	Carbon Fiber – Reinforced Polymer
CHP	Combined Heat and Power
CNs	Carbon Nanotubes
DHW	Domestic Hot Water
EP	Energy Pack
FC	Fuel Cell
FCEVs	Fuel Cell Electric Vehicles
GHG	Greenhouse Gas
HDPE	High Density Polyethylene
LHV	Lower Heating Value
LOHCs	Liquid Organic Hydrogen Carriers
MCFC	Molten Carbon Fuel Cell
MOFs	Metal – Organic Frameworks
P2H2P	Power to Hydrogen to Power
PAFC	Phosphoric Acid Fuel Cell
PEM	Proton Exchange Membrane

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

PEMFC	Proton Exchange Membrane Fuel Cell
RES	Renewable Energy Sources
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cell
SOFC	Solid Oxide Fuel Cell
YSZ	Yttria Stabilized Zirconia

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

1 Abstract

Deliverable D6.5, entitled “CHP Fuel Cell System v1”, has been developed within the framework of Work Package 6 (WP6) “Energy Symbiotic Flows”. It constitutes the first deliverable in a three-part series addressing the potential deployment of fuel cell technologies for green hydrogen utilization. The overarching objective of this series is to evaluate pathways for energy production and utilization, with particular emphasis on electricity generation systems and combined heat and power (CHP) applications.

This deliverable primarily addresses the theoretical background of the technology, starting with an introduction to hydrogen as an energy carrier, including its classification based on production pathways. In addition, it reviews key sectors and industrial processes in which hydrogen can be effectively utilized. Subsequently, the focus shifts to green hydrogen, with a detailed examination of water electrolysis as the principal production mechanism. Various electrolysis technologies are analysed, highlighting their operational principles and comparative characteristics. The document further explores hydrogen storage methods, considering both physical and material-based approaches. Additionally, the deliverable presents the main technological routes through which, green hydrogen can be converted into usable electrical and thermal energy, particularly within fuel cell and CHP systems. Finally, a concise technical overview is provided for the specific green hydrogen system installed at the CERTH/CPERI facilities in Ptolemaida. This system is currently operational and will subsequently be examined as a pilot-scale demonstration application, serving as a practical case study for evaluating the performance, functionality, and applicability of the technology.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

2 Introduction

Within the broader conceptual framework of the “THESEUS” project, which focuses on the development of hubs for circularity, the efficient utilization of energy streams—particularly those that are currently underexploited or non-utilizable—constitutes a primary objective.

Non-utilized energy can be broadly classified into two main categories. The first includes latent (thermal) energy, defined as the energy absorbed or released by a substance during a phase change or thermodynamic transformation. The second category focuses on excess energy generated from Renewable Energy Sources (RES), which cannot be directly utilized due to temporal mismatches between generation and demand or due to limitations and constraints within the energy distribution infrastructure.

Hydrogen-based energy systems, particularly when coupled with fuel cell technologies, represent a technically, environmentally and economically viable solution for enhancing the overall utilization of RES-generated energy. In this context, surplus electrical energy from RES can be converted into hydrogen via electrolysis (power-to-gas), stored and subsequently reconverted into electricity and/or heat through fuel cells (gas-to-power or combined heat and power—CHP). Furthermore, fuel cell operation produces by-products in the form of heat and water vapour. The thermal output, typically available at temperatures in the range of 60°C – 80°C, can be effectively recovered and utilized—for example, for preheating or low-temperature thermal applications—thereby increasing overall system efficiency.

More generally, the integration of hydrogen as an energy carrier enables the maximization of RES utilization by providing long-duration and scalable energy storage. Unlike conventional battery systems, hydrogen offers the additional advantage of multi-sectoral energy coupling, enabling both electrical and thermal energy recovery. This contributes to improved flexibility, enhanced system resilience and optimized energy balancing across a wide range of demand profiles and end-use applications.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

3 H_2 Technology

Hydrogen (H_2) is a colourless, odourless, non-toxic and highly flammable gaseous chemical element. Owing to its high energy content, versatility and abundance, hydrogen is considered a particularly attractive energy carrier for a wide range of applications. However, the main challenges associated with its rational and efficient utilization are related to its production methods and its effective integration into end-use systems.

3.1 Colours of Hydrogen

Hydrogen technologies can be assessed using a multifactorial framework that incorporates technological, environmental and economic parameters. This evaluation is further influenced by the maturity level of each technology and its applicability under specific operational conditions and system requirements. Nevertheless, an initial classification and comparative assessment of hydrogen production pathways has already been established by the scientific community through the so-called hydrogen colour spectrum, in which each category is conventionally associated with a specific colour. This classification is structured around three principal axes:

1. The production method or technology employed for hydrogen generation
2. The resources and energy sources utilized to supply the required energy for hydrogen production
3. The management of by-products generated during hydrogen production

With respect to the first axis, seven main hydrogen production methods can be distinguished: steam methane reforming (SMR), pyrolysis, gasification and co-gasification, partial oxidation, thermochemical splitting (thermolysis) and electrolysis. Additional methods, such as photocatalysis, is also under investigation; however, these technologies are currently at a low level of technological maturity and efficiency and remain largely confined to experimental or pilot-scale applications, without significant contribution to commercial hydrogen production. Regarding the second axis, both the source of energy and the “raw materials” play a critical role. Energy inputs may originate from grid electricity, renewable energy sources (RES) or nuclear power, while the “raw materials” include water (in the case of electrolysis), natural gas, biomass, coal, lignite and methane. The third axis primarily addresses the treatment of by-products, with particular emphasis on the application of carbon capture, utilization and storage (CCUS) technologies aimed at mitigating or eliminating greenhouse gas (GHG) emissions to the environment. Based on the combination of these criteria, the hydrogen colour spectrum currently encompasses eleven distinct categories of hydrogen production.

The simplest form of hydrogen is **white** hydrogen, which refers to naturally occurring hydrogen found in geological formations. It occurs as free hydrogen gas within layers of the continental and oceanic crust, as well as in volcanic gases, geysers and hydrothermal systems. As is generally acknowledged, the colour nomenclature applied to hydrogen production pathways is largely symbolic and reflects the environmental characteristics and carbon footprint associated with each category. In this context, hydrogen produced via the gasification or co-gasification of coal is classified as **black** or **brown** hydrogen. The distinction between these two categories is determined by the type of feedstock used, since black hydrogen is derived from bituminous coal, whereas brown hydrogen is produced primarily from lignite, and in some classifications may

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

also include biomass. Another major group within the hydrogen colour spectrum is associated with natural gas or methane based production pathways, namely **grey** and **turquoise** hydrogen. Grey hydrogen, which is currently the most widely produced and cost-effective form, is generated through steam methane reforming (SMR) or partial oxidation. It is predominantly utilized in the petrochemical sector and in ammonia synthesis, with approximately 40% of global grey hydrogen production arising as a by-product of other chemical processes. Turquoise hydrogen also relies on natural gas or methane as a feedstock but is produced via pyrolysis. A key distinction between these two pathways lies in their by-products. While grey hydrogen production results in carbon oxide emissions, turquoise hydrogen produces solid carbon as a by-product, which can be more readily stored or valorised, thereby potentially reducing the overall carbon footprint of the process. **Blue** hydrogen represents a category primarily defined by the treatment of by-products rather than by the production method. It involves the production of hydrogen from fossil fuels (either coal or natural gas) in combination with CCUS technologies. Due to its potential for significantly reduced greenhouse gas emissions, blue hydrogen is often considered a transitional low-carbon hydrogen option. A further subset of the hydrogen colour spectrum comprises three categories associated with nuclear energy inputs, commonly represented by reddish hues. **Red** hydrogen refers to hydrogen produced through high-temperature thermochemical water splitting using nuclear thermal energy. **Purple** hydrogen is generated using a combination of nuclear electricity and heat, typically through hybrid electrolysis and thermochemical processes. **Pink** hydrogen is produced via conventional water electrolysis powered by electricity from nuclear power plants. The final two widely recognized categories are **yellow** and **green** hydrogen, both of which are based on water electrolysis and are generally regarded as more environmentally sustainable options. Yellow hydrogen is produced using electricity from the grid; however, its associated carbon emissions vary significantly over time depending on the electricity generation mix. In contrast, green hydrogen is generated exclusively through electrolysis powered by RES, resulting in minimal associated greenhouse gas emissions. It should be noted that certain bibliographic sources also reference additional categories, such as *orange* hydrogen, produced via electrolysis powered exclusively by solar energy; *gold* hydrogen, referring to naturally occurring hydrogen generated by microbial processes in depleted oil reservoirs; and *aqua* hydrogen, associated with experimental processes involving oxygen injection into sealed geological formations. These categories are generally excluded from the core hydrogen colour spectrum, either because they are subsumed within existing categories (e.g. orange hydrogen as a subset of green hydrogen) or because they remain at a very low level of technological maturity and lack near-term deployment prospects (e.g. gold and aqua hydrogen). The following table summarizes the hydrogen colour categories, the energy sources and hydrogen sources, the corresponding production methods and the associated CO_2 emissions.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

Table 1. Definition of hydrogen colour spectrum

Colour	Energy Source	Hydrogen Source	Production Process	CO_2 Emissions
White		Naturally occurring	Extraction	
Black	Electricity from non RES	Bitaminous coal	Gasification/co-Gasification	High
Brown	Electricity from non RES	Lignite/Biomass	Gasification/co-Gasification	High
Grey	Electricity from non RES	Natural gas/Methane	Steam Methane Reforming	High
Turquoise	Electricity from non RES	Natural gas/Methane	Pyrolysis	No direct CO_2 emissions
Blue	Electricity from non RES	Fossil fuels	Reforming/Gasification	Low
Red	Nuclear	Water	Thermochemical splitting	No direct CO_2 emissions
Purple	Nuclear	Water	Hybrid electrolysis and thermochemical processes	No direct CO_2 emissions
Pink	Nuclear	Water	Electrolysis	No direct CO_2 emissions
Yellow	Electricity from the grid	Water	Electrolysis	Depends on the electricity mix
Green	Electricity from RES	Water	Electrolysis	No direct CO_2 emissions

The category with the greatest potential and currently regarded as the most promising from both technological and environmental perspective—and the category examined in this deliverable due to its direct relevance to the Pilot application—is green hydrogen.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

3.2 Hydrogen Use

As demonstrated by the strong interest of the scientific community in its production, hydrogen is strategically important with a broad range of applications across multiple sectors, playing a critical role in the global transition toward a more environmentally sustainable and resource-efficient model. Hydrogen finds direct application in the industrial sector, the chemical industry, transport and mobility and in particular, the energy sector, in space and aerospace applications, while additional applications also extend to the domestic and commercial domains.

Industrial Sector

At the industrial scale, hydrogen is primarily utilized in the steelmaking industry, in the production of ammonia and fertilizers and in petroleum refining processes. The most widespread industrial application of hydrogen is in the steel industry, where it is utilized in iron ore reduction processes. Hydrogen-based reduction pathways can significantly contribute to the decarbonization of steel production, as they result in substantially lower emissions compared to the conventional blast furnace route. A second major application of hydrogen is in the production of ammonia and fertilizers. Hydrogen is a key reactant in the Haber–Bosch process and is essential for the synthesis of ammonia. Finally, one of the largest consumers of hydrogen is the petroleum refining sector, particularly in hydrocracking and desulfurization processes. These processes are critical for the production of cleaner fuels and the conversion of crude oil into refined products such as gasoline and diesel. The refining industry accounts for the highest hydrogen demand, as large quantities are required to crack heavy hydrocarbons into lighter fractions and to remove sulphur compounds from petroleum streams.

Chemical Industry

Hydrogen is a critical feedstock in the chemical industry, particularly in methanol synthesis and polymer manufacturing. Methanol is among the most widely produced chemicals globally and serves as a key intermediate for a broad range of products, including plastics, fertilizers, solvents and fuels. In the methanol production process, hydrogen reacts with carbon oxides (CO and CO_2) to form methanol and water. Similarly, in the polymer industry, hydrogen plays a fundamental role in completing production processes. It is extensively used in hydrogenation reactions, which are essential for the manufacture of polymers such as plastics and synthetic rubbers. Hydrogenation involves the addition of hydrogen to unsaturated organic compounds, thereby converting them into more saturated and chemically stable compounds.

Transport and Mobility

The transport sector represents one of the most promising domains for the deployment of hydrogen technologies, as these technologies have reached a relatively advanced level of maturity and can already partially substitute the use of fossil fuels. Among the most mature and widely deployed hydrogen-based transport technologies are Fuel Cell Electric Vehicles (FCEVs). FCEVs operate by converting hydrogen into electricity via fuel cells, achieving higher efficiency compared to conventional internal combustion engine vehicles. In addition, they produce no harmful emissions, emitting only water vapor. A key advantage of FCEVs over battery electric vehicles (BEVs) lies in their higher energy density and significantly shorter

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

refueling times, which make them particularly suitable for long-range and high-utilization applications. Importantly, FCEV technology is not limited to passenger vehicles but is increasingly applied to heavy-duty and large-scale transport modes, including trucks, trains, and in aviation applications. Furthermore, hydrogen can also be utilized as a direct fuel in hydrogen-powered ships and heavy transport vehicles, such as long-haul trucks and busses. These applications are increasingly recognized as critical components of future low- and zero-carbon transport systems, particularly in segments where full electrification remains technically or economically challenging.

Space and Aerospace Applications

The space and aerospace sector can be regarded as a pioneer in the utilization of hydrogen, as liquid hydrogen has been employed as a rocket propellant since the early stages of human space exploration. Owing to its high specific energy and low molecular weight, liquid hydrogen is an optimal fuel for aerospace propulsion systems. When combined with liquid oxygen, it forms a highly efficient propellant pair, widely used for the launch of space shuttles, satellites and other spacecraft. This combination delivers an exceptionally high thrust-to-weight ratio, which is critical for achieving the velocities required to overcome Earth's gravitational field and place payloads into orbit.

Residential and Commercial Use

With regard to the utilization of hydrogen in residential and commercial applications, current interest is primarily focused on its use for space heating, domestic hot water production and cooking. In residential settings, hydrogen can be supplied to boilers to meet space heating and hot water demands, potentially substituting natural gas or propane with limited modifications to existing distribution and heating infrastructures. Similarly, in buildings where cooking appliances operate on natural gas or propane, hydrogen can be used as a substitute fuel with relatively minor adaptations to the appliances and associated systems.

Energy Sector

One of the most relevant and strategic applications—directly linked to both this Deliverable and the overall THESEUS project—is the utilization of hydrogen within the energy sector. In this context, hydrogen can assume a dual role. On the one hand, it can be used as a low-carbon fuel through direct combustion; on the other hand, it can function as an energy carrier, enabling the efficient storage of surplus energy. In practical terms, hydrogen can support the generation of both thermal and electrical energy, not only at the building scale, as previously discussed, but also at district and utility scales. With respect to thermal energy production, hydrogen may partially substitute or be blended with natural gas in existing gas networks supplying large heating systems, or it may be integrated into district heating schemes. In such applications, hydrogen can be used either directly as a fuel in boilers or indirectly by exploiting the recoverable thermal energy generated during its use in other processes. As an energy carrier, hydrogen enables the storage of substantial amounts of energy that can later be converted back into electricity when required, thereby contributing to grid balancing and system flexibility. This functionality is particularly important for maximizing the utilization of intermittent renewable energy sources, such as wind and solar. Excess electricity generated during periods of low demand can be converted into hydrogen, stored and subsequently reconverted into electricity during periods of higher demand, enhancing overall system efficiency and resilience.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

3.3 Electrolysis

As can be inferred from the above, the technology primarily addressed in this Deliverable—and more broadly, the technology to be presented and investigated within the framework of the "THESEUS" project—focuses on hydrogen production via electrolysis. Electrolysis is a process that utilizes water as its primary feedstock. Moreover, the use of energy generated from RES for the production of green hydrogen contributes both to the decarbonisation of energy production pathways and to the enhanced valorisation of surplus renewable energy generation.

The electrolysis of water is an electrochemical process in which electrical energy is applied to dissociate water molecules into their elemental components, hydrogen and oxygen. The reaction is non-spontaneous and endothermic, requiring a thermal energy input of approximately 48.6 $kJ \cdot mol^{-1}$, in addition to a substantial electrical energy demand of about 237.2 $kJ \cdot mol^{-1}$. The products of water electrolysis are hydrogen gas and oxygen gas. The sole feedstock is deionized water, while no gaseous pollutants are emitted and no secondary by-products are generated. The overall reaction can be expressed as follows:

$$H_2O + \text{Electrical Energy } (237.2\ kJ \cdot mol^{-1}) + \text{Heat } (48.6\ kJ \cdot mol^{-1}) \rightarrow H_2 + \tfrac{1}{2}\ O_2$$

The electrolysis process is conducted within electrochemical devices known as electrolysers, which can be structurally and functionally classified into three levels:

I. Cell Level

The cell constitutes the main operational unit of the electrolyser, within which the electrochemical water-splitting reaction occurs. A typical electrolysis cell is composed of two electrodes—the anode and the cathode—immersed either in a liquid electrolyte or positioned adjacent to a solid electrolyte membrane, depending on the electrolysis technology applied. It also includes two porous transport layers, which facilitate the uniform distribution of reactants and the effective removal of reaction products, as well as bipolar plates that ensure mechanical stability, enable current collection and regulate the flow of fluids within the cell assembly.

II. Stack Level

The stack comprises multiple electrolysis cells electrically connected in series in order to achieve the required operating voltage and hydrogen production capacity. Within this configuration, an electrolysis membrane or separator is positioned between the opposing electrodes, functioning simultaneously as an ionic conductor and an electrical insulator. Structural frames and end plates ensure adequate sealing, mechanical stability and the uniform compression of the individual cells, while bipolar plates are installed between adjacent cells to facilitate current transfer, regulate reactant and product fluid distribution and prevent leakage across the stack assembly.

III. System Level / Balance System

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

At the system level, the installation encompasses all auxiliary subsystems required to ensure the safe, reliable and efficient operation of the electrolyser. These include hydrogen cooling, purification and processing units, such as gas drying and purity control systems, as well as electrical supply, conversion and power conditioning equipment, including inverters. In addition, the system incorporates water treatment and supply infrastructure, typically comprising deionization units to guarantee the required feed-water quality, together with gas handling, storage and discharge systems responsible for the safe management and downstream utilization of the produced hydrogen.

The differentiation that can be observed in an electrolysis system is mainly related to the technology applied to the cell. Four types of water electrolysis technologies have been developed for hydrogen production, depending on the electrolyte used, the operating conditions and the ionization agents (OH^-, H^+, O_2^-). These technologies are distinguished in:

1. Alkaline water electrolysis
2. Anion exchange membrane (AEM) water electrolysis
3. Proton exchange membrane/polymer membrane (PEM) water electrolysis
4. Solid oxide water electrolysis (SOEC)

Alkaline water electrolysis

In alkaline electrolysis, water splitting is achieved through two reactions which take place in two different parts of the cell. The first concerns the release/production of hydrogen and takes place on the cathode surface of the cell, while the second concerns the release/production of oxygen and takes place on the anode surface. The process of alkaline hydrolysis of water is carried out in the presence of an alkaline solution (water in the presence of a catalyst (KOH or NaOH)). The overall process of alkaline electrolysis can be described according to the following reaction:

$$H_2O \rightarrow H_2 + ½O_2$$

One of the main advantages of alkaline electrolysis lies in its technological maturity. As a well-established method for hydrogen production, it benefits from comparatively low capital expenditure, typically in the range of 500–1,000 EUR/kW. System efficiencies are generally reported between approximately 50% and 78%, depending on operating conditions and system configuration. Alkaline electrolyser stacks typically operate at temperatures between 70 and 90 °C and at pressures below 30 bar. A concentrated alkaline solution (commonly ~5 M KOH or NaOH) is used as the working electrolyte. The operational lifetime of alkaline electrolysis systems is estimated at approximately between 60,000 and 90,000 operating hours. The purity of the produced gases (H_2 and O_2) generally ranges from 99.5% to 99.99998%. However, gas crossover phenomena through the diaphragm or separator can affect product purity, particularly under differential pressure conditions. The following figure (Figure 1) illustrates the main alkaline water electrolysis working principle.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

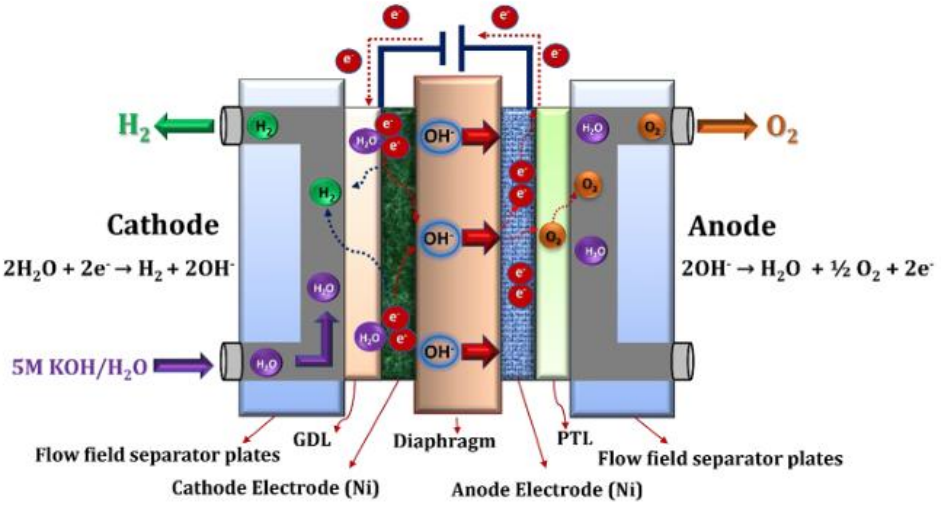


Figure 1. Alkaline water electrolysis working principle

The main advantages of this technology include its high level of technological maturity and its widespread commercial deployment in industrial applications. It is a well-established and extensively tested electrolysis technology, demonstrating reliable and stable long-term operation. In addition, it utilizes catalysts that do not contain noble metals, which contributes to relatively low capital costs compared with other electrolysis technologies. The system is also characterized by operational robustness and long-term stability, making it suitable for large-scale hydrogen production. However, several technical limitations must also be considered. One of the main disadvantages is the limited current density. Another important challenge is the risk of gas cross-contamination, particularly the mixing of hydrogen and oxygen. Furthermore, the process relies on the use of a high-concentration liquid alkaline electrolyte, typically around 5 M potassium hydroxide (KOH), which introduces additional requirements related to corrosion management, material compatibility, and operational safety.

Although the technology is considered mature and commercially reliable, significant scope for performance optimization and cost reduction remains. Current research and development efforts focus on the following areas:

- Improvement of diaphragm materials and reduction of diaphragm thickness
- Development and upgrading of catalysts capable of operating efficiently under more demanding temperature and pressure regimes
- Advancement of electrolysis cell component design
- Enhancement of thermal and electrical insulation at both stack and system levels to reduce energy losses (use of more efficient materials)
- Optimization of electrode materials and architectures to increase active surface area while reducing material cost

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

- Optimization of the overall chemical, thermal and energy balance of the electrolysis unit to maximize system efficiency

Anion exchange membrane (AEM) water electrolysis

AEM electrolysis is an electrochemical water-splitting technology that utilizes an anion exchange membrane and electrical energy to produce hydrogen and oxygen. The overall electrochemical process comprises two half-reactions occurring at separate electrodes within the electrolysis cell, the hydrogen evolution at the cathode and oxygen evolution at the anode. At the cathode, water molecules are reduced producing H_2 gas, which subsequently collected for compression and storage, while the hydroxide ions (OH^-) formed during this reaction migrate through the anion exchange membrane toward the anode. At the anode, the OH^- undergo oxidation, O_2 gas is released and collected for further utilization. The overall water electrolysis reaction can be expressed as:

$$H_2O \rightarrow H_2 + ½O_2$$

Compared to conventional alkaline electrolysis, AEM electrolysis is not yet considered a fully mature technology. It is currently in an advanced development phase, which makes precise estimation of CAPEX challenging. The main operating principle of AEM electrolysis is similar to that of alkaline electrolysis. The primary distinction lies in the replacement of traditional porous diaphragms with a solid anion exchange membrane, which enhances ion selectivity and gas separation performance. Electrolyte consists of a low-concentration alkaline solution, typically 1 M KOH. The operating temperature ranges between 40 and 60 °C, while the operating pressure can reach up to 35 bar. The current density is approximately 0.2–2 A/cm² and the overall system efficiency is estimated at around 57–59%. The operational lifetime varies depending on the membrane type, ranging from 2,000 to more than 35,000 operating hours, with an average value of approximately 30,000 hours. Finally, the purity of the produced gases can reach levels as high as 99.9999%. The Figure 2 bellow depicts the main working principle scheme of an AEM electrolysis.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

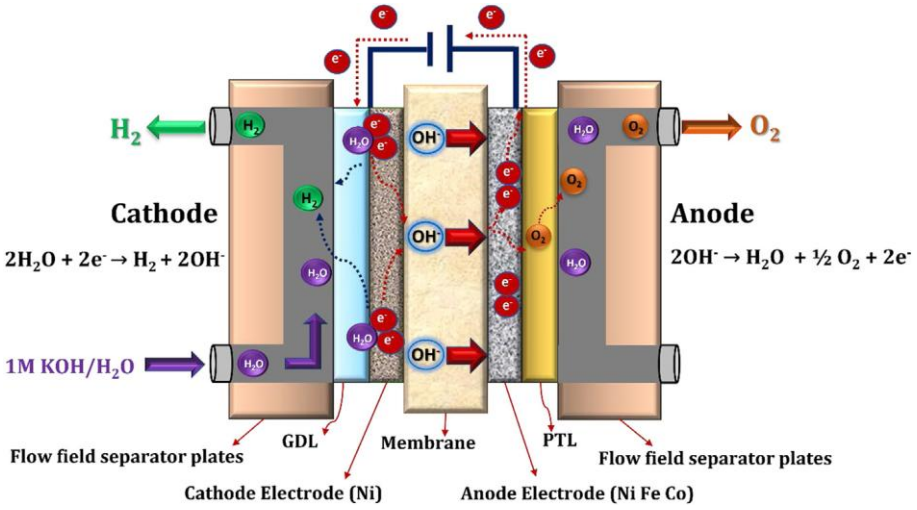


Figure 2. AEM water electrolysis working principle

AEM electrolysis technology offers notable advantages, including the use of catalysts that do not contain noble metals and the operation with a low-concentration alkaline electrolyte (typically 1 M KOH). However, the technology also presents certain limitations. Its main disadvantages relate to the relatively limited stability of the whole operation, as well as the fact that the technology has not yet reached full technological maturity and remains largely at the research and development stage.

As previously stated, AEM electrolysis is not yet a fully mature technology and has not been widely validated at commercial or industrial scale. The currently defined operating parameters are primarily derived from pilot-scale and experimental testing. Significant potential exists for further optimization and technological advancement through continued research and progressive scale-up. The main research and development priorities can be summarized as follows:

- Development and replacement of membranes with chemically and mechanically more stable membranes
- Deployment of more active and durable catalysts capable of operating under higher pressure and temperature conditions
- Optimization or replacement of secondary catalytic components to improve overall system performance and robustness
- Development of more resilient stack and system structures suitable for higher operating temperatures
- Improvement of the chemical, thermal and electrical energy balance of the unit
- Utilization of higher-performance and cost-effective electrode materials, combined with increased active surface area
- Development of innovative membrane–electrode assemblies configurations to support improved electrochemical efficiency
- Enhancement of stack and system-level insulation to reduce thermal losses

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

- Optimization of electrical operating parameters (current density, voltage regulation, load management, and power electronics integration) to maximize energy efficiency

Proton exchange membrane (PEM) water electrolysis

PEM water electrolysis technology differs fundamentally in its operating principle from alkaline and AEM electrolysis systems. Although it also relies on two electrochemical half-reactions occurring at separate electrodes within the cell, the ion transport mechanism and reaction sequence are different. In PEM electrolysis, the process starts at the anode, where water is supplied and undergoes electrochemical oxidation. During this reaction, oxygen gas (O_2), protons (H^+) and electrons (e^-) are produced. The oxygen is released at the anode surface and collected for subsequent use. The generated protons move through the proton-conductive polymer membrane toward the cathode, while the electrons are transferred through the external electrical circuit. At the cathode, the protons combine with the incoming electrons in a reduction reaction to form hydrogen gas (H_2). The produced hydrogen is then collected for compression, storage or direct utilization. The overall electrolysis reaction can be expressed as:

$$2H_2O \rightarrow 2H_2 + O_2$$

PEM electrolysis is considered a technologically mature solution and has entered the commercial deployment phase. As a result, its performance characteristics and operating parameters are well documented and supported by industrial-scale operational data. The overall system efficiency is typically reported within the range of 50% to 83%, depending on system configuration and operating conditions. The CAPEX is estimated at approximately 365 EUR/kW for systems above 1 MW, while for larger-scale installations (≥10 MW), reported investment costs range between 650 and 1,300 EUR/kW. A significant proportion of the total system cost is attributed to the use of noble and rare metals—such as platinum and iridium—in the electrocatalysts and cell components, which substantially influence stack cost. The process operates at moderate temperatures, typically between 50 and 80 °C and at comparatively high pressures relative to other electrolysis technologies, reaching approximately 70 bar. The typical current density ranges from 1 to 2 A/cm². The operational lifetime of PEM systems can reach up to 80,000 hours, with reported values generally between 50,000 and 80,000 operating hours. Key advantages of PEM electrolysis include the very high purity of the produced gases (up to 99.999%), enhanced operational safety due to rapid system response and compact cell design, the absence of caustic liquid electrolytes and a relatively low environmental footprint. The Figure bellow shows the main working principle scheme of a PEM electrolysis.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

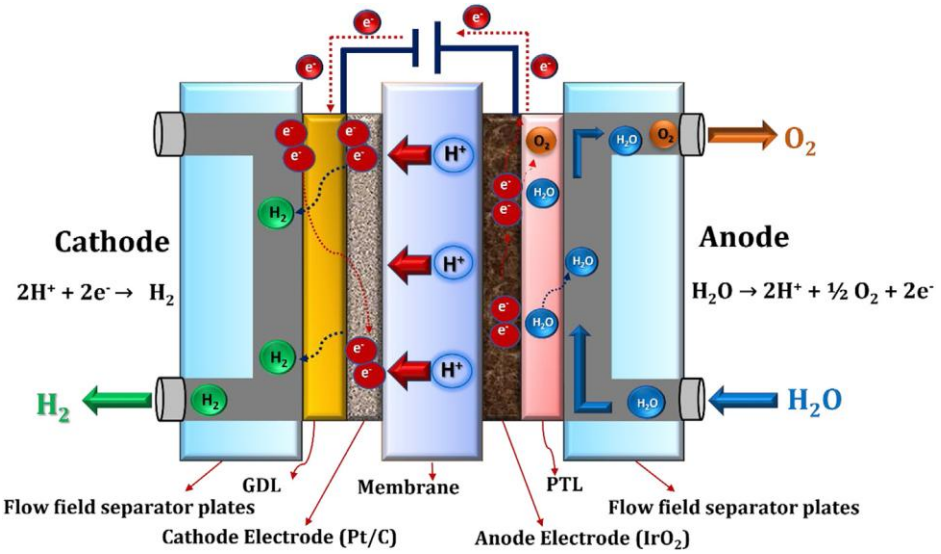


Figure 3. PEM water electrolysis working principle

PEM electrolysis represents an advanced and technologically mature solution that is already commercially available and has been widely deployed and evaluated across various operational contexts. One of its key advantages is the capability to operate at relatively high current densities, enabling compact system design and improved hydrogen production rates. In addition, PEM systems are capable of producing high-purity gases with minimal contamination. Another important advantage lies in the compact architecture of the electrolysis stack, which reduces internal losses and facilitates rapid system response and dynamic operation. However, several limitations remain. The primary disadvantages include the relatively high cost of stack components and the use of noble-metal catalysts such as platinum and iridium. Additionally, the system operates with an acidic polymer electrolyte, which imposes strict material compatibility requirements.

PEM electrolysis, together with alkaline electrolysis, represents one of the most established and widely deployed water electrolysis technologies. It is currently regarded as one of the most promising solutions for large-scale hydrogen production, as it has already achieved industrial implementation and demonstrated highly competitive efficiency performance. At the same time, substantial potential for further technological optimization remains, which is expected to enhance its techno-economic competitiveness in the medium to long term. The main research and development priorities can be summarized as follows:

- Development and deployment of thinner, more conductive and more efficient membranes
- Improvement of stack architecture and overall system configuration
- Replacement or enhancement of catalysts with higher activity and durability, capable of operating under elevated pressure and temperature conditions
- Development of more robust stack and balance-of-plant components capable of long-term operation at higher thermal and mechanical loads
- Optimization or substitution of catalytic components to increase system reliability and performance

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

- Improvement of chemical, thermal and electrical balance of the system
- Reduction of expensive coatings and development of alternative materials that maintain performance while lowering cost, for porous transport layer
- Design of innovative membrane–electrode assemblies configurations to improve the process
- Optimization of stack and system-level insulation
- Use of more cost-effective and corrosion-resistant material for bipolar plates
- Optimization of electrical operating parameters (current density, voltage control and load management) to maximize energy efficiency
- Improvement in feed water treatment and deionization processes to ensure higher purity

Solid oxide water electrolysis

The basic operating principle of Solid Oxide Electrolysis Cell (SOEC) technology is based on the electrolysis of water in the form of steam under high-temperature conditions in order to produce hydrogen and oxygen. In this process, water vapor is supplied to the cathode side of the electrolysis cell, where it is electrochemically reduced in the presence of electrons, producing hydrogen (H_2) and oxygen ions (O^{2-}). The hydrogen generated at the cathode is collected and directed toward storage and subsequent utilization. The oxygen ions formed during the cathodic reaction migrate through the solid oxide electrolyte (ion-conducting ceramic membrane) toward the anode side of the cell. At the anode, these ions undergo oxidation, forming molecular oxygen (O_2) and releasing electrons. The produced oxygen is removed from the anode side for further handling or release, while the electrons flow through the external circuit back to the cathode, thereby sustaining the electrochemical process. The overall electrochemical reaction of water electrolysis in SOEC systems can be expressed as follows:

$$H_2O \rightarrow H_2 + ½O_2$$

Although SOEC electrolysis is considered a highly promising technology, it remains at a relatively early stage of technological maturity and has primarily been demonstrated in laboratory-scale applications. Literature reported energy efficiency values of up to approximately 89%, while the capital investment cost is estimated to exceed 2000 EUR/kW for systems at the 1 MW scale. A significant share of the total cost is associated with the substantial energy requirements of the process, particularly for maintaining the high operating temperatures, as one of the main characteristics of SOEC technology is its operation at very high temperatures, typically in the range of 700–850 °C. Under these conditions, water is supplied in the form of steam, which reduces the electrical energy demand of the electrolysis reaction and improves overall thermodynamic efficiency. In contrast, the operating pressure remains relatively low, typically slightly above 1 bar. The current density usually ranges between 0.3 and 1 A/cm². Despite its high efficiency potential, SOEC technology currently exhibits shorter system lifetimes compared with other electrolysis technologies, with typical values estimated at approximately 20,000 operating hours. In addition, the purity of the produced gases is somewhat lower than that achieved with other electrolysis technologies, generally around 99.9%.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

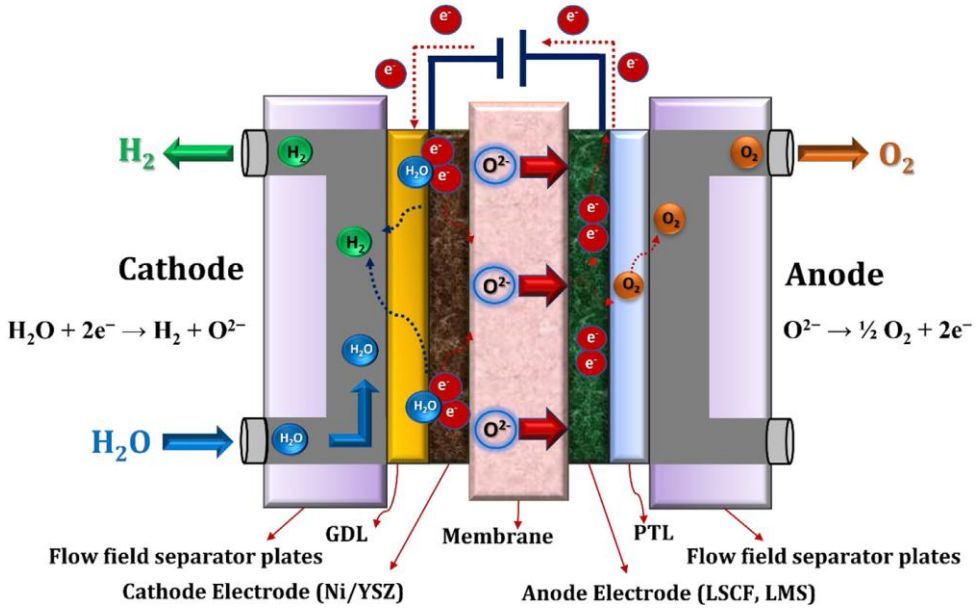


Figure 4. SOEC water electrolysis working principle

The main advantages of SOEC technology include its operation at high temperature conditions and its ability to achieve very high efficiency levels compared to other electrolysis technologies. However, the principal disadvantages include the relatively limited operational stability of system components and, most importantly, the fact that SOEC technology is still at a developmental stage. It remains primarily within the research and pilot-testing phase and has not yet been extensively validated or deployed at large commercial scale.

Among the electrolysis technologies discussed previously, SOEC is the least technologically mature. To date, it has been tested mainly under laboratory conditions and in limited pilot-scale applications. Although experimental results have been encouraging, several technological challenges must still be addressed before large-scale commercial and industrial deployment can be achieved. The potential for technological improvement is significant, but substantial research and development efforts are still required. All stages of the electrolysis process and all major system components remain active areas of research, including materials, cell design, thermal management, and system integration. These efforts aim to improve operational stability, extend system lifetime and enhance overall efficiency, thereby enabling SOEC technology to become a competitive option for large-scale hydrogen production.

Comparison

Based on the brief analysis previously presented for each water electrolysis technology, it can be concluded that significant differences exist among the four technologies in terms of operating principles, technical characteristics and technological maturity. Specifically, AEM and SOEC technologies are still at the R&D stage and have not yet reached full commercial deployment. Nevertheless, both technologies demonstrate considerable potential and are receiving increasing research attention, as they may provide efficient

Funded by the European Union
This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

solutions for future hydrogen production systems. In contrast, PEM electrolysis represents a significantly more advanced technological option. The technology has reached the commercialization stage and is already being implemented in large-scale hydrogen production projects. Similarly, alkaline water electrolysis has long been considered a mature solution, with well-documented operational characteristics. A comparative overview of the main technical characteristics of the four water electrolysis technologies is presented in the following table.

Table 2. Comparative overview of water electrolysis technologies

	Alkaline	AEM	PEM	SOEC
Electrolyte	KOH/NaOH (5M)	Polymer support with 1 M KOH/NaOH	Solid polymer electrolyte	Yttria stabilized Zirconia (YSZ)
Separator	Asbestos/Zirfon/Ni	Fumatech	Nafion®	Solid electrolyte YSZ
Materials	Nickel coated perforated stainless steel, Nickel mesh, Stainless steel/Nickel coated stainless steel	Nickel, NiFeCo alloys, Nickel foam/carbon cloth, Stainless steel/Nickel coated stainless steel	Iridium oxide, Platinum carbon, Titanium mesh/carbon cloth, Platinum/Gold-coated Titanium or Titanium	Ni/YSZ, Perovskites, Nickel mesh/foam, Cobalt coated stainless steel
Current Density	0.2–0.8 A/cm^2	0.2–2 A/cm^2	1–2A/cm^2	0.3–1 A/cm^2
Voltage	1.4–3 V	1.4–2 V	1.4–2.5 V	1–1.5 V
Operating Temperature	70–90 °C	40–60 °C	50–80 °C	700–850 °C
Pressure	<30 bar	<35 bar	<70 bar	1 bar
H_2 purity	99.5–99.9998%	99.9–99.9999%	99.9–99.9999%	99.9%
Efficiency	50%–78%	57%–59%	50%–83%	89% (laboratory)
Lifetime	60,000 h	>30,000 h	50,000–80,000 h	20,000 h
Development Status	Mature	R&D	Commercialized	R&D
Capital Cost (minimum per 1MW)	235€/kW	Unknown	345€/kW	>1,720€/kW

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

3.4 Storage

One of the key factors influencing the utilization and overall efficiency of a green hydrogen production system is the storage subsystem. Due to the intrinsic physical properties of hydrogen, as it has an extremely low density and occupies a large volume under normal conditions, the design and dimensioning of storage systems and in particular the selection of an appropriate storage method, constitute a technically complex and challenging task.

The classification of hydrogen storage methods can be based on several criteria, including the physical state of hydrogen during storage, operating pressure conditions and the type of storage environment. In general, hydrogen storage technologies can be grouped into three principal categories: physical-based storage systems, solid-state storage systems based on chemisorption or physiosorption mechanisms and underground storage solutions.

I. Physical – Based Storage Systems

Storage methods classified as physical-based systems represent the most widely adopted and commercially mature approaches for hydrogen storage, relying primarily on the intrinsic physical properties of the gas.

Compressed hydrogen storage

Compressed hydrogen storage represents the simplest and most widely implemented method for hydrogen storage, with applications spanning both stationary systems (e.g., hydrogen-based power generation units) and mobile appliances. It is a technologically mature solution, characterized by high charging (filling) and discharging (release) rates, without significant additional energy requirements for hydrogen release.

In terms of performance metrics, compressed hydrogen storage exhibits a volumetric energy density of approximately 4.5 MJ/L, a volumetric storage capacity in the range of 10–15 g/L and a gravimetric capacity of about 1–2%. The associated cost is typically estimated between 430 and 870 €/kg of stored hydrogen.

The principle of compressed hydrogen storage is based on increasing the gas pressure through mechanical compression in order to enhance its volumetric energy density. However, this approach presents several inherent limitations. The requirement for high operating pressures introduces safety risks and results in significant energy consumption, typically accounting for approximately 13–18% of the lower heating value (LHV) of hydrogen, thereby negatively affecting the overall cost-effectiveness of the system. In addition, compressed hydrogen storage is relatively inefficient in both volumetric and gravimetric terms. Despite these challenges, compressed hydrogen storage remains a key technology within the broader hydrogen energy landscape. Its effective and reliable operation depends on the use of specialized high-pressure vessels designed to withstand extreme mechanical loads, while also mitigating issues such as hydrogen embrittlement and permeation. These storage systems must achieve an optimal balance between structural integrity, weight, cost and resistance to hydrogen diffusion. Storage vessels are typically manufactured from steel, aluminum or advanced composite materials, with hydrogen commonly stored at pressures ranging from 15 to 70 MPa. Based on material composition, structural configuration and manufacturing processes, five main categories of pressure vessels (Type I, II, III, IV, and Type V—currently under development) are

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

employed for the storage of compressed hydrogen gas. In summary, the characteristics of these pressure vessel types are presented in the following table.

Table 3. Different types of compressed hydrogen storage vessels

Types	Description	Use	Advantages	Cost
Type I	Fully metallic pressure vessel (usually 4130 steels, stainless steel, high strength carbon steel), aluminium	• Industrial gas storage • Low-pressure applications	• Low cost • Availability	€72/kg
Type II	Metallic pressure vessel hoop-wrapped with glass fiber composite	• CNG storage • Transport, moderate pressure	• Light weight • Highest pressure tolerance	€75/kg
Type III	Full composite wrap with metal liners such as aluminum, stainless steel	• Hydrogen refueling stations • Heavy-duty vehicles • Aerospace	• High strength-to-weight ratio • Reducing weight no permeation	€600/kg
Type IV	Fully composite high-density polyethylene (HDPE) inner with carbon glass or carbon fiber	• FCEVs • Portable hydrogen storage • High-pressure transport	• Lightweight • Ideal for mobile applications • Longer life • Lower burst pressure • Permeation through liner	€550/kg
Type V	Fully composite materials, such as carbon fiber-reinforced polymer (CFRP), with no metal liner	• FCEVs • Aerospace • High-pressure storage	• Lighter type • Very high pressures (>100MPa) storage • No risk of hydrogen embrittlement	No commercial yet

Liquefied hydrogen storage

The storage of liquefied hydrogen is a well-established technology based on the cooling and liquefaction of hydrogen at cryogenic temperatures, typically around −250 °C. Due to the intrinsic physical properties of hydrogen and in particular its extremely low boiling point, all equipment involved in the cooling, liquefaction and storage processes must be highly insulated to minimize heat ingress and prevent evaporation (boil-off) phenomena.

Liquefied hydrogen is ultimately stored in low-pressure, high-vacuum, cryogenic vessels designed to ensure thermal stability. Such storage tanks are typically composed of three structural components. The inner vessel, which is in direct contact with the liquefied hydrogen, is designed to maintain mechanical integrity under cryogenic conditions and is constructed from materials suitable for low-temperature operation. The outer shell provides structural protection and serves as the interface with the external environment, while also enabling mechanical integration with transport and support systems. Between these two layers, a multilayer insulation system is implemented to minimize heat transfer by radiation. Additionally, the interstitial space between the inner vessel and the outer shell is maintained under high vacuum conditions, effectively reducing heat transfer via conduction. Material selection is critical and typically includes nickel-based alloys

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

for structural strength, as well as aluminum alloys and stainless steel, the latter being widely preferred due to its excellent cryogenic performance and resistance to hydrogen embrittlement.

Liquefied hydrogen storage offers several advantages, including suitability for long-term storage and large-scale transport applications. It provides a high volumetric density (approximately 70.8 kg/m³) and a volumetric energy density of up to 8.5 MJ/L. Furthermore, storage is conducted at relatively low pressures (typically below 1 MPa), which, in comparison to compressed hydrogen systems, can enhance operational safety and reduce certain structural requirements. However, the technology also presents significant challenges. The liquefaction process is highly energy-intensive, typically consuming more than 30% of the total energy content of the hydrogen, thereby reducing overall system efficiency. In addition, maintaining cryogenic conditions introduces complexity and leads to potential losses due to boil-off, which are influenced by parameters such as storage volume, storage duration, ambient conditions and tank geometry. These factors must be carefully considered during system design and operation. Consequently, key disadvantages of liquefied hydrogen storage include relatively low overall energy efficiency, high capital and operational costs—typically ranging between 1300 and 2500 €/kg—and substantial energy requirements during the liquefaction process.

Despite these limitations, liquefied hydrogen storage remains a viable and implemented technology, particularly in applications where liquid hydrogen is used directly as a fuel, such as in the aerospace sector.

Cryo - compressed hydrogen storage

Cryo-compressed hydrogen storage represents a hybrid technology that combines key features of both compressed and liquefied hydrogen storage. The underlying principle involves storing hydrogen at cryogenic temperatures, typically in the range of −253 °C to −163 °C, while simultaneously maintaining moderate to high pressures, generally between 25 and 35 MPa. Is considered a commercially advanced technology, particularly in the transportation sector and in applications such as fuel cell electric vehicles (FCEVs). The performance and safety of the system are strongly dependent on the design and materials of the storage tanks. Specifically, double shell insulated vessels, combined with advanced pressure and thermal management systems, are essential to ensure safe operation and to optimize system efficiency.

The primary advantages of this approach include significantly increased hydrogen volumetric density, reaching approximately 80 g/L, reduced boil-off losses due to the combined pressure–temperature conditions and improved operational stability of the stored gas. However, the technology also presents notable challenges. These include relatively low overall well-to-wheel efficiency and high manufacturing costs. A critical limitation is the temperature rise that occurs during the filling process, which can reduce hydrogen density and introduce safety concerns related to pressure build-up within the storage vessel.

II. Solid – State Storage Systems

Solid-state hydrogen storage is widely regarded as a promising, efficient and reliable technology for hydrogen storage and transportation. In such systems, hydrogen is typically stored at pressures ranging from 1 to 10

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

MPa, achieving high volumetric storage capacities on the order of 100–130 g/L, with gravimetric capacities in the range of 1–1.5%. Compared to other storage methods, solid-state storage generally requires lower energy input during operation, although capital costs remain relatively high, typically estimated between 1700 and 4250 €/kg of stored hydrogen. This technology can be broadly classified into two main categories based on the storage mechanism and materials employed. The first category involves physisorption processes, where hydrogen is adsorbed onto high-surface-area porous materials; this approach typically requires low operating temperatures to achieve sufficient storage capacity. The second category is based on chemisorption, where hydrogen is stored through the formation of metal or complex hydrides.

Physisorption

Physisorption is a process in which hydrogen molecules are weakly adsorbed onto the surface of materials (through van der Waals interactions) without changing their molecular structure, which contributes to improved storage kinetics and enables relatively high adsorption rates.

Physisorption-based storage systems typically employ materials with highly porous structures, including carbon-based materials (e.g., graphene, fullerenes and carbon nanotubes), zeolites, covalent organic frameworks and metal–organic frameworks (MOFs). The suitability of these materials arises from their high specific surface area and tunable pore characteristics, which enable efficient hydrogen storage under relatively low pressure and temperature conditions. Two of the most extensively studied material classes in this context are MOFs and Carbon Nanotubes (CNs).

MOFs represent a class of highly porous materials with modular structures, offering large surface areas, adjustable pore sizes and significant pore volumes. These characteristics make them attractive for hydrogen storage applications. MOFs typically exhibit optimal performance at cryogenic temperatures (approximately −196 °C) and moderate pressures (around 8 MPa), achieving hydrogen storage capacities of up to approximately 8 wt%. CNs, on the other hand, are cylindrical nanostructures composed of carbon atoms, characterized by high porosity and large surface area. Their tubular morphology enables hydrogen storage both within their internal cavities and on their external surfaces. CNs can achieve storage capacities of up to approximately 6 wt% and their low mass makes them attractive for mobile applications. However, practical implementation is limited by high material costs and challenges associated with hydrogen desorption at cryogenic temperatures, which can lead to storage losses analogous to boil-off phenomena. These limitations similarly affect MOF-based systems and currently constrain their widespread deployment in practical hydrogen storage applications.

Chemical Storage

Chemical storage of hydrogen relies on chemical reactions which can transform, store and release again the gas. A wide range of materials has been investigated for such applications, including formic acid and complex hydrocarbons; however, the most widely studied and technologically relevant carriers are ammonia (NH_3), Liquid Organic Hydrogen Carriers (LOHCs) and metal hydrides.

Ammonia (NH_3), a compound of nitrogen and hydrogen, stores hydrogen through chemical bonds and releases it via reforming or direct combustion processes. It is considered an effective hydrogen carrier due

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

to its high gravimetric hydrogen content (17.6 wt%), high volumetric hydrogen density (108 kg H_2/m^3), and relatively high volumetric energy density (10.5 MJ/L). In addition, ammonia is non-flammable under ambient conditions and can be produced from a variety of energy sources, including renewable pathways, enabling low-carbon or carbon-free hydrogen production. The existence of a well-established global infrastructure for ammonia synthesis, transport and distribution further enhances its attractiveness as a hydrogen carrier. However, key challenges include its toxicity, the potential contamination of hydrogen streams with residual ammonia, the requirement for high operating temperatures during cracking processes and the dependence on catalytic systems, often involving noble metals.

Liquid organic hydrogen carriers (LOHCs) are organic compounds, capable of reversibly binding and releasing hydrogen through hydrogenation and dehydrogenation reactions. In this process, hydrogen is chemically stored within the molecular structure of the carrier and released when required. Typical hydrogen storage capacities for LOHC systems range between 5–8 wt%, with hydrogenation processes occurring at temperatures around 300 °C and dehydrogenation generally at temperatures below 200 °C, depending on the system. Ideal LOHCs are liquids under ambient conditions, non-toxic, safe and cost-effective. Commonly studied LOHC materials include methylcyclohexane, N-ethylcarbazole and toluene. The primary advantage of LOHC technology lies in its liquid-phase operation, which facilitates handling, storage, transport and controlled hydrogen release using conventional fuel infrastructure. However, the technology is associated with high energy requirements, particularly due to the endothermic nature of the dehydrogenation process, as well as challenges related to catalyst performance (balance activity, stability and cost) and limited operational lifetimes.

Metal hydrides represent another hydrogen storage approach, in which hydrogen is chemically absorbed into metals or metal alloys, forming metal hydride compounds. The process involves the dissociation of molecular hydrogen into atomic hydrogen at the material surface, followed by diffusion into the bulk and chemisorption within the metal structure. This process can result in lattice expansion of approximately 20–30% relative to the original volume. A wide range of materials can be utilized, including lithium (Li), lanthanum (La), nickel (Ni), magnesium (Mg), iron (Fe), titanium (Ti), aluminium (Al) and boron (B), forming hydrides such as MgH_2–$LiBH_4$, MgH_2–$NaAlH_4$, MgH_2–$LiAlH_4$, Mg_2NiH_4, Mg_2FeH_6, $FeTiH_2$, and $LaNi_5H_6$. Among these, magnesium hydride (MgH_2) is considered particularly promising, offering a hydrogen storage capacity of approximately 7.6 wt%, with hydrogen release temperatures typically in the range of 350–400 °C and energy density of around 9 MJ/kg. The primary advantages of metal hydride systems include high storage safety, high hydrogen purity and relatively low operational and maintenance costs, making them suitable for both stationary and transport applications, such as maritime systems. However, significant limitations remain, including slow absorption and desorption kinetics, high material costs, elevated dehydrogenation temperatures and in some cases, relatively low effective storage capacities.

III. Underground Storage Systems

Underground hydrogen storage is a promising large-scale storage option, offering significant potential alongside notable technical and regulatory challenges. The working principle is based on the utilization of

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

natural subsurface geological formations, such as depleted oil and gas reservoirs, deep saline aquifers and salt caverns, for the storage of hydrogen.

Key advantages of this approach include enhanced safety due to reduced exposure to external hazards (e.g., fire or mechanical damage), relatively low leakage risk when appropriate geological conditions are met and efficient utilization of existing subsurface voids. In addition, underground storage systems can support large storage capacities, exhibit relatively fast injection and withdrawal rates and are generally considered cost-effective and sustainable for long-term, grid-scale energy storage applications. However, the implementation of underground hydrogen storage is highly site-specific and depends on the availability of suitable geological formations. Critical requirements include adequate reservoir integrity, sufficient storage capacity, appropriate permeability and compliance with regulatory, technical and environmental constraints. Additional limitations include the relatively low volumetric density of stored hydrogen compared to other hydrogen stored on other physical storing systems and the potential for geochemical interactions between hydrogen and surrounding rock formations. For example, hydrogen may react with organic-rich formations, potentially leading to methane formation or other undesirable by-products. The effective deployment of underground hydrogen storage therefore requires detailed geotechnical and geochemical assessment, including analysis of reservoir permeability, porosity, heterogeneity and diffusion behavior.

The three principal types of geological formations considered suitable for underground hydrogen storage are salt caverns, saline aquifers and depleted hydrocarbon reservoirs.

Salt caverns

Salt caverns represent the most widely utilized geological formations for underground hydrogen storage. They are caves created by dissolving salt deposits with water. Their main advantages, compared to other subsurface storage options, include relatively low maintenance costs and extremely low gas permeability. Additionally, salt caverns offer large storage volumes, very low porosity (typically around 1%), favorable rheological behavior and robust mechanical properties. In parallel, the intrinsic characteristics of salt enable safe and efficient hydrogen storage even under high-pressure conditions. However, the successful implementation of salt cavern storage requires detailed site-specific assessment. Critical factors include the internal cavern geometry and integrity, as well as key geological parameters such as cavern depth, geographic location, salt formation structure and mineralogical composition. Comprehensive characterization of these parameters is essential to ensure storage performance, structural stability and long-term operational safety.

Saline aquifers

Underground hydrogen storage in saline aquifers is a less mature and less deployed technique compared to other subsurface storage options. The basic principle is the storage of hydrogen in an aquifer, which is usually found in an underground layer of porous permeable rock, containing either fresh or salt water and often extending to a depth of tens or hundreds of meters. The storage mechanism is based on the displacement of saline water, analogous in principle to storage in salt caverns. Compared to salt caverns, saline aquifers offer advantages in terms of broader geographical availability and potentially larger storage capacities. However, the implementation of this technology presents significant technical challenges. The coexistence of gas and liquid phases within the porous medium can complicate storage and withdrawal processes, affecting overall

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

system performance. Critical parameters that must be thoroughly characterized prior to deployment include reservoir porosity, permeability and pH.

Depleted hydrocarbon reservoirs

Depleted gas reservoirs are geological formations that have previously contained hydrocarbons or other gases, which have been extracted through production activities or, in some cases, diminished due to natural processes such as chemical reactions or migration. Their suitability for hydrogen storage is primarily attributed to their favorable reservoir properties, including high porosity, adequate permeability and substantial storage capacity. In addition, the presence of residual gas can contribute to maintaining reservoir pressure and may facilitate storage operations. This storage approach offers several advantages, including proven long-term containment integrity, large-scale storage potential and relatively high operational efficiency.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

3.5 Fuel cell

A fuel cell is an electrochemical energy conversion device that directly transforms the chemical energy of a fuel—typically hydrogen—into electrical energy and heat through redox reactions with oxygen or another oxidizing agent. The process is characterized by high efficiency, low noise emissions and the production of water and heat as the primary by-products, rendering it a clean and continuous power generation technology. Within the hydrogen value chain, the fuel cell constitutes the final conversion stage. Following hydrogen production (e.g., via electrolysis) and subsequent storage, the fuel is reconverted into usable energy in the form of electricity and heat through electrochemical processes, thereby enabling its end-use in a wide range of applications.

The main structure of a fuel cell contains two electrodes—an anode and a cathode—separated by an electrolyte membrane. The operation initiates with the supply of hydrogen to the anode, while oxygen is introduced at the cathode. At the anode, a catalyst facilitates the dissociation of hydrogen molecules into protons (H^+) and electrons (e^-). The electrolyte membrane permits the selective transport of protons to the cathode while preventing electron passage. Consequently, the electrons are forced to travel through a circuit, thereby generating an electricity and thermal energy. Upon reaching the cathode, the electrons recombine with the transported protons and react with oxygen molecules. This electrochemical reaction produces water (H_2O) and releases heat as byproducts of the overall process. The following figure briefly presents the operation of a fuel cell.

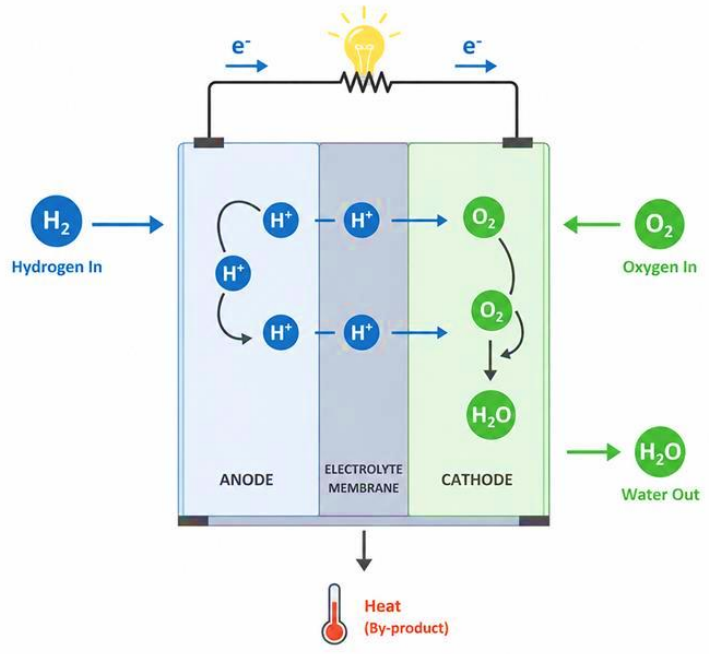


Figure 5. Typical operation of a fuel cell

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

Fuel cells, capable of utilizing hydrogen for energy conversion, are typically classified into five (5) categories, primarily based on the type and material of the electrolyte membrane employed.

The first category is the Polymer Electrolyte Membrane Fuel Cell (PEMFC), also known as the Proton Exchange Membrane fuel cell. This technology utilizes a solid polymer electrolyte, most commonly based on perfluorosulfonic acid, which enables proton conduction. The electrochemical reactions are facilitated by noble metal catalysts, predominantly platinum, which promote hydrogen dissociation at the anode. PEM fuel cells operate within a temperature range of approximately 60–200°C, with optimal performance typically achieved at temperatures below 120°C. Their electrical efficiency generally ranges between 40% and 60%, while their power output spans from approximately 1 kW to 100 kW, depending on system configuration and application. Key advantages include low operating temperatures, fast start-up times, high power density and a compact and relatively simple system architecture. Additionally, the solid-state electrolyte reduces issues related to corrosion and electrolyte leakage. However, several limitations are associated with this technology. These include membrane degradation and mechanical fragility, stringent requirements for purified water and thermal management, the necessity for high-purity hydrogen (typically ≥99.99%) to prevent catalyst poisoning and the reliance on expensive noble metals such as platinum, which significantly increases system cost. Are widely used in applications requiring rapid response and operational flexibility, including backup power systems, portable power generation, distributed energy systems and transportation (notably fuel cell electric vehicles).

Alkaline Fuel Cells (AFCs) represent one of the earliest fuel cell technologies to be deployed. Their operating principle differs significantly from that of PEMFCs, primarily due to the nature of the electrolyte. AFCs utilize either an aqueous potassium hydroxide (KOH) solution retained within a porous matrix or an alkaline polymer membrane for the electrolyte. In contrast to PEMFCs, where proton conduction occurs, AFCs operate via the conduction of hydroxide ions (OH^-). More specifically, air and water enter the cathode, the oxygen reduced and the hydroxyl ions (OH-) travel to the anode, where the hydrogen fuel enters. Electricity is produced between the two electrodes, while water is formed as a by-product. AFCs typically operate within a temperature range of 50–230°C, with optimal performance generally achieved at temperatures below 100°C. Their power output commonly ranges from 1 kW to 100 kW, while electrical efficiencies are relatively high, typically exceeding 60% and reaching up to approximately 70%. The main advantages of AFC technology include high electrical efficiency, low operating temperature, rapid start-up capability and relatively simple system operation. Additionally, AFC systems are characterized by favorable thermal management, low weight and compact design. However, there are several limitations too. AFCs are highly sensitive to CO_2 and CO and there is a great demand for high-purity hydrogen. Furthermore, systems utilizing liquid electrolytes may encounter handling, sealing and leakage issues. In addition, the use of noble metal catalysts, such as platinum, is also required. AFCs were initially developed for military reasons and were extensively used in space applications. They are also used as backup power systems and in transportation use cases.

The third technology of FC which used for hydrogen utilize is the Solid Oxide Fuel Cells (SOFCs). SOFCs characterized primarily by the use of a solid ceramic electrolyte, typically yttria-stabilized zirconia, which enables the conduction of oxygen ions (O^{2-}). SOFCs operate based on the transport of oxide ions from the cathode to the anode, while at the cathode, oxygen is reduced to form oxide ions, which subsequently

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

migrate through the electrolyte and react with the hydrogen. The procedure generates electricity, heat and water. SOFC systems operate at elevated temperatures, typically in the range of 500–1000°C, which contributes to relatively high percentages of efficiency, generally around 60%. The technology is suitable for a wide range of scales, from small distributed units (~1 kW) to large-scale installations reaching up to several megawatts (~2 MW per stack or system configuration). The principal advantages of SOFC technology include high efficiency, generation of high-grade waste heat, which is particularly advantageous for CHP applications. Additionally, the use of non-precious metal catalysts and the solid-state nature of the electrolyte reduce issues related to corrosion and electrolyte management. However, several technical challenges remain. The high operating temperatures impose stringent requirements on materials and thermal management and contribute to long start-up times. SOFC systems are also sensitive to fuel impurities, particularly sulfur compounds. Furthermore, despite significant progress, the technology is still considered relatively costly and not fully mature compared to low-temperature fuel cell alternatives. SOFCs are primarily deployed in stationary power generation applications, including distributed generation systems, auxiliary power units and CHP installations, where their high efficiency and thermal output can be effectively utilized.

The earliest developed and most technologically mature fuel cell systems are Phosphoric Acid Fuel Cells (PAFCs). Their operating principle is similar to that of PEMFCs, with the key distinction being the use of liquid phosphoric acid (H_3PO_4) as the electrolyte. This electrolyte is typically immobilized within a porous matrix or, in some configurations, incorporated into a polymer membrane structure. PAFC systems operate at intermediate temperatures, typically in the range of 150–200°C. Their efficiency is lower compared to other fuel cell technologies, generally ranging between 35% and 45%. The power output of PAFC systems typically spans from approximately 5 kW to 400 kW, depending on system configuration and design. Larger-scale units (exceeding 100 kW) are generally associated with liquid electrolyte implementations, whereas configurations employing polymer membrane electrolytes are usually limited to smaller-scale applications (typically below 10 kW). The primary advantage of PAFC technology lies in its high level of technological maturity and proven reliability. Additionally, the moderate operating temperature allows for manageable start-up times and relatively simple thermal management. The electrolyte materials are cost-effective and the system exhibits lower sensitivity to hydrogen purity. However, several limitations are associated with PAFCs. These include comparatively low efficiency, sensitivity to carbon monoxide (CO) and sulfur and requirement for platinum-based catalysts. Furthermore, the corrosive nature of the liquid phosphoric acid electrolyte necessitates careful handling, material selection and system design. Due to their thermal characteristics and the availability of usable waste heat, PAFC systems are particularly well-suited for CHP applications and are commonly deployed in distributed generation systems.

The last fuel cell technology that can utilize hydrogen as fuel is Molten Carbone Fuel Cells (MCFCs). Their operating principle differs significantly from that of other fuel cell types, as, in addition to hydrogen and oxygen, the electrochemical reactions require the presence of carbon dioxide (CO_2). The system operates through the conduction of carbonate ions (CO_3^{2-}). The electrolyte in MCFCs consists of a molten carbonate salt mixture, typically composed of lithium carbonate (Li_2CO_3), sodium carbonate (Na_2CO_3) or potassium carbonate (K_2CO_3). An important operational aspect of MCFC technology is the continuous involvement of carbon dioxide in the electrochemical cycle. The CO_2 produced as by-product, must either be recirculated or appropriately managed and treated to prevent uncontrolled emissions. MCFC systems operate at high

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

temperatures, typically in the range of 600–700°C, enabling electrical efficiencies of approximately 45–55%. The typical power range of MCFC installations spans from approximately 300 kW to 3 MW. The key advantages of MCFC technology include relatively high efficiency, significant production of high-grade waste heat suitable for CHP applications and the use of non-precious, cost-effective catalyst materials. However, several technical challenges are associated with this technology. The high operating temperature imposes strict requirements on materials and thermal management. The molten, corrosive nature of the electrolyte can lead to material degradation, corrosion of metallic components and electrolyte losses through evaporation. Furthermore, MCFCs are sensitive to sulfur compounds. Due to these characteristics, MCFC systems are primarily deployed in stationary applications, including utility-scale power generation, distributed energy systems and CHP installations.

The following table provides a summary of the key characteristics and a brief comparison between the five fuel cell technologies.

Table 4. Brief comparison between the different types of Fuel Cells

Type of FC	Operating Temperature	Stack Size	Efficiency	Application	Advantages	Disadvantages
PEMFC	60 - 200°C	1 - 100kW	40 - 60%	Backup power systems Portable power generation Distributed energy systems Transportation	Low temperatures Fast start-up High power density Compact and simple architecture Reduced issues of corrosion and leakages	Membrane degradation Mechanical fragility Requirements for thermal management Necessity for high-purity hydrogen
AFC	50 - 230°C	1 - 100kW	60 - 70%	Military applications Space applications Backup power systems Transportation	High efficiency Low temperature Rapid start-up Simple operation Favorable thermal management Low weight Compact design	Highly sensitive to CO_2 and CO Demand for high-purity hydrogen Sealing and leakage issues Use of noble metal catalysts
SOFC	500 - 1000°C	1kW - 2MW	60%	Stationary power generation applications Distributed generation systems CHP installations	High efficiency Generation of high-grade waste heat Non-precious catalysts Reduced issues of corrosion	High temperatures Long start-up Sensitive to fuel impurities Costly and not fully mature technology

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

PAFC	150 - 200°C	5 - 400kW	35 - 45%	CHP applications Distributed generation systems	Technological maturity Manageable start-up times Simple thermal management Low sensitivity to hydrogen purity Cost-effective materials	Low efficiency Sensitivity to CO and sulfur Platinum-based catalysts Corrosive nature of electrolyte
MCFC	600 - 700°C	300kW - 3MW	45 - 55%	Utility-scale power generation Distributed energy systems CHP installations	High efficiency Production of high-grade waste Non-precious materials Cost-effective catalyst	High temperature Material degradation Corrosion of metallic components Sensitive to sulfur compounds

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

4 Specific Technology

The practical validation, testing and performance assessment of the technology at a real operational scale will be carried out through the monitoring and evaluation of an Energy Pack (EP) system installed by BER – Blue Energy Revolution at the CERTH/CERTH facilities in Ptolemaida. The installation has been implemented within the framework of a European research initiative called EVELIXIA and serves as a pilot-scale demonstration.

The EP is a fully integrated, containerized, turnkey Power-to-Hydrogen-to-Power (P2H2P) system, incorporating all major stages of the green hydrogen value chain within a single modular infrastructure. The system architecture has been designed to support the complete conversion cycle, from renewable electricity utilization and hydrogen production to hydrogen storage and subsequent reconversion into electrical energy. The overall container design is illustrated in the following figure.

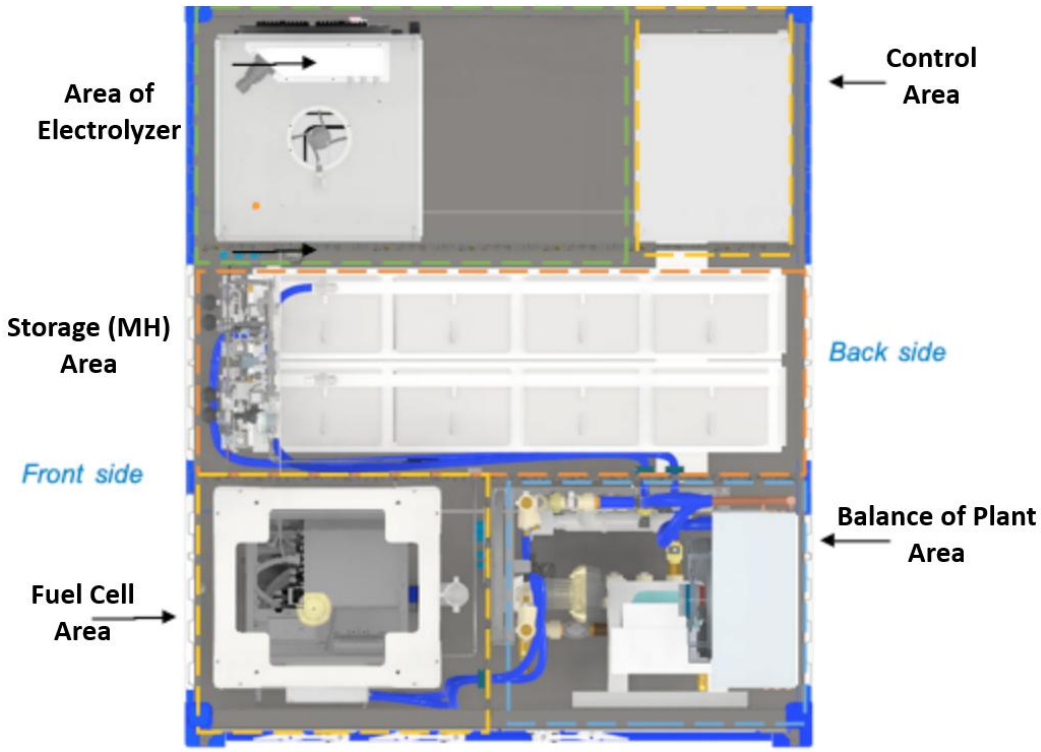


Figure 6. Energy Pack's design

More specifically, the system incorporates a PEM electrolyser rated at 7 kW, with a hydrogen production capacity of approximately 1,600 NL/h. The electrolyser utilizes surplus electrical energy generated by the photovoltaic system installed on the roof of the CERTH/CPERI building. Excess renewable electricity that would otherwise remain underutilized is directed to the electrolyser, enabling the production of green

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

hydrogen through water electrolysis. For hydrogen storage, the system includes a metal hydride storage tank. The storage unit has a total capacity of approximately 29,000 NL of H_2, corresponding to an energy content of approximately 40 kWh. The generated hydrogen is stored and retained within this subsystem until energy demand conditions require its utilization. The final stage of the EP consists of a 10 kW fuel cell (Fuel Cell), responsible for converting the stored hydrogen back into electrical energy. The FC operates at a hydrogen consumption rate of approximately 7,600 NL/h, generating electricity on demand and thereby completing the P2H2P cycle. The figure below provides a graphic description of the EP interfaces and its main system components.

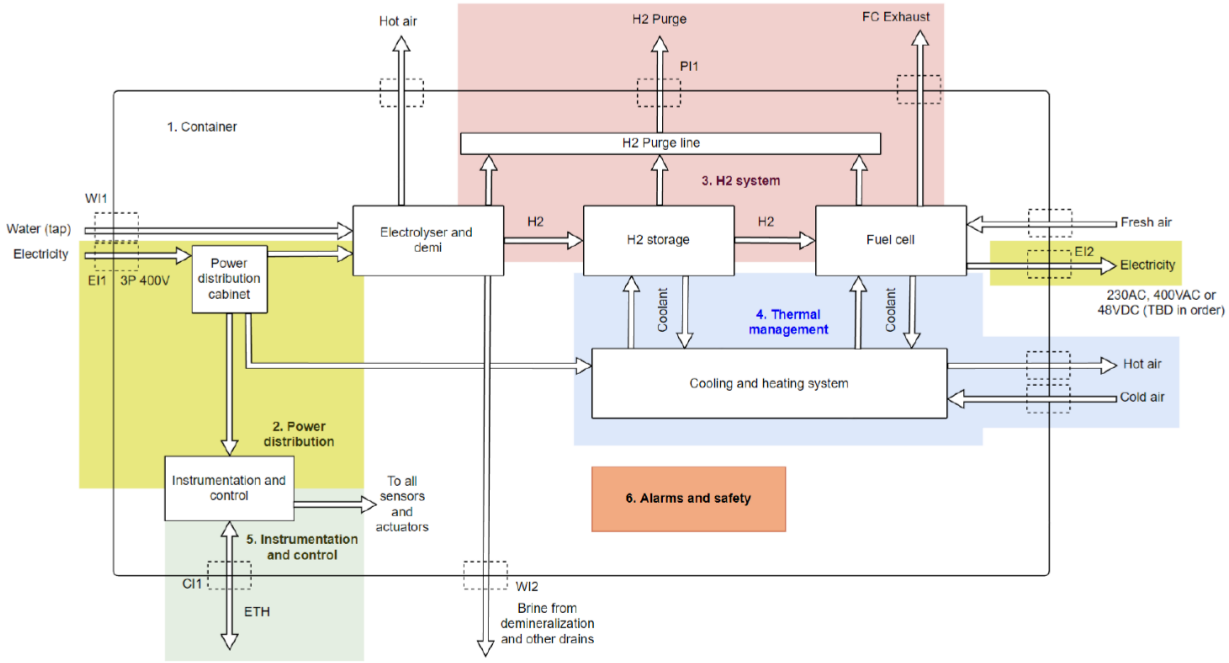


Figure 7. Graphical description of EP interfaces and system components

The EP has already entered its operational phase and is currently supporting the energy requirements of the CERTH/CPERI facilities. At present, the system contributes to the production of electrical energy that is supplied exclusively to the operation of the building's two domestic hot water (DHW) boilers, thereby indirectly supporting the hot water demand of the facility. In a subsequent implementation phase, additional modifications and optimization measures are planned to further enhance energy recovery. More specifically, the waste thermal output and exhaust stream generated during fuel cell operation—including heated exhaust gases, oxygen and water vapour—will be utilized through heat recovery strategies to preheat water intended for laboratory applications. The following figure presents the installed EP as deployed and currently operating.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059



Figure 8. Installed Energy Pack

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

5 Conclusions

The first of the three Deliverables dedicated to CHP fuel cell system technology was developed with the objective of establishing the theoretical foundation and providing a comprehensive understanding of the technology. Its purpose is to create the necessary technical background for the subsequent Deliverables, which will address more specialized engineering aspects, system-specific design considerations and analyses of monitoring activities and operational performance evaluation under real conditions.

As demonstrated throughout the present Deliverable, the deployment of fuel cell technologies for CHP applications represents a particularly promising, efficient and sustainable solution, especially when hydrogen is employed as the primary fuel source. Hydrogen becomes a clean and environmentally sustainable energy vector when it is generated through water electrolysis powered by electricity originating from RES. Under such conditions, hydrogen can be considered a green fuel capable of supporting low-carbon and decarbonized energy systems.

A key parameter in the hydrogen production chain is the selection of the electrolyser technology employed. This selection must be assessed from multiple perspectives, including technological maturity, economic feasibility, operational performance and environmental sustainability. Among the available alternatives, particular emphasis is placed on electrolyser technologies that have reached a significant level of technological maturity and demonstrate favourable economic characteristics, while also minimizing environmental impacts through reduced dependence on rare or noble metals and critical raw materials. In integrated hydrogen-based CHP systems, hydrogen primarily functions as an energy carrier. Consequently, the hydrogen storage subsystem constitutes another critical element within the overall architecture. The storage methodology must ensure safe, reliable and efficient retention of hydrogen while simultaneously enabling rapid availability and effective utilization whenever energy demand conditions require it. Equally important is the design and technological configuration of the fuel cell subsystem itself. The structural characteristics, operating principles, performance capabilities and integration potential of fuel cells significantly influence the overall performance of CHP applications. All of these parameters are thoroughly analysed within the present Deliverable, while alternative technological pathways, implementation strategies and future perspectives are systematically examined.

The analysis concludes with the presentation of the system installed and currently operating at the CERTH/CPERI facilities in Ptolemaida, which serves as a practical pilot-scale case study demonstrating the successful integration of all the aforementioned technological components. More specifically, the installed system represents a complete implementation framework that aligns with the key design principles discussed throughout this work. It produces the required hydrogen using electricity generated from RES—specifically rooftop photovoltaic installations—in combination with a PEM electrolyser. The generated hydrogen is subsequently stored within a metal hydride storage tank and is finally reconverted into electrical energy on demand through the operation of the corresponding fuel cell system. This integrated configuration constitutes a representative example of a renewable hydrogen-based CHP architecture and demonstrates the practical feasibility of P2H2P concepts in real operational environments.

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

References

Colours of Hydrogen

1. J. Incer-Valverde, A. Korayem, G. Tsatsaronis, T. Morosuk; **2023**. *"Colors" of hydrogen: Definitions and carbon intensity*
2. J. M. Marín Arcos and D. M. F. Santos; **2023**. *The Hydrogen Color Spectrum: Techno-Economic Analysis of the Available Technologies for Hydrogen Production*
3. P. Phogat, B. Chad, Shreya; **2025**. *Hydrogen economy: Pathways, production methods and applications for a sustainable energy future*
4. INTERNATIONAL ENERGY AGENCY (IEA); **2025**. *Global Hydrogen Review 2025*

Hydrogen Use

1. INTERNATIONAL ENERGY AGENCY (IEA); **2025**. *Global Hydrogen Review 2025*
2. P. Cheekatamarla; **2024**. *Hydrogen and the Global Energy Transition—Path to Sustainability and Adoption across All Economic Sectors*
3. G. Migliavacca, C. Carlini, P. Domenighini and C. Zagano; **2024**. *Hydrogen: Prospects and Criticalities for Future Development and Analysis of Present EU and National Regulation*
4. International Renewable Energy Agency (IRENA); **2019**. *HYDROGEN: A RENEWABLE ENERGY PERSPECTIVE*
5. International Renewable Energy Agency (IRENA); **2018**. *HYDROGEN FROM RENEWABLE POWER: TECHNOLOGY OUTLOOK FOR THE ENERGY TRANSITION*
6. P. Phogat, B. Chad, Shreya; **2025**. *Hydrogen economy: Pathways, production methods and applications for a sustainable energy future*

Electrolysis

1. M. Abubakr, S. Shahid and I. Arman; **2023**. *A Review on Hydrogen Production Technologies and Its Future Demand*
2. M. E. Sahin; **2024**. *An Overview of Different Water Electrolyzer Types for Hydrogen Production*
3. S. Shiva Kumar and H. Lim; **2022**. *An overview of water electrolysis technologies for green hydrogen production*
4. A. Vedrtnam, K. Kalauni and R. Pahwa; **2025**. *Water Electrolysis Technologies and Their Modeling Approaches: A Comprehensive Review*
5. O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, S. Few; **2017**. *Future cost and performance of water electrolysis: An expert elicitation study*
6. P. Phogat, B. Chad, Shreya; **2025**. *Hydrogen economy: Pathways, production methods and applications for a sustainable energy future*

Storage

1. C. Tarhan, M. Ali Çil; **2021.** *A study on hydrogen, the clean energy of the future: Hydrogen storage methods*

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

2. E. Rivard, M. Trudeau and K. Zaghib; **2019**. *Hydrogen Storage for Mobility: A Review*
3. M. R. Usman; **2022**. *Hydrogen storage methods: Review and current status*
4. A. S. Mekonnin, K. Wacławiak, M. Humayun, S. Zhang and H. Ullah; **2025**. *Hydrogen Storage Technology, and Its Challenges: A Review*
5. S. Niaz, T. Manzoor, A. H. Pandith; **2015**. *Hydrogen storage: Materials, methods and perspectives*
6. H. Barthelemy, M. Weber, F. Barbier; **2017**. *Hydrogen storage: Recent improvements and industrial perspectives*
7. N. Ma, W. Zhao, W. Wang, X. Li, H. Zhou; **2024**. *Large scale of green hydrogen storage: Opportunities and challenges*

Fuel cell

1. P. Ramasamy, B. Muruganantham, S. Rajasekaran, B. D. Babu, R. Ramkumar, A. V. Aparna Marthanda, S. Mohan; **2024**. *A comprehensive review on different types of fuel cell and its applications*
2. A. M. Elaibi; **2025**. *Development of Fuel Cell Technology and Applications: A Review*
3. D. Manzo, R. Thai, H. T. Le, G. K. Venayagamoorthy; **2025**. *Fuel cell technology review: Types, economy, application, and vehicle-to-grid system*
4. N. Sazali, W. N. Wan Salleh, A. S.Jamaludin and M. N. Mhd Razali; **2020**. *New Perspectives on Fuel Cell Technology: A Brief Review*

Specific Technology

1. *https://bluenergyrevolution.com/en/*

Funded by the European Union

This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059