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Comparative Assessment of Next-Generation Hydrogen Production Technologies: Insights from Hydrogen Expo Hamburg 2025

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Abstract

The rapid expansion of the hydrogen economy has intensified the need for accessible production technologies. This study presents a comparative assessment of two next-generation hydrogen production systems showcased at the Hydrogen Expo Hamburg 2025: the containerised HyPro electrolyser and the modular Enapter EL 4.1. The analysis focuses on their technical specifications, operational philosophies, and indicative costs. Data were gathered through technical consultations with exhibitors and catalogue analyses. The evaluation highlights key differences in system architecture, production capacity, and installation requirements within academic research environments. The results demonstrate how suitability depends on the intended scale of application, contrasting a laboratory-ready modular approach with an industrial-oriented turnkey configuration. This study provides practical insights to support universities and research institutions in selecting hydrogen production equipment that aligns with their specific infrastructural and budgetary conditions.

Keywords: hydrogen economy; electrolysis; energy efficiency; research infrastructure; decision-making framework

1. Introduction

Hydrogen is increasingly recognized as a key energy carrier in the transition toward low-carbon and sustainable energy systems. As global efforts to reduce greenhouse gas emissions intensify, hydrogen technologies are gaining significant attention in sectors such as energy storage, transportation, and industrial decarbonization. In particular, hydrogen produced through water electrolysis using renewable electricity—often referred to as green hydrogen—is considered one of the most promising pathways for achieving climate neutrality [1–3].

In the context of European Union energy and raw materials policy, hydrogen is increasingly recognised as a strategic resource contributing to energy security, decarbonisation, and the sustainable utilisation of primary and secondary resources. This perspective is reflected in key EU policy frameworks, including the European Green Deal and the Critical Raw Materials Act, which emphasise the role of hydrogen in reducing dependency on fossil fuels and enhancing resource resilience.

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Electrolysis-based hydrogen production technologies have experienced significant technological progress in recent years. Several types of electrolyser systems are currently deployed, including alkaline electrolysers (AEL), proton exchange membrane electrolysers (PEM), solid oxide electrolysers (SOE), and anion exchange membrane electrolysers (AEM). These technologies differ in terms of efficiency, operating conditions, materials, scalability, and investment requirements [4,5]. Consequently, the selection of an appropriate electrolyser technology depends on the intended application, infrastructure conditions, and economic constraints.

An important aspect of hydrogen production via electrolysis is its water demand and the associated implications for resource sustainability. The theoretical requirement for hydrogen production is approximately 9 kg of water per kilogram of hydrogen. However, in practical systems, total water consumption may reach 20–30 L per kilogram of hydrogen when purification, cooling, and system losses are considered. This highlights the importance of sustainable water resource management, particularly in regions already experiencing water stress. Consequently, the integration of hydrogen production with water treatment or desalination systems is increasingly being explored as part of sustainable energy and resource strategies [6,7].

Hydrogen production systems are currently being implemented at various scales, ranging from compact laboratory units to containerised pilot installations and large industrial facilities. For research institutions and universities, the choice of hydrogen production technology plays an important role, as such systems often serve not only as production units but also as platforms for experimental research, education, and technology demonstration.

Despite the increasing availability of hydrogen production technologies, comparative assessments of different electrolyser configurations remain relatively limited, particularly in the context of their applicability within academic and research environments. Many studies focus primarily on large-scale industrial hydrogen production or national energy infrastructure development, while smaller-scale systems suitable for research institutions receive less attention.

This study aims to address this gap by providing a comparative technical and economic assessment of two hydrogen production systems: the HyPro 10-foot containerized electrolyser system developed by Fuel Cell Systems Ltd. (Hungerford, UK) and the Enapter EL 4.1 modular AEM Electrolyser. The comparison focuses on key parameters, including hydrogen production capacity, electrical and water requirements, system scalability, spatial footprint, and indicative capital costs.

By analyzing these systems within a unified framework, the study seeks to support informed decision-making regarding the deployment of hydrogen production technologies in academic and pilot-scale environments. The findings contribute to a better understanding of how different electrolyser architectures may align with institutional research objectives, infrastructure conditions, and long-term hydrogen strategies. This work, therefore, provides a structured comparative framework for evaluating decentralised hydrogen production systems with particular emphasis on their suitability for academic research infrastructure [8].

2. Hydrogen Technology Expo Hamburg 2025

The Hydrogen and Carbon Capture Technology World Expo 2025 represents one of the largest international events dedicated to hydrogen and carbon capture, utilisation, and storage (CCUS) technologies. The fifth edition of the event was held at Hamburg Messe and spanned seven exhibition halls, covering more than 4650 m^2 of exhibition space over a three-day period. The event brought together more than 1000 exhibiting companies and attracted over 20,000 participants from around the world, reflecting the growing global interest in hydrogen and CCUS technologies.

The Hydrogen Expo Hamburg 2025 showcased a wide range of hydrogen production and utilisation technologies. The majority of exhibitors presented solutions based on established electrolysis technologies, particularly alkaline (AEL) and proton exchange membrane (PEM) systems, which currently dominate the market. At the same time, emerging technologies such as anion exchange membrane (AEM) electrolysers were also represented, reflecting ongoing technological diversification and innovation in the sector.

The selection of the HyPro and Enapter systems for detailed analysis in this study was based on their representativeness of two distinct technological and deployment approaches observed at the event—namely, centralised containerised systems and decentralised modular solutions.

3. History of Hydrogen

Hydrogen is far from a recent discovery; the gas was first identified in the 18th century. The following section outlines several key milestones that have shaped its historical development. Since then, its scientific, industrial, and societal relevance has evolved considerably, driven by advances in chemistry, energy technology, and materials science. Over the centuries, hydrogen has transitioned from a laboratory curiosity to a key component of various industrial processes, and more recently, to a central element of global decarbonization strategies. Its historical development reflects both technological progress and changing energy paradigms. The timeline presented below highlights several major milestones that have contributed to shaping the modern understanding and application of hydrogen as an energy carrier.

- 1766 The discovery: British scientist Henry Cavendish identifies hydrogen as a separate element for the first time. The key: the reaction of zinc with hydrochloric acid. During a presentation at the Royal Society of London, Cavendish later detonates his “inflammable air”, thereby producing water.
- 1783 The dawn of hydrogen mobility: Jacques Alexander Cesar Charles, a French physicist, launches the first hydrogen balloon flight from the Champ de Mars in Paris. The balloon, called the “Charlière”, rises to an altitude of three km.
- 1788 The baptism: Builiding on Cavendish’s discoveries French chemist Antoine Lavoisier gave hydrogen the name “hydrogèn”. I tis derived from the Greek words “hydro” and “genes”, which means water and born from.
- 1800 The first electrolysis: English scientists William Nicholson and Sir Anthony Carlisle discover that applying electricity to water produces both hydrogen and oxygen gas. This process is later called “electrolysis”.
- 1838–1842 The first fuel cell: In 1838, Swiss scientist Christian Friedrich Schoenbein discovered that the reaction between hydrogen and oxygen produces also electricity. In 1842, British scientist Sir William Grove developed a “gas voltaic battery”. Today, he is considered the “father of the fuel cell”.
- 1900 Through the skies with hydrogen: Count Ferdinand von Zeppelin launches the first hydrogen airship, the “Zeppelin LZ1”. In 1937, after ten flights from Germany to the United States, its successor, the LZ129 “Hindenburg”, bursts into flames upon landing in New Jersey.
- 1931 Hydrogen en masse: In the 1920s, Carl Bosch developed steam reforming from natural gas for BASF Leuna. Georg Schiller (IG Farben AG) patented it around 1930. In 1931, Standard Oil Company (Baton Rouge, LA, USA) opened the first modern hydrogen plant in Baton Rouge, Louisiana.

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- 1966 With hydrogen into space: Liquid hydrogen (LH_2) was tested as rocket fuel in the USA as early as 1943, but it was not until NASA was founded in 1958 that its use was introduced on a large scale. In 1966, it launched its first LH_2 rocket into space with Saturn IB 2.
- 1973 Start of PEM electrolysis: In the 19th and 20th centuries, electrolysers mostly used alkaline technology. It was not until 1973 that the concept of polymer exchange membrane (PEM) electrolysis was developed. It was based on the invention of the PEM fuel cell by General Electric in the 1960s.
- 1999 First hydrogen refueling stations in Europe: Hydrogen refuelling stations emerged relatively late: on 5 May 1999, the world's first public station opened at Munich Airport. Today, there are around 70 active hydrogen refuelling stations in Germany, and around 1160 worldwide at the end of 2024.
- 2013 The birth of power to gas: In 2013, Uniper launched "WindGas Falkenhagen" in Brandenburg—one of the first power-to-X plants in the world. The idea is that hydrogen is produced by electrolysis from locally surplus wind power and then fed directly into the regional gas network.

4. The Colours of Hydrogen

A wide spectrum of hydrogen "colours" exists, each representing a specific production pathway and its associated carbon footprint. However, these colour classifications are not standardized globally, nor are they consistently applied across different sectors and industries. To address these inconsistencies and provide conceptual clarity, hydrogen pathways are often grouped into broader categories based on their energy sources and resulting environmental impacts. A commonly used structure distinguishes between fossil-based hydrogen, low-carbon hydrogen, and renewable hydrogen, each encompassing several colour labels that reflect the underlying production process. This categorization enables a more systematic comparison of technological maturity, emission profiles, and potential applications across the hydrogen value chain. The following table summarizes the most widely referenced colour classifications within these three overarching groups. As shown in Table 1, hydrogen can be classified into several colour categories according to its production pathway [9,10].

Table 1. Classification of hydrogen colours according to production pathways [9,10].

Fossil Hydrogen	**Low-Carbon Hydrogen**	**Renewable (CO_2–Free) Hydrogen**
GREY HYDROGEN: steam reforming of natural gas	YELLOW HYDROGEN: Electrolysis using grid electricity or nuclear energy	GREEN HYDROGEN: Electrolysis using renewable electricity
BLACK HYDROGEN: Gasification of hard coal	BLUE HYDROGEN: Fossil fuel production combined with CCS	ORANGE HYDROGEN: Using bioenergy or from organic materials such as biomass, biofuel, biogas and biomethane or through pyrolysis from waste.
BROWN HYDROGEN: Gasification of lignite	TURQUOISE HYDROGEN: Methane pyrolysis—thermal cracking of methane—methane is broken down into its components hydrogen and carbon in the absence of oxygen. Instead of CO_2 solid carbon is produced.	
GOLDEN OR WHITE HYDROGEN: Comes from natural underground deposits	PINK/RED OR PURPLE HYDROGEN: Electrolysis using nuclear energy	

5. Hydrogen in Inorganic Chemistry

Hydrogen is the first element in the periodic table, characterized by the smallest atomic radius and the simplest electronic configuration, 1 s^1. Three isotopes are known: light hydrogen (protium), heavy hydrogen (deuterium), and the radioactive tritium. As the simplest chemical element, hydrogen occurs under standard conditions as a clear, colorless gas with no taste or odor. It is also the lightest gas, approximately 14.5 times lighter than air. Molecular hydrogen is relatively stable and, due to its high bond energy, exhibits low reactivity. Its thermal conductivity is about seven times higher than that of air. The extremely small size of H_2 molecules allows them to permeate porous materials with ease. Hydrogen dissolves only minimally in water at 0 °C and 0.1 MPa, roughly 22 mL of gaseous hydrogen dissolve in one liter of water. It dissolves much more readily in metals such as nickel, palladium, and platinum, where hydrogen molecules dissociate into individual atoms. Atomic hydrogen is significantly more reactive than its molecular form, causing reactions to proceed faster in the presence of these metals. Consequently, nickel, palladium, and platinum act as highly effective catalysts [11–19].

$$\begin{array}{ccc} {}^{1}_{1}\mathrm{H} & {}^{2}_{1}\mathrm{H} & {}^{3}_{1}\mathrm{H} \\ \text{protium} & \text{deuterium} & \text{tritium} \end{array}$$

The hydrogen atom possesses a high ionization energy (1311 kJ/mol), which makes its behavior in several respects more similar to that of the halogens than to the alkali metals. This is example 1, 2 of an equation:

$$\mathrm{H(g) + e^-(g) \rightarrow H^-(g)} \tag{1}$$

$$\Delta_{ea}H^{\ominus} = -72 \text{ kJ mol}^{-1} \tag{2}$$

$$\mathrm{H^-} : [\uparrow\downarrow]$$

Its chemical properties are determined by its electronic structure and its position in the periodic table. When forming compounds, hydrogen can modify its electron configuration in two principal ways:

1. By gaining an electron, it attains the electron configuration of the nearest noble gas, helium, resulting in the hydride anion H^-.
2. By losing its single 1 s electron, the hydrogen atom becomes a proton. In aqueous solutions, the proton (H^+) binds to the lone electron pair of oxygen, forming the hydronium cation H_3O^+.

Hydrogen is a typical non-metal with an electronegativity of X = 2.2, forming either nonpolar bonds (e.g., H_2) or polar bonds (e.g., HCl). It also participates in hydrogen bonding with nitrogen (N), oxygen (O), and fluorine (F). Molecular hydrogen is relatively stable, exhibits low reactivity, and is characterized by a high H–H bond dissociation energy (436 kJ mol^{-1}).

5.1. Reactions with Nonmetals

At standard temperature, hydrogen reacts with fluorine to form hydrogen fluoride (HF), and this reaction proceeds spontaneously even in the absence of light. With chlorine, hydrogen forms hydrogen chloride (HCl), but only under exposure to sunlight containing ultraviolet radiation or when the reaction mixture is ignited. In mixtures with air or with pure oxygen, hydrogen combines to form water once ignition occurs. An example of a reaction between hydrogen and a non-metal is shown in Equation (3).

$$\mathrm{2H_2(g) + O_2(g) \rightarrow 2H_20(L)} \tag{3}$$

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This reaction is highly vigorous and exhibits an explosive character. The hydrogen flame reaches extremely high temperatures (up to approximately 2800 °C), which enables its use in metal cutting and welding applications. At elevated temperatures and in the presence of suitable catalysts, hydrogen reacts with nitrogen to produce ammonia. This is example (4) of an equation:

$$3H_2(g) + N_2(g) \xrightarrow{t} 2NH_3(g) \tag{4}$$

Ammonia subsequently serves as a precursor for the production of nitric acid and various nitrogen-based fertilizers [14].

Hydrogen exhibits the ability to react with oxygen bound in metal oxides, demonstrating its reducing properties. This reaction is expressed by Equation (5).

$$CuO(s) + H_2(g) \rightarrow Cu(s) + H_2O(g) \tag{5}$$

The reaction between hydrogen and carbon monoxide is of considerable technological relevance, since controlled reaction conditions allow the production of a wide range of organic compounds, for example 6 of an equation:

$$CO(g) + 2H_2(g) \underset{CeO_3}{\overset{ZnO}{\rightarrow}} CH_3OH(g) \tag{6}$$

The dissociation of molecular hydrogen leads to the formation of atomic hydrogen (H), commonly described as nascent hydrogen in the singlet state. Due to its extremely high reactivity and strong reducing ability, atomic hydrogen readily reacts with numerous substances at relatively low temperatures (Table 2).

Table 2. Selected physical and chemical properties of hydrogen.

Element Symbol	Ar	Melting Temperature	Boiling Temperature	Electronegativity	Oxidation State
H	1.0079	−259.2 °C	252.6 °C	2.2	-I, O, I

5.2. Laboratory Preparation of Hydrogen

1. By the reaction of non-noble metals with non-oxidizing acids or, in some cases, with hydroxides. An example of this reaction is given in Equations (7) and (8).

$$Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g) \tag{7}$$

$$Zn(s) + 2NaOH(aq) + 2H_2O(l) \rightarrow Na_2[Zn(OH)_4](aq) + H_2(g) \tag{8}$$

2. Through the reaction of alkali metals and alkaline earth metals with water, for example 8 of an equation:

$$2Na(s) + 2H_2O(l) \rightarrow 2NaOH(aq) + H_2(g) \tag{9}$$

3. Through the electrolysis of water with the addition of a small amount of sulfuric acid (H_2SO_4) or sodium hydroxide (NaOH).
4. By the reaction of steam with iron. This is example 10 of an equation:

$$3Fe(s) + 4H_2O(g) \rightarrow Fe_3O_4(s) + 4H_2(g) \tag{10}$$

5.3. Industrial Production of Hydrogen

1. Thermal decomposition of methane.

$$CH_4(g) \overset{1200\ ^\circ C}{\rightarrow} C(s) + 2H_2(g) \quad (11)$$

2. Reaction of steam with red-hot coke.

$$C(s) + H_2O(g) \overset{1000\ ^\circ C}{\rightarrow} CO(g) + H_2(g) \quad (12)$$

3. By the reaction of water gas with steam in the presence of catalysts at approximately 300 °C, highly pure hydrogen is obtained, which is used, for example, in the hydrogenation of fats. The reaction can be described by Equation (13).

$$CO(g) + H_2(g) + H_2O(g) \rightarrow CO_2(g) + 2H_2(g) \quad (13)$$

4. As a by-product of the electrolysis of an aqueous sodium chloride solution during sodium hydroxide (NaOH) production [15].

6. Comparative Analysis of Methane and Hydrogen as Energy Carriers

Natural gas is widely used across numerous industrial applications and is composed primarily of methane (CH_4), a carbon-based molecule that inevitably produces carbon dioxide (CO_2) during combustion. In many of these processes, hydrogen (H_2) can serve as an effective substitute for natural gas. Owing to its exceptionally high energy density and its status as the smallest molecule in the universe, hydrogen is capable of generating elevated temperatures without producing CO_2 emissions. Nevertheless, the use of hydrogen also introduces specific safety considerations and potential risks that must be addressed. Table 3 offers a structured comparison of the fundamental chemical and physical properties of hydrogen and methane, enabling a clearer understanding of their differences as energy carriers.

Table 3. Comparison of hydrogen and methane. According to the World Guide 2025–2026 [16].

	Methane	Hydrogen	Meaning
Mass	16 u	2 u	Hydrogen is 8 times lighter.
Boiling	−162 °C	−253 °C	Hydrogen is harder to liquefy.
Density	0.668 kg/m^3	0.084 kg/m^3	Methane has approximately 8 times higher density.
Storage pressure	200–250 bar	350–700 bar	Hydrogen requires more stable tanks and higher compression.
Heating value per kilogram	50 MJ/kg	120 MJ/kg	Hydrogen contains more than twice as much energy per weight.
Heating value per cubic meter	36 MJ/m^3	11 MJ/m^3	Methane contains around three times as much energy per volume.
Explosion limit in air	5–15% vol.	4–75% vol.	Hydrogen ignites in a much wider range.
Flame	Yellow-orange, clearly visible	Bluish, nearly invisible	Hydrogen leaks are harder to detect.
Ignition energy	0.28 MJ	0.02 MJ	Hydrogen exhibits substantially higher reactivity than methane, resulting in greater technical complexity when handling and applying it in practical systems.

7. Natural Hydrogen Deposits: Origin, Characteristics, and Global Reserves

Naturally occurring hydrogen, often referred to as gold or white hydrogen, can accumulate in geological formations through several mechanisms:

- via bacterial degradation of organic material
- through water-rock interactions driven by the decay of radioactive elements in the Earth's crust
- through serpentinisation, where mantle-derived rocks react with water to produce hydrogen along with secondary minerals

At present, natural hydrogen deposits remain insufficiently characterized, and only a limited number of occurrences have been documented. In principle, such reserves could be exploited using methods similar to hydraulic fracturing; however, both the extent of these deposits and the feasibility of their extraction require further investigation. The three largest natural hydrogen deposits worldwide are presented in Table 4 and Figure 1.

Table 4. The largest known deposits in the world [17–19].

3rd Place	1st Place	2nd Place
Bulqizë, Albania	**Lorraine, France**	**Bamako, Mali**
5000 to 50,000 t of hydrogen	46 to 60 million t of hydrogen	5 million t of hydrogen
30 square m H_2 tank	discovered in early 2024	discovered by chance back in 1987
It emits approximately 11 t of hydrogen per year, while the entire mining area likely releases around 200 t of hydrogen annually.	The hydrogen concentration increases with depth: at approximately 1200 m it reaches around 20%, whereas at a depth of about 3000 m the hydrogen content approaches 90%.	Hydrogen has been continuously extracted from several boreholes for a period exceeding ten years.
Purity: 84%		Purity: 98%

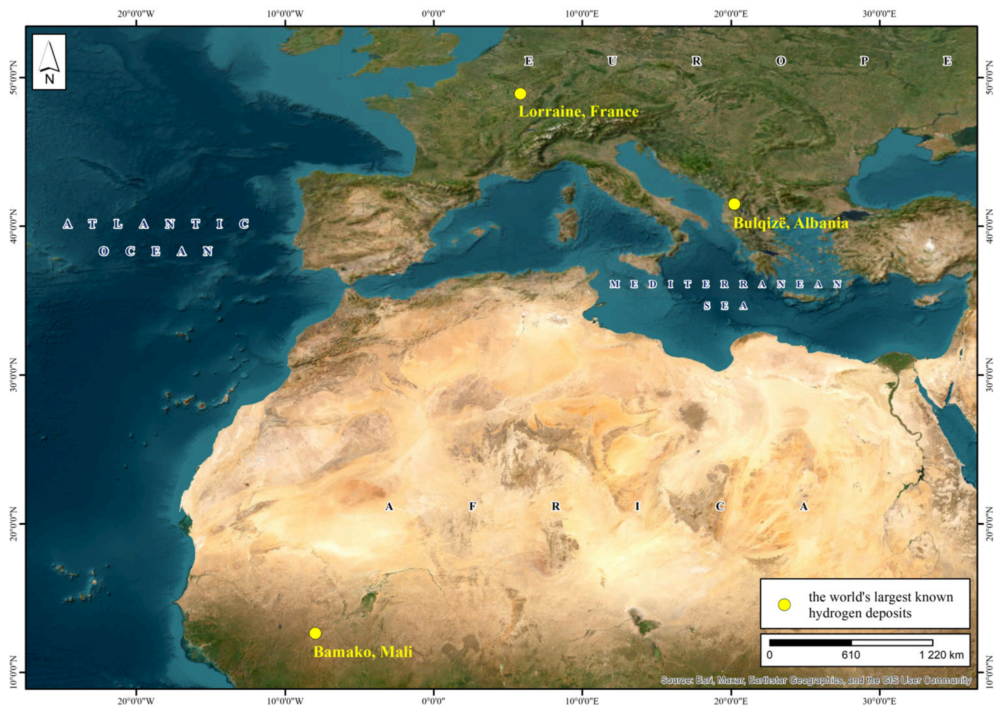

Figure 1. Map of the world's largest known hydrogen deposits.

8. Electrolyser

Electrolysers represent a fundamental technology in the transition toward a hydrogen economy supported by renewable energy sources (RES), as they enable the conversion of electrical energy into hydrogen. In conventional electrolysis systems, water molecules are decomposed into hydrogen and oxygen by applying a direct current between the cathode and anode immersed in an electrolyte. From a chemical perspective, the dissociation process occurring within the electrolyser cell can be expressed by the corresponding electrochemical reaction. The main components of an electrolytic cell include the electrodes, the electrolyte, and a separating diaphragm. The diaphragm plays a crucial role by allowing ionic transport while simultaneously preventing the mixing of the generated gases [20,21]. Figure 2 schematically representation of the electrolyser operating principle and structural configuration. An example of this reaction is given in Equation (14).

$$H_2O(l) \rightarrow H_2(g) + \frac{1}{2}O_2(g) \tag{14}$$

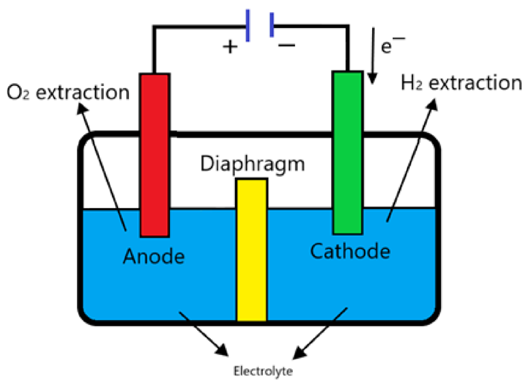

Figure 2. Schematic representation of the electrolyser operating principle and structural configuration [Source: authors' own elaboration].

8.1. Alkaline Electrolyser (AEL)

For most alkaline electrolysis applications, a 30 wt.% potassium hydroxide solution is commonly employed as the electrolyte, although sodium hydroxide and, in some cases, sodium chloride may also be utilized. The separator diaphragm can be manufactured from a range of materials, including ceramic oxides (e.g., asbestos or potassium titanate) and polymer-based materials such as polypropylene and polyphenylene sulfide. Historically, conventional AEL systems frequently incorporated asbestos diaphragms with a typical thickness of approximately 3 mm; however, due to associated health risks and operational temperature limitations (generally below 80 °C), alternative materials are increasingly being adopted [22,23]. The anode is typically fabricated from nickel-coated steel, whereas the cathode consists of steel coated with a catalytic layer, with an inter-electrode spacing of about 5 mm [24].

8.2. Proton Exchange Membrane Electrolyser (PEM)

PEM cells employ a gas-tight, cross-linked polymer membrane that is typically thinner than 0.2 mm and exhibits strongly acidic characteristics due to the presence of sulfonic acid functional groups. These groups enable efficient proton transport through the membrane via an ion-exchange mechanism. Nafion®, a well-known DuPont trademark, remains the most widely used membrane material in PEM water electrolysis systems [24]. The electrochemical reactions occurring at the anode and cathode of a PEM.

8.3. Solid Oxide Electrolyser (SOE)

Solid oxide electrolysis (SOE) technology has been developed to reduce overall energy demand and, consequently, operational costs. The electrolyte in SOE systems typically consists of yttria-stabilized zirconia (YSZ), which exploits oxygen vacancies within its mixed oxide lattice to achieve high ionic conductivity at elevated operating temperatures. The anode generally comprises a composite of YSZ and perovskite materials designed to enhance electrocatalytic performance through tailored structural and electronic properties, while the cathode is commonly formed as a nickel–YSZ cermet [24].

8.4. AEM Electrolysers

Anion exchange membrane electrolysers (AEM electrolysers) use an anion exchange membrane as the electrolyte. This membrane enables the transport of anions between the electrodes. AEM electrolysers are designed to combine the advantages of AELs and PEMs: this technology uses inexpensive catalysts and operates under slightly alkaline conditions. However, the technology is still relatively new and not yet fully developed.

Table 5 provides a comparison of individual Electrolysers.

Table 5. Comparison of individual Electrolysers. According to the World Guide 2025–2026 [16].

Type of Electrolysis	Temperature Range	Special Features
AEL	40–90 °C	Tried and tested, affordable, durable, industrial equipment.
PEM	<100 °C	High purity, expensive materials, load flexible.
AEM	<100 °C	Cost-effective, new technology, max. 1 MW output.
SOE	600–1000 °C	High temperature, still under development.

8.5. Chlor–Alkali Electrolysis

Chlor–Alkali electrolysis is an industrial process for producing chlorine. The production process also generates caustic soda and hydrogen from table salt and water. As a by-product, approximately 28 kg of high-purity hydrogen is produced per tonne of chlorine. Given current global production levels, this amounts to a considerable quantity of hydrogen. However, with the introduction of the oxygen consumption cathode (SVK), the technology is now developing in a direction where hydrogen is no longer produced as a by-product [16,25].

8.6. Advanced Hydrogen Production Technologies and Emerging Trends

In addition to the established electrolysis technologies discussed above, several advanced hydrogen production pathways are currently being intensively researched and developed. Among these, proton exchange membrane (PEM) electrolysis represents one of the most advanced and commercially deployed technologies. PEM systems are characterised by high current density, rapid dynamic response, and compatibility with fluctuating renewable energy sources. Compared to alkaline electrolysis, PEM systems enable more compact designs and higher operational flexibility; however, they rely on expensive noble metal catalysts such as platinum and iridium, which increases capital costs.

Beyond conventional electrolysis technologies, emerging hydrogen production approaches such as photocatalytic and electrocatalytic water splitting are gaining increasing research attention. Photocatalytic water splitting utilises solar radiation to directly drive the dissociation of water molecules, potentially enabling simplified system configurations with reduced external energy input. Electrocatalytic processes focus on enhancing reaction kinetics through advanced catalyst materials, thereby reducing energy consumption and improving system efficiency.

Despite their significant potential, these emerging technologies are currently at a relatively low technology readiness level (TRL) and are not yet widely implemented at industrial scale. Challenges such as low conversion efficiency, material stability, and scalability remain key barriers to their commercial deployment. Therefore, while these technologies represent important future directions in hydrogen production, the present study focuses on commercially available and practically deployable electrolysis systems suitable for academic and pilot-scale applications [26,27].

9. Fuel Cell Systems

Fuel Cell Systems Ltd. (FCSL), established in 2010, is a technology provider specializing in fuel cell and hydrogen refuelling solutions for off-grid and mobility applications. Through collaboration with SFC Energy, the company has developed a strong position in the distribution and integration of fuel cell systems. In response to the growing demand for hydrogen infrastructure, FCSL expanded its portfolio to include hydrogen refuelling technologies and on-site hydrogen production solutions based on electrolysis. The company and its technology portfolio were identified during the Hydrogen Technology Expo in Hamburg, which served as a platform for surveying current industrial solutions in hydrogen production. Owing to its integrated approach to hydrogen systems, FCSL represents a relevant industrial stakeholder for the present comparative analysis [28].

HyPro 10 Ft Electrolyser Container by Fuel Cell Systems

The HyPro Electrolyser Container developed by Fuel Cell Systems Ltd. represents a modular and scalable solution for on-site hydrogen production (Figure 3). The system is designed to support green hydrogen generation while ensuring reliable and continuous operation through its containerised architecture and built-in redundancy features. Owing to its modular configuration, the HyPro unit can be adapted to varying hydrogen demand levels and facilitates simplified maintenance procedures.

Figure 3. HyPro–hydrogen production [29].

The technology is available in both 10-foot and 20-foot container formats, enabling flexible deployment across small-scale and larger industrial applications. In particular, the HyPro 10-foot configuration is intended for installations with limited space or lower hydrogen consumption requirements. The system can also be integrated with downstream refuelling infrastructure, such as the HyQube 500 platform, providing a compact end-to-end hydrogen production and dispensing solution. These characteristics make the HyPro electrolyser a suitable candidate for comparative evaluation within laboratory and pilot-scale hydrogen deployment scenarios [29].

The HyPro 10-foot electrolyser container supplied by Fuel Cell Systems Ltd. is designed as a compact on-site hydrogen generation unit suitable for small to medium hydrogen demand scenarios. The system operates with a hydrogen production capacity of approximately 5 $Nm^3 \cdot h^{-1}$ (equivalent to about 10 $kg \cdot day^{-1}$) and delivers hydrogen at an output pressure of 35 bar with a purity of 99.999%.

The unit requires a 63 A three-phase electrical supply and consumes up to 40 $L \cdot h^{-1}$ of water, while the discharge flow may reach 36 $L \cdot h^{-1}$, depending on feedwater quality. The electrolyser is designed to operate within an ambient temperature range of 5–45 °C. The complete system is integrated into a 10-foot container (3050 × 2440 × 2590 mm) with an approximate total weight of 5000 kg, enabling modular deployment and relatively straightforward site integration.

These technical characteristics (Table 6) position the HyPro system as a suitable candidate for pilot-scale hydrogen production and comparative evaluation in research and applied hydrogen infrastructure studies [29].

Table 6. Technical specifications of the HyPro 10-foot electrolyser container [29].

Electrical Supply	Container: 200 A Three Phase
Water Inlet	Up to 160 L per h (depending on quality)
Water Quality	Standard UK tap water
Water Discharge	Up to 144 L per h
H_2 Production Rate	20 Nm^3 per h 40 kg per day
H_2 Output Pressure	35 bar
H_2 Output Purity	99.9999%
Ambient Operative Temperature Range	5–45 °C
Dimensions	20-foot Shipping Container 6310 mm × 2840 mm × 2590 mm
Weight	10,000 kg approx.

The indicative capital costs of the analysed system, based on supplier communication, are approximately £308,000 (€352,483.41) for the HyPro10 electrolyser, £264,000 (€302,128.63) for the HyQube 500 refuelling unit, and £54,000 (€61,799.04) for the 500 bar buffer storage system. These values correspond to a typical laboratory-scale hydrogen production and refuelling configuration [30].

10. Enapter

Enapter is an emerging hydrogen technology company focused on the development and commercialization of anion exchange membrane (AEM) electrolysers. The company's origins are linked to the earlier Italian company ACTA, S.p.A. established in 2004 with a focus on fuel cell and AEM electrolysis research. Following its acquisition and restructuring in 2017, Enapter accelerated the industrialization of AEM technology and expanded its global presence.

Since then, the company has demonstrated rapid technological progress, introducing successive generations of modular AEM electrolysers and scaling its production capacity. Notable milestones include the launch of the EL 4.0 next-generation AEM electrolyser in 2022 and the subsequent development of megawatt-class AEM Multicore systems and the flexible AEM Flex 120 platform in 2023. Owing to its strong focus on modular hydrogen production technologies, Enapter represents a relevant technology provider for comparative evaluation of modern electrolysis systems [31].

Enapter EL 4.1 by Enapter

The Enapter EL 4.1 electrolyser is a modular hydrogen generation unit based on anion exchange membrane (AEM) technology, primarily intended for laboratory and small-scale on-site hydrogen production (Figure 4). According to manufacturer communication, the system is capable of producing approximately 1 kg of hydrogen per 24 h, making it suitable for research environments and pilot hydrogen applications. The EL 4.1 unit is designed for flexible deployment either as a standalone module or as part of a scalable hydrogen production configuration. The electrolyser operates with an output pressure of up to 35 bar, while the achievable hydrogen purity is approximately 99.9%, which can be increased to 99.999% when an external hydrogen dryer is integrated. Owing to its modular architecture, multiple EL 4.1 units (typically up to five modules) can be combined within a single system to increase overall production capacity. The compact design, relatively low production rate, and scalability features position the EL 4.1 electrolyser as a suitable solution for laboratory research, educational purposes, and distributed hydrogen generation scenarios. These characteristics (Table 7) make the system an appropriate benchmark for comparison with larger containerised hydrogen production solutions [32,33].

Figure 4. Enapter AEM EL 4.1 electrolyser [32].

The indicative capital cost of the Enapter EL 4.1 electrolyser, based on manufacturer communication, is approximately €11,800 per unit. Unlike containerised large-scale systems, the EL 4.1 represents a modular AEM-based solution, allowing multiple units to be stacked in order to achieve the desired hydrogen production capacity. Consequently, the total investment cost depends on the required hydrogen output and the configuration of auxiliary components such as dryers, balance-of-plant systems, and storage infrastructure. This modular approach makes the EL 4.1 particularly suitable for laboratory applications, pilot projects, and scalable hydrogen research platforms [30].

Table 7. Technical specifications of the Enapter EL 4.1 electrolyser [33,34].

Electrical Supply	208–240 V (AC), 50/60 Hz, both split phase and 3-phase
Water Inlet	0.42 L per h (at 25 °C)
Water Quality	ASTM D1193-06—Standard Specification for Reagent Water Type II (deionised water) [34], and required acidity <0.1 meq/L according to ASTM D1067—Standard Test Methods for Acidity or Alkalinity of Water [35], conductivity <2 µS/cm
Water Discharge	0 L per h
H_2 Production Rate	0.5 Nm^3 per h, up to 1.08 kg per day 40 kg per day
H_2 Output Pressure	up to 35 bar (datasheet: 35 barg; also available: 8 barg version)
H_2 Output Purity	99.9% (at 35 barg; up to 99.999% with dryer—manufacturer communication)
Ambient Operative Temperature Range	5–45 °C
Dimensions	482 mm × 635 mm × 266 mm
Weight	42 kg

11. Comparative Technical and Economic Assessment of the Analysed Electrolyser Systems

Before engaging in a detailed technical discussion, it is essential to highlight the fundamental strategic differences between the two systems. The comparison focuses on two contrasting architectural philosophies: turnkey integration versus modular scalability. The HyPro system represents a complete, ready-to-use infrastructure designed for centralized output, while the Enapter EL 4.1 serves as a building block in a decentralized, stackable configuration. Understanding these starting points is crucial for evaluating their operational requirements and economic viability.

The comparative assessment presented in Table 8 provides a structured overview of the key technical and economic parameters of the analysed hydrogen production systems—the HyPro 10-foot containerised electrolyser and the Enapter EL 4.1 modular AEM unit. While both technologies enable on-site hydrogen generation, their design philosophy, production capacity, infrastructure requirements, and investment scale differ substantially.

The HyPro system represents an integrated, containerised solution designed for medium-scale hydrogen production, suitable for pilot or semi-industrial applications. In contrast, the Enapter EL 4.1 reflects a decentralised and modular approach, where multiple units can be combined to achieve the required hydrogen output. This fundamental difference in system architecture directly influences capital expenditure, operational flexibility, installation complexity, and scalability.

From a technical perspective, the systems differ significantly in hydrogen production rate, water requirements, electrical demand, and spatial footprint. Economically, the contrast between a high-capacity containerised installation and a relatively low-cost modular unit creates distinct strategic options for research institutions. Therefore, the comparison does not aim to determine technological superiority, but rather to evaluate suitability under specific deployment conditions, particularly within an academic and research-oriented environment [29,32,33,36,37].

Table 8. Comparative analysis of the HyPro 10-foot system and Enapter EL 4.1 electrolyser [29,36,37].

Parameter	HyPro 10-Foot (Fuel Cell Systems)	Enapter EL 4.1
System Type	Containerised integrated electrolyser system	Modular AEM electrolyser unit
Hydrogen Production Rate	5 Nm^3 per h 10 kg per day	0.5 Nm^3 per h 1.08 kg per day
H_2 Output Pressure	35 bar	35 bar (standard version)
H_2 Output Purity	99.999%	99.9% (up to 99.999% with dryer)
Electrical Supply	63A/200 A Three Phase	Approx. 10–12 A, 208–240 V AC
Water Requirement	Up to 40 L per h	Approx 0.42 L per h
Water Quality	Standard UK tap water	ASTM Type II deionised water, and required acidity <0.1 meq/L according to ASTM D1067, conductivity <2 µS/cm
Water Discharge	Up to 36 L per h	0 L per h
Dimensions	10-foot container 3050 × 2440 × 2590 mm	482 × 635 × 266 mm
Weight	Approx. 5000 kg	42 kg
Capital Cost (Indicative)	€352,483.41	€11,800
Scalability	System-based scaling (larger container units)	Modular stacking of multiple units
Typical Application Scale	Pilot/semi-industrial hydrogen production	Laboratory/pilot research applications

The systems were selected to represent two distinct philosophies of hydrogen infrastructure deployment suitable for academic and research environments: an integrated containerized solution for medium-scale production (HyPro 10-foot by Fuel Cell Systems Ltd.) and a decentralized modular approach (Enapter EL 4.1). These companies were identified during Hydrogen Expo Hamburg 2025 as relevant industrial actors offering solutions applicable at pilot and laboratory scales.

Comparison criteria were chosen with the needs of research institutions in mind. Priority was given to technical parameters affecting installation and operation within the constrained conditions of universities: production capacity, power and input water quality requirements, footprint, and scalability.

Data obtained from technical catalogues were validated and supplemented through direct technical consultations with exhibitors and expert representatives of the manufacturers during the Expo Hamburg 2025. This allowed for the acquisition of indicative price ranges and operational details that are not commonly available in promotional materials.

For comparison purposes, economic values (capital costs) were converted into a common currency (EUR) based on current exchange rates at the time of the study (e.g., converting British pounds for the HyPro system). In the discussion, we emphasized that a direct comparison of unit costs must be interpreted within the context of the overall system architecture—while HyPro is a "turnkey" solution (all-in-one container), Enapter represents a modular building block where the final cost depends on the number of modules and auxiliary infrastructure.

11.1. In-Depth Technical and Economic Discussion

A deeper evaluation of the analysed systems reveals that the primary distinction lies not only in production capacity but also in their overall system philosophy and deployment strategy.

11.2. Production Capacity and Operational Scale

The HyPro 10-foot system, with a production rate of approximately 5 $Nm^3{\cdot}h^{-1}$ (10 $kg{\cdot}day^{-1}$), is designed for continuous medium-scale hydrogen generation. Its output level enables refuelling applications and pilot-scale industrial integration. In contrast, the Enapter EL 4.1 produces approximately 0.5 $Nm^3{\cdot}h^{-1}$ (1.08 $kg{\cdot}day^{-1}$), positioning it primarily as a laboratory-scale or modular pilot solution.

This tenfold difference in hydrogen output significantly affects infrastructure design, storage requirements, compression needs, and overall system integration complexity. While the HyPro system is suited for applications requiring immediate higher throughput, the EL 4.1 allows gradual scaling through modular stacking.

11.3. Capital Expenditure and Investment Strategy

From an economic perspective, the capital cost gap is substantial. The HyPro electrolyser unit alone represents an investment exceeding €352,483,41, whereas a single EL 4.1 module is priced at approximately €11,800.

However, direct comparison of unit costs must be interpreted cautiously. The HyPro represents a containerised, integrated solution, whereas the EL 4.1 is a single modular building block. To achieve equivalent production capacity, multiple EL 4.1 units would need to be installed, increasing total capital expenditure but maintaining flexibility.

This difference reflects two fundamentally distinct investment philosophies:

- Centralised high-capacity deployment (HyPro)
- Decentralised modular expansion (Enapter)

11.4. Water and Infrastructure Requirements

The systems also differ considerably in water management and infrastructure demands. The HyPro system tolerates standard tap water and includes measurable water discharge, indicating integrated process handling. In contrast, the EL 4.1 requires high-purity deionised water (ASTM Type II) but does not generate liquid discharge.

While the EL 4.1 imposes stricter water quality requirements, its significantly lower water consumption (~0.42 $L{\cdot}h^{-1}$) reduces overall resource demand. For academic deployment, this difference may influence operational costs and auxiliary system requirements, such as water purification units.

11.5. Strategic Suitability for Academic Deployment

Electrical requirements further highlight the contrast in scale. The HyPro system requires a three-phase high-current supply, reflecting its higher throughput and industrial orientation. The EL 4.1 operates at comparatively low electrical input (approximately 2.4 kW), enabling easier integration into laboratory environments without extensive electrical infrastructure upgrades.

From a research and educational standpoint, modularity represents a critical advantage. The EL 4.1 enables experimentation with:

- multi-unit system behavior
- load variability
- degradation studies
- distributed hydrogen systems

The HyPro system, while technically robust, is less adaptable for experimental variability due to its integrated containerised architecture. For a faculty environment focused on research, education, and pilot experimentation, modular systems may offer higher pedagogical and experimental flexibility. Conversely, institutions aiming to demonstrate semi-industrial hydrogen mobility infrastructure may benefit from containerised integrated systems such as the HyPro.

Therefore, the selection between these technologies should not be interpreted as a matter of superiority, but rather as alignment with institutional objectives, available infrastructure, and long-term hydrogen strategy.

12. Discussion

The comparative assessment of the HyPro 10-foot containerised system and the Enapter EL 4.1 modular electrolyser highlights two fundamentally different approaches to decentralised hydrogen production. Rather than representing competing technologies in a direct performance sense, the analysed systems reflect distinct deployment philosophies aligned with different operational scales and strategic objectives.

The HyPro system exemplifies a centralised, integrated configuration aimed at medium-scale hydrogen production and potential mobility infrastructure deployment. Its higher production capacity, three-phase electrical requirements, and containerised architecture indicate suitability for pilot industrial environments or institutional demonstration projects. In contrast, the Enapter EL 4.1 embodies a modular and distributed generation concept, where scalability is achieved through unit stacking rather than through single high-capacity installations. This reflects broader technological trends toward flexible, decentralised hydrogen systems, particularly in research and innovation environments.

From an economic standpoint, the significant difference in capital expenditure must be interpreted in relation to production capacity and system integration. While the nominal cost of a single EL 4.1 unit is substantially lower, achieving production levels comparable to the HyPro system would require multiple modules, increasing total investment. However, the modular approach reduces initial financial barriers and enables phased expansion, which may be advantageous for academic institutions operating under budget constraints.

Operational considerations further differentiate the systems. The HyPro system tolerates standard tap water and integrates discharge management, potentially simplifying auxiliary infrastructure. Conversely, the EL 4.1 requires high-purity deionised water, introducing additional requirements for water treatment systems. Nevertheless, its considerably lower water consumption and reduced electrical demand may decrease long-term operational burden in laboratory environments.

It is also important to acknowledge the limitations of this study. The analysis is based primarily on manufacturer-provided technical datasheets and direct supplier communication. No experimental validation, efficiency benchmarking under dynamic load, degradation assessment, or lifecycle cost analysis was conducted. Therefore, the presented comparison reflects design specifications rather than measured field performance. Future research should incorporate empirical testing, long-term durability studies, and comprehensive techno-economic modelling to provide a more robust evaluation framework.

Overall, the findings suggest that system selection should be driven by institutional objectives rather than by isolated technical parameters. For faculties focused on experimental research, teaching flexibility, and modular system investigation, compact AEM-based units may offer greater adaptability. Conversely, institutions aiming to demonstrate semi-industrial hydrogen infrastructure or refuelling capability may benefit from containerised integrated systems.

13. Conclusions

This study presented a comparative technical and economic assessment of two distinct hydrogen production systems: the HyPro 10-foot containerised electrolyser and the Enapter EL 4.1 modular AEM unit. The analysis demonstrated that, although both technologies enable on-site hydrogen generation, they represent fundamentally different deployment strategies in terms of production capacity, system architecture, infrastructure requirements, and capital investment.

The HyPro system is positioned as a medium-scale, integrated solution suitable for pilot and semi-industrial hydrogen applications, particularly where higher throughput and refuelling capability are required. In contrast, the Enapter EL 4.1 offers a modular and scalable approach that aligns well with laboratory research, educational environments, and phased infrastructure development. The findings indicate that system selection should not be based solely on nominal production performance or capital cost, but rather on alignment with institutional objectives, available infrastructure, and long-term hydrogen strategy. Modular systems may provide enhanced experimental flexibility and lower initial financial barriers, while containerised systems may better support demonstration-scale or mobility-oriented projects.

However, it is important to frame this study as a preliminary comparative screening rather than a definitive techno-economic assessment. Since the systems evaluated—specifically the 2025 iterations—are in early deployment or pilot stages, the analysis relied primarily on manufacturer-provided technical specifications and data gathered during expert consultations at the Hydrogen Expo Hamburg 2025. Consequently, certain limitations must be acknowledged: verified long-term operational data (OPEX), real-world efficiency under varying environmental conditions, and detailed lifecycle cost analyses (LCCA) were not available at the time of writing. Furthermore, the economic considerations focused on initial capital expenditure (CAPEX) without providing a full levelized cost of hydrogen (LCOH).

Despite these limitations, this work establishes a structured comparative framework that serves as a technical baseline for academic and research institutions considering hydrogen infrastructure. Future research should focus on longitudinal empirical monitoring of these systems once they are fully integrated into research facilities. This will allow for more robust benchmarking of specific energy consumption, degradation analysis, maintenance costs, and cost-per-kilogram hydrogen modelling under real operational conditions. Additionally, subsequent studies could expand the scope to include a wider range of hydrogen storage and distribution technologies to provide a more holistic view of the hydrogen value chain for academic institutions. Overall, this preliminary assessment contributes to informed decision-making in the early-stage deployment of hydrogen technologies within academic and pilot-scale environments.

From a broader strategic perspective, the deployment of hydrogen technologies is closely aligned with European Union policies aimed at sustainable resource management, energy security, and decarbonisation. In this context, hydrogen represents an important link between energy systems and raw material strategies, supporting the transition toward a more resilient and sustainable European energy framework [36–39].

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