

## Article

# Preliminary Assessment of a Hydrogen Farm Including Health and Safety and Capacity Needs

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**Abstract:** The safety engineering design of hydrogen systems and infrastructure, worker education and training, regulatory compliance, and engagement with other stakeholders are significant to the viability and public acceptance of hydrogen farms. The only way to ensure these are accomplished is for the field of hydrogen safety engineering (HSE) to grow and mature. HSE is described as the application of engineering and scientific principles to protect the environment, property, and human life from the harmful effects of hydrogen-related mishaps and accidents. This paper describes a whole hydrogen farm that produces hydrogen from seawater by alkaline and proton exchange membrane electrolyzers, then details how the hydrogen gas will be used: some will be stored for use in a combined-cycle gas turbine, some will be transferred to a liquefaction plant, and the rest will be exported. Moreover, this paper describes the design framework and overview for ensuring hydrogen safety through these processes (production, transport, storage, and utilisation), which include legal requirements for hydrogen safety, safety management systems, and equipment for hydrogen safety. Hydrogen farms are large-scale facilities used to create, store, and distribute hydrogen, which is usually produced by electrolysis using renewable energy sources like wind or solar power. Since hydrogen is a vital energy carrier for industries, transportation, and power generation, these farms are crucial in assisting the global shift to clean energy. A versatile fuel with zero emissions at the point of use, hydrogen is essential for reaching climate objectives and decarbonising industries that are difficult to electrify. Safety is essential in hydrogen farms because hydrogen is extremely flammable, odourless, invisible, and also has a small molecular size, meaning it is prone to leaks, which, if not handled appropriately, might cause fires or explosions. To ensure the safe and dependable functioning of hydrogen production and storage systems, stringent safety procedures are required to safeguard employees, infrastructure, and the surrounding environment from any mishaps.

**Keywords:** hydrogen farm; alkaline electrolyser; proton exchange membrane electrolyser; hydrogen safety; combined-cycle gas turbine; safety distance



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## 1. Introduction

All current analyses of the future of global energy assume that a wide energy mix is increasingly necessary to meet the growth in demand, including renewable or sustainable energy sources [1]. However, it has been the development of concrete environmental issues, which are probably more obvious than ever, that has been one of the most important proponents for the development of renewable energy. One of these leading issues is the release and build-up of carbon dioxide (CO<sub>2</sub>) and other climate-changing chemicals in the atmosphere. Currently, these emissions are significantly above pre-industrial levels and are considered to be causing the now-famous greenhouse effect, which causes increases in global (average) temperature. This increase will continue unless carbon emissions are drastically reduced.

An appealing alternative fuel is hydrogen. Contrary to coal, gas, or oil, the main source of energy is not hydrogen itself. Instead, it plays a more similar role to that of

employing secondary “energy carriers” such as electricity, which must first be generated by transferring latent energy from one source to another for later consumption. Various sources of hydrogen can be used, both renewable (geothermal, biomass, solar, wind, and wave) and non-renewable (coal, natural gas, and nuclear) resources. Hydrogen can be used and kept as a fuel. When using hydrogen fuel-based systems for transportation and distributed heating and power generation, the only by-product at the output of fuel cells, internal combustion engines, or turbines at the point of use is water. Hydrogen’s potential to replace fossil fuels means one of the world’s greatest environmental issues could be solved by rectifying transportation sector problems [2]. Vehicle exhaust emissions are one of the most significant sources of air pollution today, particularly in cities, and also greatly increase global carbon dioxide emissions.

Due to both the transition of existing energy systems to low-carbon-based systems and our ongoing need for energy, renewable energy sources have gained increased attention in recent years. Hydrogen can be a crucial energy carrier for the future in this gradual but ongoing energy transition because it not only links with current natural gas-based production systems and growing electricity-based supply sources across various industries, but it also enables long-distance carbon-free energy transport. Over the coming ten years, the developing hydrogen economy is expected to contribute to the global energy system, driven by the energy transition.

The main obstacle to the expansion of the H<sub>2</sub> market is scaling up the current H<sub>2</sub> supply chain technologies (which are required to lower the price of H<sub>2</sub> and open up new markets).

A hydrogen farm is a facility that uses renewable energy sources, such as solar or wind, to produce hydrogen on a massive scale. The electrolysis process is a chemical phenomenon that employs an electric current to induce a non-spontaneous chemical reaction. The process of water electrolysis entails the dissociation of water molecules (H<sub>2</sub>O) into hydrogen (H<sub>2</sub>) and oxygen (O<sub>2</sub>) gases. This procedure transpires within an electrolytic cell wherein water is subjected to an electric current, often facilitated by a catalyst. These farms are essential for supplying clean, renewable hydrogen to a range of sectors, such as industry, power generation, and transportation, which lowers their carbon emissions and aids in the shift to a more sustainable energy system.

Numerous studies and endeavours have been undertaken to mitigate carbon emissions within industrial sectors through the application of hydrogen. Certain investigations have employed non-carbon chemical substances, notably hydrogen, as a viable solution for carbon reduction in industrial processes, whereas a significant body of literature exists regarding the specialised generation of hydrogen within hybrid renewable energy systems.

Colangelo et al. [3] undertook a feasibility assessment concerning hydrogen generation through the utilisation of renewable energy resources (RERs), with a particular emphasis on wind and solar energy sources, with the latter predominantly involving photovoltaic technology. The evaluation conducted was predicated upon climatic data about the Province of Brindisi, located in Apulia, Italy. A comprehensive analysis of the various categories of electrolyzers was executed, ultimately culminating in the selection of the most suitable option for the specified case study.

Hosseini et al. [4] investigated an innovative grid-integrated wind electrolyser–reformer system across four distinct industrial urban centres in Iran, each characterised by varying climatic conditions, to fulfil the electricity and hydrogen requirements. In this context, the arrangement of the wind farm comprises twenty wind turbines, each possessing a generation capacity of 850 kW. The findings indicated that the wind farm produces an electrical output ranging from approximately 17.8 to 36.4 GWh annually.

Raweasat and Pilidis [5] investigated strategies for the decarbonisation of Libya, concentrating on the utilisation of wind-generated renewable electricity, hydrogen production, and combined-cycle gas turbine technology. They assessed various scenarios of energy self-sufficiency and the exportation of hydrogen, underscoring the substantial land and financial investments necessary for the transition away from fossil fuel dependency.

Rehman et al. [6] examined a comprehensive numerical modelling endeavour aimed at evaluating the viability of hydrogen production derived from onshore wind energy farms for an arid coastal community situated to the south of the Aqaba Gulf in Saudi Arabia. This analytical framework integrated mathematical formulas to calculate wind power output, the sizing of electrolyser plants, and the generation of hydrogen in response to variable wind speed conditions. The findings indicated that the most efficient onshore wind hydrogen system (OWHS) comprises 26 wind turbine units (each rated at 6.15 MW), an alkaline electrolyser facility with an operational capacity of 120 MW, and a collective arrangement of hydrogen storage tanks with a cumulative capacity of 300 tons.

Dute et al. [7] examined a substantial offshore wind farm and investigated the necessity for hydrogen storage at both the onshore and offshore segments of an extensive transportation pipeline that links the wind farm to the mainland. The findings indicated that while the pipeline equipped with line pack storage was crucial for managing daily fluctuations, it did not provide adequate storage capacity to accommodate seasonal variations. Moreover, the findings revealed that with a pipeline of appropriate dimensions, supplemental storage was required exclusively on one side of the pipeline, thereby potentially minimizing the requisite investments. The results further demonstrated that the regulatory framework governing the allocation of wind-generated electricity to the grid versus the conversion into hydrogen substantially impacts the seasonal storage requirements.

Raweasat and Pilidis [8] introduced a decarbonisation framework tailored for Libya, employing submersible helium closed-cycle gas turbines while conducting an analysis of electricity consumption and hydrogen utilisation. Their study delineated the considerable investment requirements for achieving self-sufficiency (27 GW) and facilitating hydrogen export (129 GW) as part of the transition to a sustainable green economy.

Javanshir et al. [9] assessed the economic feasibility and ideal operational methodologies for the incorporation of wind-powered green hydrogen production systems. This analysis scrutinised multiple wind energy farms located in western Finland, assessing their performance against electricity market conditions spanning from 2019 to 2022, with projections extending to the year 2030. Their findings suggested that the amalgamation of hydrogen production with wind energy installations yields superior economic advantages compared to isolated wind energy initiatives.

Li et al. [10] studied these investigations to enhance the economic viability of a hydrogen energy system. Nevertheless, the case analyses frequently presupposed that the efficiency of an electrolyser remained invariant when integrated with sporadic renewable energy sources.

Kojima et al. [11] examined the attributes of variable power and its generation, in addition to the prevailing conditions and challenges associated with the operational parameters, water electrolyser architecture, system specifications, and stack and catalyst longevity, as well as degradation mechanisms, in the context of the direct utilisation of variable power sources. Furthermore, they delineated an accelerated degradation testing protocol aimed at facilitating equitable comparisons of catalyst performance and promoting the dissemination of effective design strategies. Ultimately, they addressed prospective obstacles and offered recommendations for enhancing water electrolyser components and systems that are amenable to practical implementation, positing that a significant advancement could be attainable in the pursuit of a sustainable hydrogen-centric society.

All these studies are related to our research in several aspects such as the reduction of carbon emissions within energy supply systems, particularly in energy-intensive sectors such as power generation facilities, aiming to diminish reliance on fossil fuel resources, alleviate detrimental environmental repercussions, and encourage the investigation of alternative energy sources.

The utilisation of hydrogen generated from low-carbon sources constitutes a promising approach for the abatement of carbon emissions in energy systems, thereby mitigating adverse climate effects through the reduction in greenhouse gas emissions and functioning as a versatile energy carrier.

Additionally, the generation of hydrogen on a large scale from sustainable foundations can help to address the escalating demand for hydrogen in diverse regions. It is noteworthy that hydrogen exists in various forms, which are categorised according to the origins of their production. Hydrogen obtained from renewable sources, devoid of hydrocarbons or supplementary heat during the production process, via a non-fossil-fuel-based method, such as water electrolysis, is referred to as “green hydrogen”, which is distinguished by its exceedingly low CO<sub>2</sub> emissions, utilizing various energy sources including solar and wind power.

So, based on the above, this study examines potential designs for hydrogen farms in Libya, examining electrolyzers for hydrogen production, hydrogen storage, plant layout, and the associated health and safety requirements that will be needed. In the context of a country like Libya, which relies entirely on oil across all energy sectors, this study contributes to reducing dependence on oil, thereby lowering greenhouse gas emissions and supporting global decarbonisation efforts.

## 2. Methodology

The methodology of this thesis is intended to describe one hydrogen supply chain, beginning with the electrolysis of seawater and ending with the processing of the electrolyser outputs, storage of the hydrogen as gas or, alternatively, liquid following liquefaction, then transport to the power plant and use within the gas turbine for peak power generation.

Subsequently, a process was developed that would enable us to evaluate and quantify the impact of health and safety constraints on the economic profitability of the overall investment.

The methodology to establish a design for a hydrogen farm started with a review of hydrogen production methods, as shown in Figure 1, then the determination of electrolyser type, as two technologies are used to produce hydrogen from seawater: an alkaline water electrolyser and a proton exchange membrane electrolyser. The power requirement and number of electrolyzers that are required in these farms were determined.

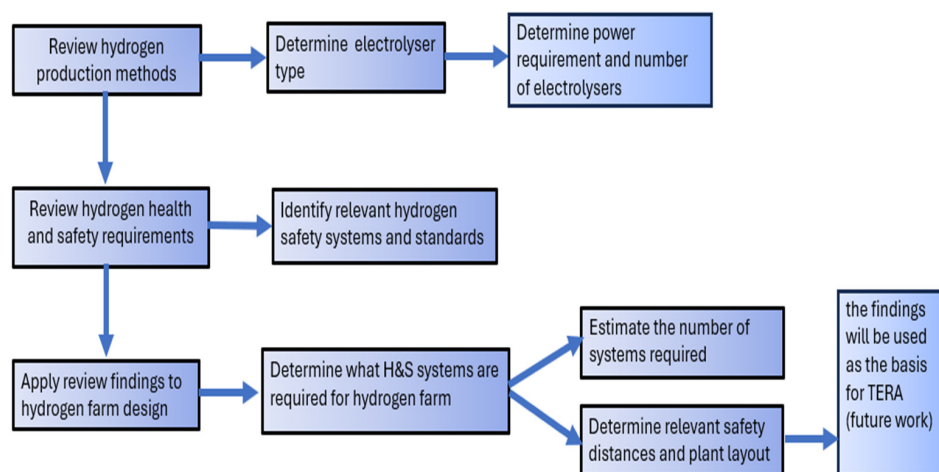


**Figure 1.** Methodology approach.

Then, the hydrogen health and safety requirements were reviewed to identify relevant hydrogen safety systems and standards.

After that, the review findings were applied to the hydrogen farm design to determine what health and safety systems were required for hydrogen farms and estimate the number of systems required.

Finally, the relevant safety distances that should be applied and the plant layout were determined.

These findings will be used as the basis for a techno-economic environmental risk analysis (TERA) in our future work.

### 3. Hydrogen Production

This all-encompassing strategy seems constrained, though, and hydrogen will likely play more focused roles in a decarbonised society in addition to a wide range of alternative energy storage technologies. The idea of a hydrogen economy has been around since the oil crisis of the 1970s, and recent developments such as hydrogen refuelling stations in Europe and the US and a power-to-gas energy storage facility in Germany demonstrate the first steps in that direction [12]. The possibility of using hydrogen as a single substance to offer electrical storage, transportation fuel, and heating makes the idea of hydrogen being utilised as a universal energy vector appealing [13]. The state of development of hydrogen production technologies, the required feedstock and resources (natural gas, oil, coal, biomass, and water), and the associated GHG emissions vary. The colour terms “grey”, “blue”, “turquoise”, and “green” are frequently used to describe conventional, low-CO<sub>2</sub>, CO<sub>2</sub>-free, and carbon-free production routes.

Industrial-scale processes will be required in a prospective hydrogen economy to meet the high demand for hydrogen while reducing the environmental impact of hydrogen production in a reasonable time frame.

### 4. Hydrogen Production Methods

Hydrogen is the most abundant element in nature; it is present in enormous amounts, although it cannot be found as a “pure” element. Its manufacturing or extraction methods consume a tremendous amount of energy [14]. According to [15,16], about half of all hydrogen produced is utilised to make ammonia, with the remaining hydrogen being used to make methanol (approximately 8%), and the petroleum sector accounts for around 37%. Water, biomass, and fossil fuels are the three different sources from which hydrogen can be produced. According to [17], the steam-reforming method is used to produce about 90% of the hydrogen that is produced from fossil fuels. Even though the possibility of electrolytically splitting water has been recognised for centuries, hydrogen produced in this way now accounts for only 4% of the hydrogen produced worldwide due to more practical processes like steam reformation of fossil fuels being applied. Natural gas accounts for 48% of the remaining hydrogen, oil accounts for 30%, and coal accounts for 18% [18].

So, in this study, hydrogen will be produced by electrolyzers from seawater, and those electrolyzers will operate using electricity generated from solar plants; moreover, the hydrogen produced will be compressed to be stored and transferred by pipeline to a combined-cycle gas turbine, liquefaction plant, and other exports, as shown in Figure 2.

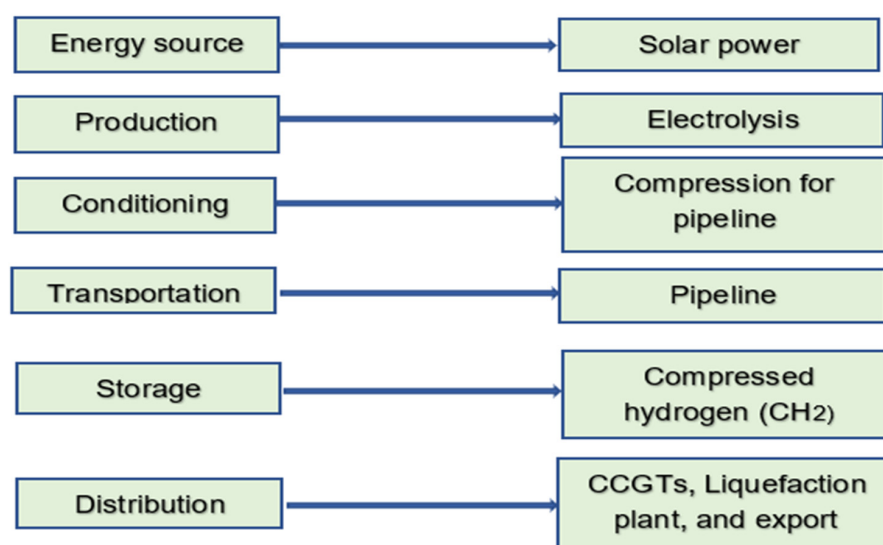


Figure 2. Hydrogen supply chain.

## 5. Hydrogen Production from Water

Over the past 200 years, advances in water electrolysis technology have been made following the discovery of the phenomenon of the electrolytic splitting of water into hydrogen and oxygen, leading to the creation of contemporary electrolyzers.

Today, electrolysis has emerged as the primary technique for producing hydrogen (H<sub>2</sub>) with exceptional performance, making it the most crucial method for various power applications. Additionally, hydrogen has gained recognition as a promising fuel for a sustainable energy supply. The electrolysis process can leverage renewable energy sources like wind and solar thermal energy to generate hydrogen. The growing demand for hydrogen in both transportation and stationary applications is closely linked to the escalating demand for energy in general. Unfortunately, conventional energy sources, such as coal, gas, and liquefied petroleum, are depleting rapidly due to the increasing global energy demand. To address this issue, renewable energy sources can serve as a supplementary energy supply. As a result, hydrogen production through electrolysis has become one of the most valuable technologies in the world for renewable energy generation [19].

Alkalis, acids, and solid oxides are the three main technologies used in the electrolytic splitting of water. Aqueous alkaline electrolytes are used in alkaline electrolysis, an acidic solid polymer electrolyte is used in proton exchange membrane (PEM) electrolysis, and high temperatures and a ceramic electrolyte are used in solid oxide electrolysis [20].

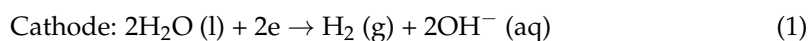
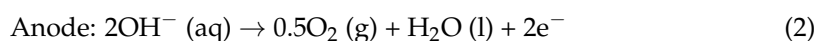
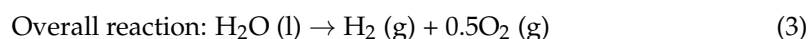
### 5.1. Alkaline Electrolyser

One of the most important technologies for producing hydrogen at scale using renewable energy is alkaline water electrolysis.

#### 5.1.1. Alkaline Water Electrolysis (AWE)

Commercial alkaline electrolyzers have been in use since the early 1900s. Norsk Hydro Electrolysers, a Norwegian business, constructed the first significant industrial system in 1927, using generated hydrogen as a feedstock for the synthesis of ammonia [20]. Early alkaline systems were designed with the goal of creating strong, dependable systems that required little upkeep and had lifetimes of more than 10 years, according to numerous reports. To keep operational costs low, the early systems were introduced in areas with nearby, inexpensive electricity sources (mostly hydroelectric facilities).

Using electric energy, alkaline water electrolysis separates water into the gases hydrogen and oxygen. Equations (1)–(3) show the chemical processes. Water molecules are converted to hydrogen and negatively charged hydroxide ions at the cathode by electrons. Hydroxide ions are converted at the anode into oxygen and water while releasing electrons. Overall, a water molecule reacts at a ratio of 2:1 with hydrogen and oxygen [21].



#### 5.1.2. Alkaline System

Aqueous alkaline solutions, for example, solutions containing about 25 to 30 weight per cent KOH or NaOH, are used as the electrolyte in an alkaline electrolyser (AE). Two electrodes and a diaphragm, a microporous separator, are further elements of AEs. In AEs, electrodes are often made of nickel-based materials.

Commonly used cathode materials include nickel with a catalytic coating, whereas anode materials include nickel or copper metals coated with metal oxides (such as manganese, tungsten, or ruthenium oxide). Low-carbon stainless-steel mesh is frequently employed as the cathode in AEs. Water is introduced into a cell's cathode side, where the potential

difference between the electrodes causes it to break down into hydrogen and hydroxyl (OH) ions. The OH ion then travels to the anode via the electrolytic material and diaphragm and is transformed into oxygen (O<sub>2</sub>) gas. Using a gas–liquid separation unit, the created hydrogen is separated outside of the electrolyser. The AE can operate between 60 and 80 °C. Based on the LHV of hydrogen, an AE's typical current density is between 0.2 and 0.4 A/cm<sup>2</sup>, and its typical efficiency is between 63 and 71% [22].

Pumping the electrolyte through the electrolysis stack creates the product gases. While gas covering the electrode surface can reduce the required cell voltage, it also increases operating expenses, so natural convection can be a cost-effective alternative. Additionally, to keep the electrolyte within an ideal temperature range, most alkaline water electrolyser systems include a temperature control system.

### 5.1.3. AWE Stack

This electrolyser stack has a higher hydrogen output (4460 Nm<sup>3</sup>/h) and single-stack power (19.6 MW) than those offered by stacks already on the market thanks to its operation at a high current density of 1.3 A cm<sup>−2</sup>.

Despite having more cells, it is a little shorter because the cells are not as thick, as shown in Figure 3. The zero-gap cell design, which is made possible by nickel mattresses that gently press the electrode meshes against the diaphragm, is the most significant internal feature.

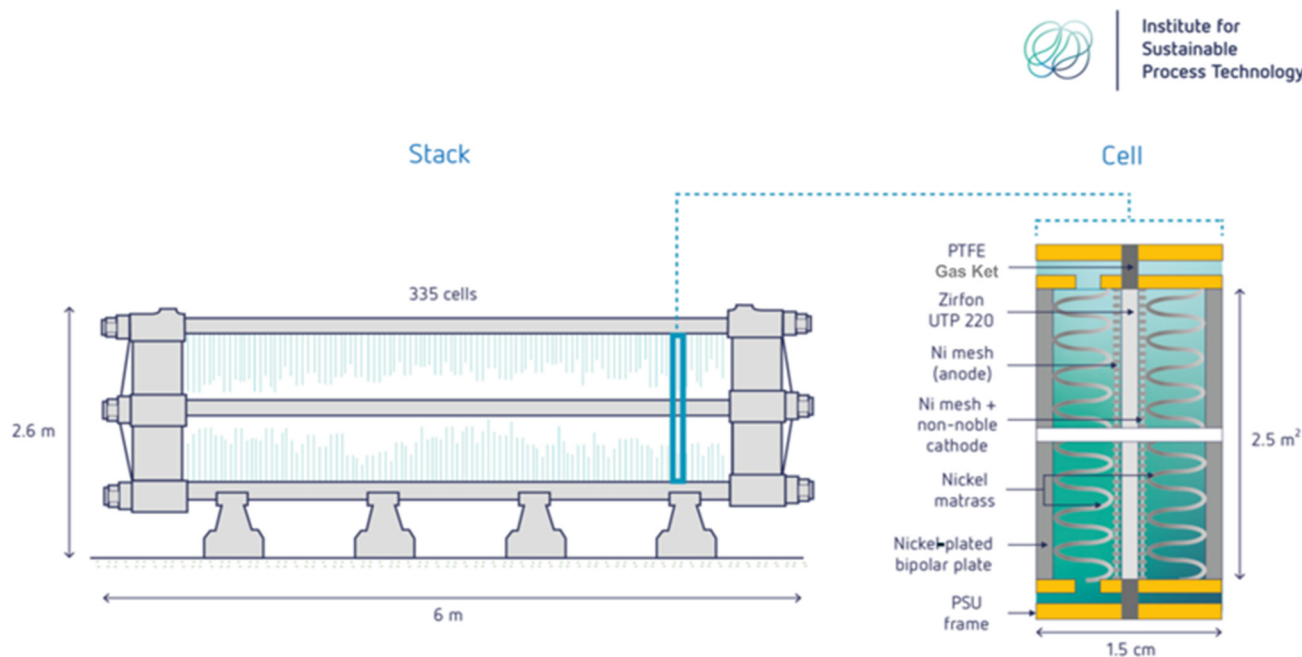


**Figure 3.** Schematic of the advanced AWE stack. This work is licensed under the Creative Commons Attribution—No Derivatives License (CC BY-ND 4.0).

The zero-gap arrangement, in conjunction with the use of a narrow diaphragm, and the temperature of 100 °C allow for efficient operation (1.8 V) at the current density of 1.3 A cm<sup>−2</sup>. As a result, the nominal stack power is increased to 19.6 MW, and the hydrogen production rate is increased to 4460 Nm<sup>3</sup>/h, which is substantially more than is feasible with the electrolyzers that are currently on the market.

To balance the benefits of atmospheric and pressured electrolysis, the pressure is set at 5 Bara. Compared to atmospheric electrolysis, this pressure provides the benefit of a lower gas hold-up, enabling thinner cells and faster ramp rates. The lower pressure level results in less gas crossing compared to electrolysis at high pressures, which is usually carried out at 15 to 30 bar. As a result, it is possible to employ a narrow diaphragm and lower the

electrolyser's minimum load. The Table 1 lists the primary operational circumstances and performance characteristics [23].

**Table 1.** The advanced AWE stack's operational conditions and performance.

| Operating Temperature                                        | 100 °C                               |
|--------------------------------------------------------------|--------------------------------------|
| Operating pressure                                           | 5 Bara                               |
| Nominal current density                                      | 1.3 A cm <sup>2</sup>                |
| Cell potential @ nominal load (at the start)                 | 1.8 V                                |
| Nominal stack power                                          | 19.6 MW                              |
| Current efficiency                                           | 98%                                  |
| Nominal stack hydrogen output                                | 4460 Nm <sup>3</sup> h <sup>-1</sup> |
| Minimal load                                                 | 15%                                  |
| H <sub>2</sub> in O <sub>2</sub> (nominal load/minimum load) | 0.3/1.6%                             |
| Degradation rate                                             | 1% per year                          |

Figure 4 depicts a 1 GW alkaline electrolyser composed of 60 modules, each with a capacity of 17.6 MW, resulting in a total of 1056 MW ( $60 \times 17.6$  MW). The setup includes rectifiers, switchgear, a STOCOM, and additional facilities such as a maintenance room, workshop, office, control room, and safety office. This single electrolyser serves as a prototype that will be scaled up to form a complete hydrogen farm.

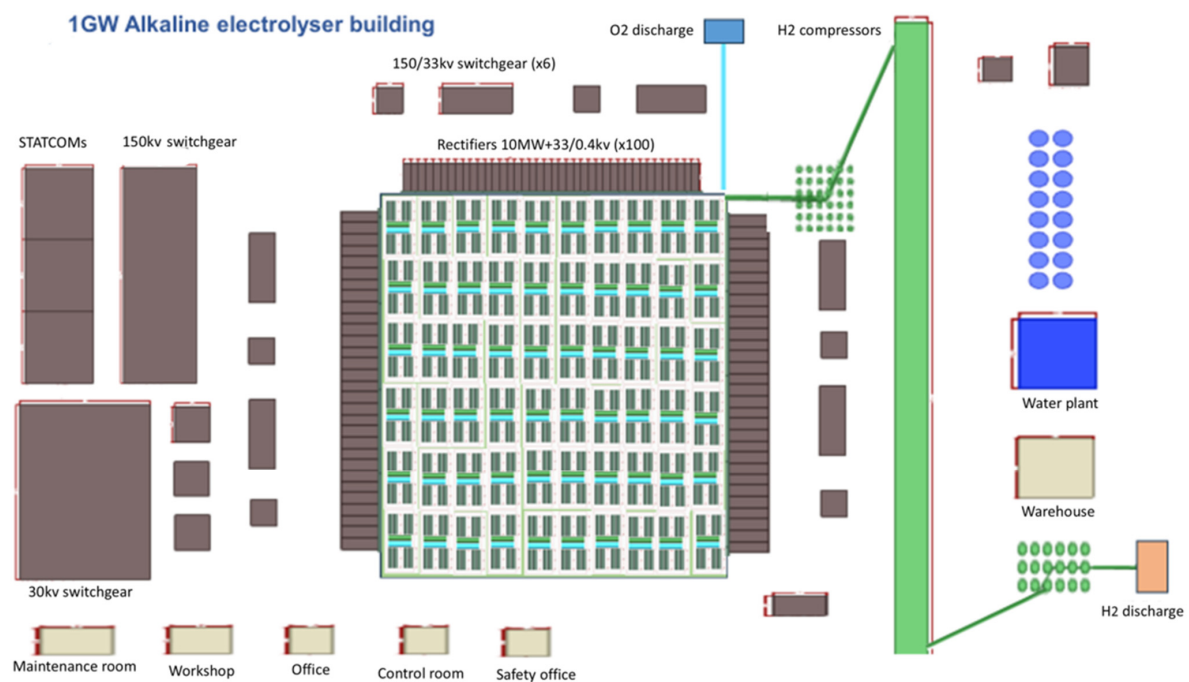


**Figure 4.** Alkaline electrolyser.

In addition, compressors are used to raise the hydrogen pressure to grid pressure, deoxidisers are used to eliminate oxygen traces, and drying equipment is used to eliminate water traces from the gas.

A study conducted in 2020 by the Institute for Sustainable Process Technology in the Netherlands has been taken as a guide for designing the 1 GW alkaline electrolyser building layout in this study.

## 5.2. Proton Exchange Membrane (PEM) Water Electrolysis

A solid sulfonated polystyrene membrane is used as the electrolyte in PEM electrolysis; it has been around for more than 60 years and was invented by General Electric.

Polymer electrolyte membrane electrolysis is another term for this method. The proton exchange membrane serves as both an electrolyte and a gas separator. Deionised water is the only substance put into the cell during electrolysis; no other electrolytic additives are used. PEM electrolysis has many benefits, including a wide operating temperature range (20–80 °C), high current density, improved energy efficiency, low gas permeability, and ease of handling and maintenance. However, because precious metals like Pt, Ir, and Ru are commonly used as electrocatalysts in PEM electrolysis, this process requires a higher initial investment than alkaline electrolysis. Researchers have worked hard in this area to lower the price and increase the inherent activity of PEM electrocatalysts [24].

#### 5.2.1. PEM System

Pt black, iridium, ruthenium, and rhodium are generally used as electrode catalysts in proton exchange membrane electrolyzers (PEMEs), and a polymer electrolyte membrane (e.g., Nafion<sup>®</sup>, Fumapem<sup>®</sup> (Institute for Sustainable Process Technology in Switzerland), etc.) separates the electrodes. When water is put into a PEME, it splits into protons (H<sup>+</sup>) and oxygen (O<sub>2</sub>) on the anode side. Through the polymer membrane, the protons are directed to the cathode, where they interact with electrons to produce hydrogen gas. Due to PEMEs' low ionic resistances, high current densities of 0.6 e 2 A/cm<sup>2</sup> can be attained while still retaining 56–60% efficiency levels. The disadvantages of PEME technologies include issues with corrosion of the materials due to the acidic nature of the solution, expensive noble metal catalysts (such as Pt, Ru, Rh, etc.), and relatively reduced efficiency. Efforts are being made to increase PEMEs' effectiveness in the upcoming years [22].

#### 5.2.2. PEM Stack

The current technology readiness level (TRL) of the stack ranges from 3 to 7. This advancement in development paves the way for future stack designs that significantly better the performance of existing stacks. These improved designs achieve a current density of 3.5 A cm<sup>−2</sup> while maintaining a stack efficiency of approximately 80%.

A lower cell potential at a high current density will be achieved with the use of fewer rare materials because of the development of improved functional materials and cell designs, which are projected. The goal of advanced electrode designs will also be to maximise catalyst use while minimizing transport losses in the electrodes and catalytic layers. The use of expensive materials will be minimised by using readily available materials for the coating of bipolar plates and electrodes.

By increasing the cell area and the number of cells in a stack, significant cost savings can also be obtained. But as the cell size and stack height grow, it is increasingly important that the flows and compression pressures are identical. The dimensions listed in Table 2 are thought to be a reasonable approximation for stacks that will be put into operation in the upcoming years based on calculations of flow velocities, heat distribution, and stack weight. Figure 5 depicts the stack configuration that was utilised to compute costs and performance.

**Table 2.** The advanced PEM stack's operational conditions and performance.

| Operating Temperature Nominal Load             | 70 °C                                |
|------------------------------------------------|--------------------------------------|
| Minimum load                                   | 10%                                  |
| Operating pressure (cathode)                   | 30 Bara                              |
| Operating pressure (anode)                     | 4 Bara                               |
| Nominal current density                        | 3.5 A cm <sup>−2</sup>               |
| Cell potential and nominal load (at the start) | 1.83 V                               |
| Number of cells                                | 310                                  |
| Effective cell area                            | 0.50 m <sup>2</sup>                  |
| Total cell area                                | 0.84 m <sup>2</sup>                  |
| Nominal stack power                            | 10 MW                                |
| Nominal stack hydrogen output                  | 2250 Nm <sup>3</sup> h <sup>−1</sup> |

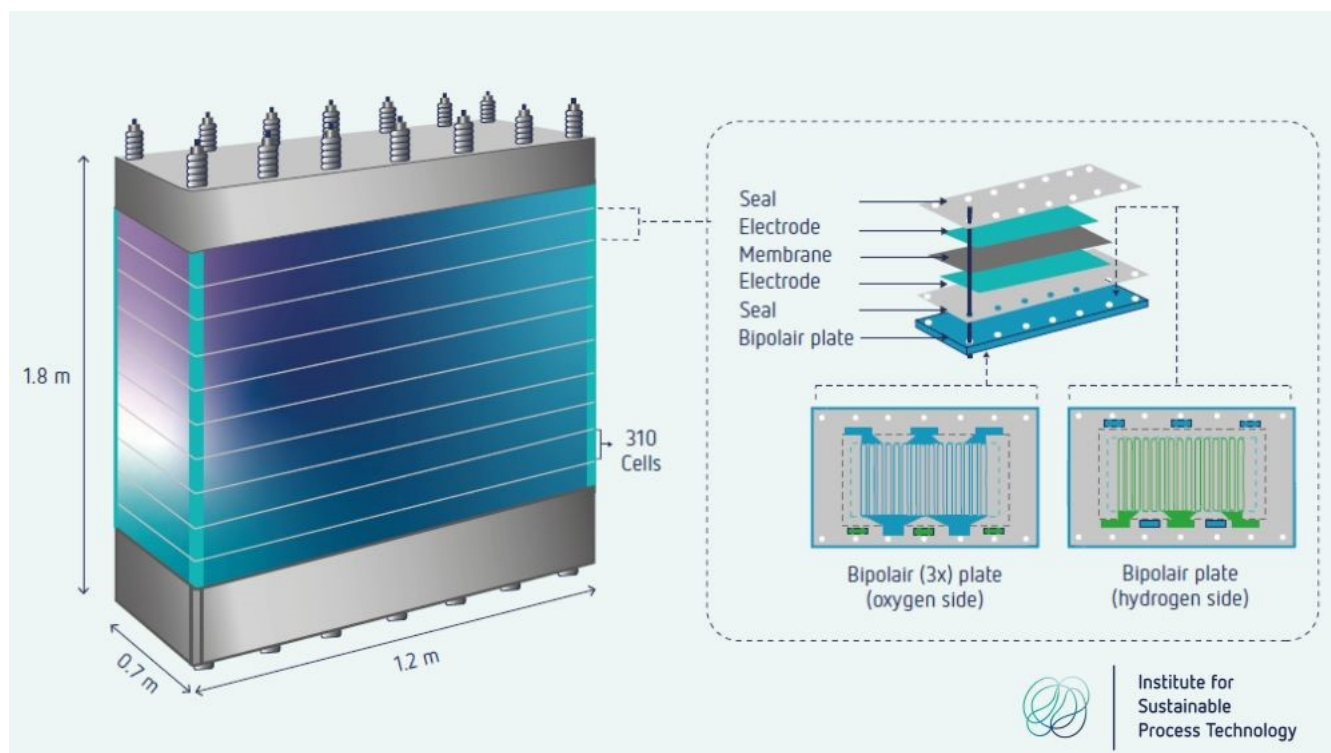


**Figure 5.** Schematic of the advanced PEM stack. This work is licensed under the Creative Commons Attribution—No Derivatives License (CC BY-ND 4.0).

This stack has a 10 MW capacity and produces hydrogen at a rate of  $2250 \text{ Nm}^3/\text{h}$ , which is substantially more than is currently attainable with PEM electrolyzers. Each cell has an active area of  $0.5 \text{ m}^2$ . Table 2 lists the primary operational factors and performance characteristics.

Figure 6 depicts a 1 GW proton exchange membrane electrolyser composed of 25 modules, each with a capacity of 40 MW, resulting in a total of 1000 MW ( $25 \times 40 \text{ MW}$ ). The setup includes rectifiers, switchgear, a STOCOM, and additional facilities such as a maintenance room, workshop, office, control room, and safety office. This single electrolyser serves as a prototype that will be scaled up to form a complete hydrogen farm.

In addition, compressors are used to raise the hydrogen pressure to grid pressure, deoxidisers are used to eliminate oxygen traces, and drying equipment is used to eliminate water traces from the gas.

A study conducted in 2020 by the Institute for Sustainable Process Technology in the Netherlands has been taken as a guide for designing the 1 GW PEM electrolyser building layout in this study.

### 5.3. Solid Oxide Electrolyte Electrolysis (SOE)

Yttria-stabilised zirconia (YSZ), nickel-containing YSZ, and metal-doped lanthanum metal oxides are utilised as the electrolyte, anode, and cathode, respectively, in solid oxide electrolysis cells (SOECs). Hydrogen is left at the cathode side as oxygen ions ( $\text{O}_2$ ) which pass through the solid electrolyte in this instance.

The activation energy necessary to split water is a combination of electrical and thermal energy; thus, SOECs operate at high temperatures ( $650\text{--}1000^\circ\text{C}$ ). The efficiency of SOECs is temperature-dependent; it is observed that at higher temperatures, the anode and cathode overpotentials fall, and as a result, the efficiency of the electrolyser rises. For instance, when the operating temperature of SOECs was raised from  $375$  to  $1050^\circ\text{C}$ , the overall electrical energy need decreased by about 35%. When only electrical input is taken into account, SOEC efficiency is exceptionally high (74 to 81%) [25]. The efficiencies, however,

are dramatically reduced when the heat input is taken into account. The solid electrolyte in SOEC is not corrosive, and there are no problems with flow distribution. The disadvantages of SOEC technology, however, include the necessity for a heat source, pricey materials, and expensive fabrication techniques. Even though SOECs are thought to be the most effective, they are still in the development stage [22].

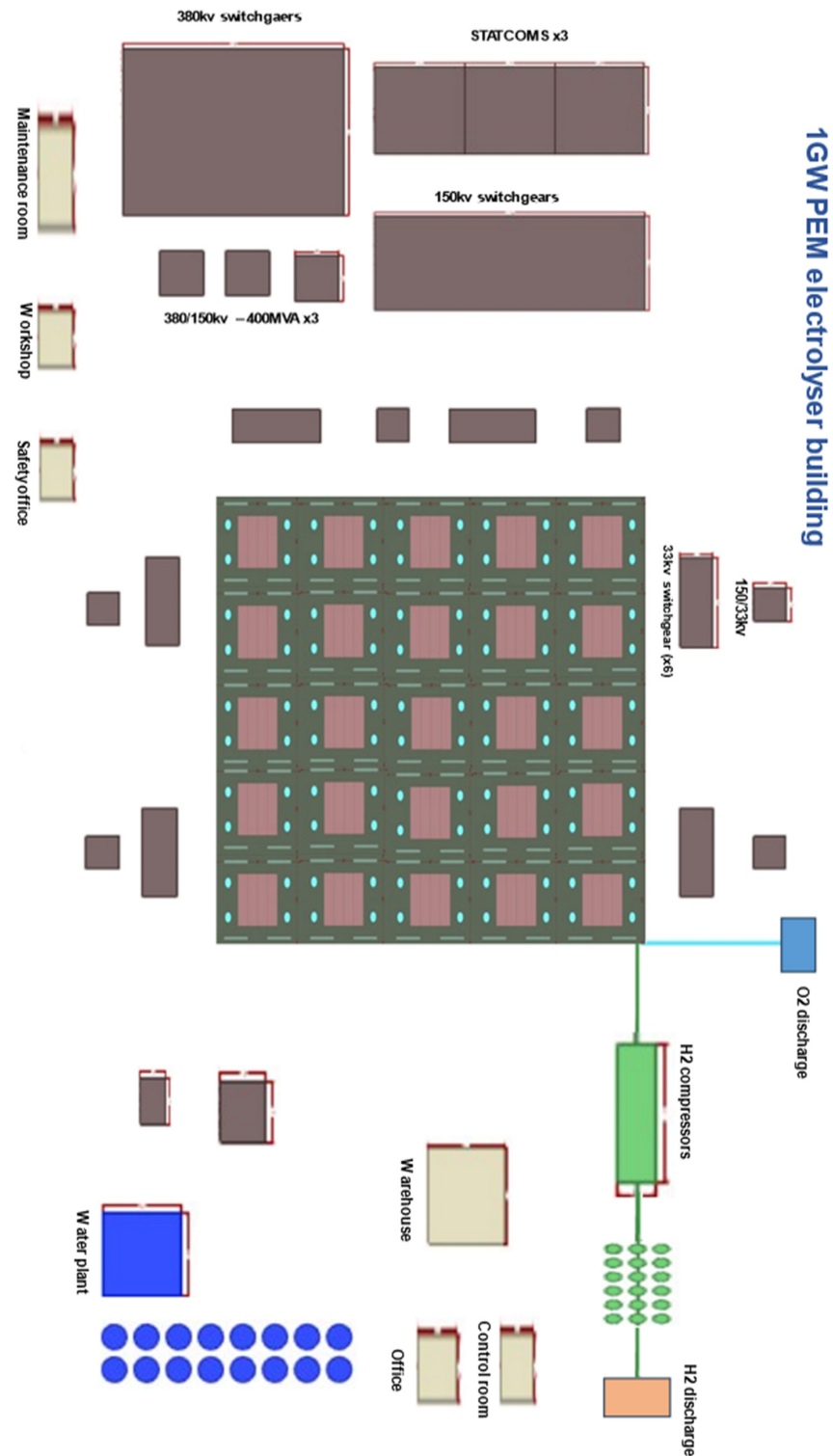


**Figure 6.** Proton exchange membrane electrolyser.

## 6. A View of the System

On the assumption that seawater will be utilised for electrolysis, it is advantageous to choose a site for the hydrogen grid that is close to the coast. To reduce hydrogen transmission inland, electrolyzers,  $H_2$ CCGTs, and storage farms will be situated close to the coast.

Based on the research conducted in [26], the required electrolyser capacity is 199 GW. The necessary amount of hydrogen storage is determined by the maximum value, or 26,000 tonnes, that was generated over the summer. Firstly, seawater was desalinated then electrolysed. Given the dearth (or unequal geographic distribution) of fresh water, the production of hydrogen from seawater is needed.

In this scenario, solar energy will be used to generate the electricity, and a 207 GW grid capacity will be required during the summer when demand is at its maximum for the year. The solar farm chosen in this study is located in Libya on the 25th parallel and has a total area of 4900 km<sup>2</sup>. It is divided into three farms with a total area of 1633 km<sup>2</sup>. The southern portion of the nation is where the solar farms are geographically located to put them closer to the equator, which will provide better illumination and enable more efficient usage of the solar farms' generated electricity. The number of  $H_2$ CCGTs needed is set by the greatest demand, which, in the winter, was 54 units.

So, from this point, the hydrogen grid will be divided into three locations, which are in Tripoli, Sirte, and Benghazi.

## 7. Electrical Layout

In this part, the electrical layout will be discussed for the 1 GW electrolyser, then we will account for the electrical equipment based on the number of electrolyzers required, as follows:

1. Switchgear (with a 380 kV voltage), with two feeders coming in for 380 kV lines and feeders leaving for transformers within the building, is needed.
2. To optimise CAPEX, the transformers are positioned in front of or close to the 380 kV switchgear and are used to lower the voltage to 150 kV (400MVA).
3. It is necessary to also have 150 kV switchgear, which are fed by the transformers mentioned above. Preferably, the switchgear will be positioned close to the transformers to minimise the length of cable routing.
4. For voltage stability, static synchronous compensators (STATCOMs) are also added.
5. The 150 kV switchgear's outgoing feeders at 150 kV are fed into six 150/33/33 kV transformers (180/90/90MVA). To minimise cable routing, these transformers are situated close to the electrolyser building's margins.
6. At the margins of the electrolyser building, 33 kV/400 V transformers receive power from 33 kV switchgears that receive the incoming feed.
7. It is possible to position the 33 kV/400 transformer and 10 MW diode rectifier near the electrolyzers because they are both enclosed in a container [27].

## 8. Hydrogen Farm

Hydrogen farms will be implemented in Libya close to the sea where the hydrogen will be produced from the seawater using two methods: alkaline electrolyzers and proton exchange membrane electrolyzers. These farms will be in three locations in Tripoli, Sirte, and Benghazi. The geographic locations of the hydrogen farms are on the Mediterranean coast of Libya, as shown on the map below in Figure 7, and account for an important fraction of the demand.

Furthermore, the airports in Tripoli and Benghazi are the biggest in the nation and will be the primary locations for the use of liquid hydrogen. These hydrogen farms would include electrolyzers (alkaline and PEM), a desalination plant, hydrogen combined-cycle gas turbines ( $H_2$ CCGTs), storage facilities, and, where appropriate, a liquefaction plant.



**Figure 7.** Map of Libya, courtesy of Encyclopædia Britannica (Edinburgh, Scotland), Inc., copyright 2002; used with permission.

In [26], the national requirements for greening oil-exporting countries were outlined. Libyan hydrogen, solar, and gas turbines were taken as a case study, and they used winter demand because this is representative of the highest demand in the year. Two scenarios were examined. The first of these was winter self-sufficiency, for which a 199 GW electrolyser was required, and the second was oil export replacement, for which a 519 GW electrolyser was required, as shown in Table 3.

**Table 3.** The two scenarios divided into three different locations (199 is the number of electrolyser GW needed for a self-sufficiency scenario and 519 is the number of electrolyser GW needed for oil export replacement).

| Scenario               | Electrolyser GW | Tripoli |       | Sirte  |       | Benghazi |       |
|------------------------|-----------------|---------|-------|--------|-------|----------|-------|
| Self-sufficiency       | 199 GW          | 60 GW   | 20 GW | 79 GW  | 25 GW | 60 GW    | 20 GW |
|                        |                 |         | 20 GW |        | 25 GW |          | 20 GW |
|                        |                 |         | 20 GW |        | 29 GW |          | 20 GW |
| Oil export replacement | 519 GW          | 170 GW  | 60 GW | 179 GW | 60 GW | 170 GW   | 60 GW |
|                        |                 |         | 60 GW |        | 60 GW |          | 60 GW |
|                        |                 |         | 50 GW |        | 59 GW |          | 50 GW |

These requirements were then distributed across three locations, with each location divided into three hydrogen farms, as shown in Table 3. For instance, the self-sufficiency assessment in Tripoli involved examining a GW of 60, which was divided into three farms for easier management.

As has been mentioned above, the hydrogen farm comprises  $H_2$ CCGs, the numbers of which have been identified: 54  $H_2$ CCGs in the case of 600 MW and 36  $H_2$ CCGs in the case of 900 MW. These have also been divided into locations, as Table 4 shows.

**Table 4.** The two scenarios for different CCGT sizes.

| Scenario        | The Engine | Tripoli Farm | Sirte Farm | Benghazi Farm |
|-----------------|------------|--------------|------------|---------------|
| First scenario  | 600 MW     | 18 CCGTs     | 18 CCGTs   | 18 CCGTs      |
| Second scenario | 900 MW     | 12 CCGTs     | 12 CCGTs   | 12 CCGTs      |

### 9. A View of the Whole Hydrogen Farm

In each location, both types of electrolyzers, alkaline and proton exchange membrane, will be combined. First of all, the hydrogen farm was scaled up from a 1 GW electrolyser to a 20 GW alkaline electrolyser, which comprises 20 single 1 GW electrolyzers (Figure 8). The layout was based on a 1 GW alkaline electrolyser that was designed based on the Institute for Sustainable Process Technology's study, and each electrolyser was connected with switchgear, rectifiers, and STATCOMs to convert alternating current into direct current. Also, safety distances were applied to the hydrogen farm (see Section 5).

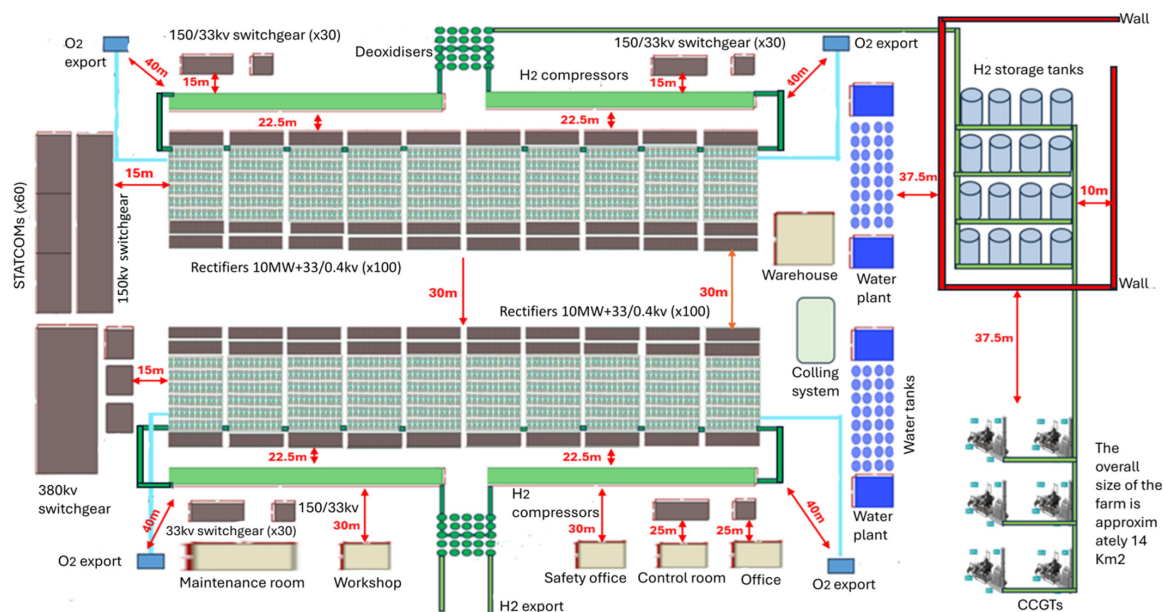


**Figure 8.** The 20 GW alkaline hydrogen farm.

Furthermore, the farm includes compressors that are used to raise the hydrogen pressure to grid pressure; deoxidisers that are used to eliminate oxygen traces; and drying equipment that is used to eliminate water traces from the gas. A water plant, hydrogen storage tanks, and hydrogen combined-cycle gas turbines are used to generate electricity from the stored hydrogen.

In addition, the design of a proton exchange membrane farm has been outlined, as shown in Figure 9, which was scaled up based on the 1 GW PEM electrolyser shown in Figure 6 to contain 20 GW, and for every single electrolyser, equipment such as switchgear, rectifiers, and STATCOMs, in addition to hydrogen safety distances, were applied on the farm.

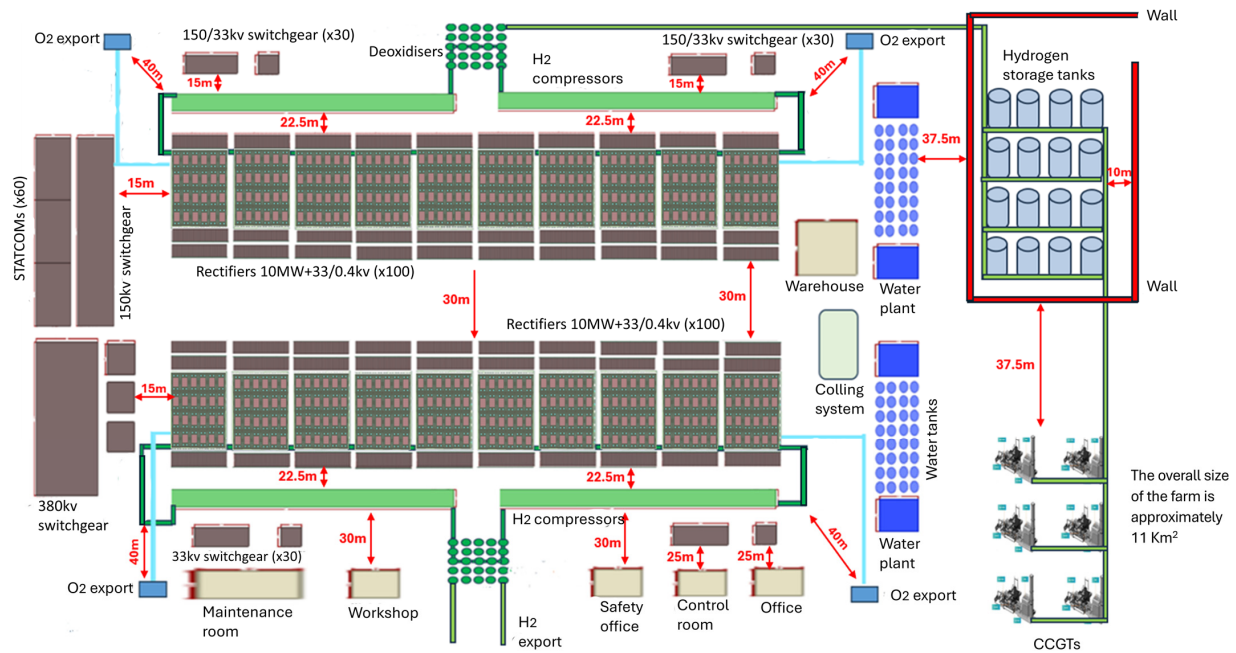


Figure 9. The 20 GW PEM hydrogen farm.

Moreover, the hydrogen farm layout also includes compressors used to raise the hydrogen pressure to grid pressure; deoxidisers used to eliminate oxygen traces; and drying equipment used to eliminate water traces from the gas, hydrogen storage tanks, water plants, and hydrogen combined-cycle gas turbines.

Based on these data for this farm, the amount of hydrogen that will be produced is 1800 Ktonne for the 20 GW electrolyser.

## 10. The Total Amount of Hydrogen

The amount of hydrogen presented in Table 5 was considered for two scenarios: in Tripoli and Benghazi, the self-sufficiency scenario produced 5400 Ktonne in both locations, while in Sirte, it produced 7110 Ktonne.

Table 5. The amounts of hydrogen produced in the two scenarios and three different locations.

| Scenario               | Electrolyser GW | Tripoli | H <sub>2</sub> Production Ktonne | Sirte  | H <sub>2</sub> Production Ktonne | Benghazi | H <sub>2</sub> Production | Total H <sub>2</sub> Production Ktonne |
|------------------------|-----------------|---------|----------------------------------|--------|----------------------------------|----------|---------------------------|----------------------------------------|
| Self-sufficiency       | 199 GW          | 60 GW   | 5400                             | 79 GW  | 7110                             | 60 GW    | 5400 GW                   | 17,910                                 |
| Oil export replacement | 519 GW          | 170 GW  | 15,300                           | 179 GW | 16110                            | 170 GW   | 15,300 GW                 | 46,710                                 |

On the other hand, the Tripoli and Benghazi oil export replacement scenario produced 15,300 Ktonne in both locations, while the Sirte oil export scenario produced 16,110 Ktonne.

The amount of hydrogen in both scenarios in Sirte is more than in the other locations because it is located in the middle of the coast of Libya; thus, it helps to export and feed the south of Libya, so the number of electrolysers was increased in this location.

Hydrogen storage tanks with a capacity between 10,000 and 50,000 L are frequently used to store 1000 to 5000 kg of hydrogen at high pressures, usually 350 to 700 bar. This mass-to-volume ratio is consistent with the density of gaseous hydrogen at these pressures [28].

So, on this farm, large hydrogen storage tanks should be used to store compressed hydrogen gas with a capacity of 1000 to 5000 kg of hydrogen and a volume between 10,000 and 50,000 litres (10 and 50 cubic meters) per tank. These types of tanks are commonly found

on hydrogen farms, as these larger tanks are ideal for meeting higher storage requirements, enabling efficient buffering to handle production fluctuations.

The maximum hydrogen mass flow rate depends on variables including flow velocity, hydrogen density at operating pressures, and pipeline diameter; it can be produced and transferred via pipelines in a hydrogen farm. For effective gas transportation, pipes carrying compressed hydrogen usually have pressures between 30 and 100 bar and velocities between 10 and 20 m/s [28].

So, on this hydrogen farm, the pipeline diameter will be 18 inches, and in general conditions, such as a density of approximately  $4 \text{ kg/m}^3$  and pressure at 50 bar, this will give a range for the maximum hydrogen mass flow rate of approximately 6 to 13 kg/s for an 18-inch pipeline, though this range may vary based on pipeline design and operational constraints. This applies for both types of electrolyzers (alkaline and PEM).

It can be noted that the alkaline electrolyser building is larger than that of the PEM electrolyser because the AWE electrolyser stack is a large 20 MW stack with 335 cells. It operates at a high current density of  $1.3 \text{ A cm}^{-2}$  and uses non-noble electrodes, at a temperature of  $100^\circ\text{C}$ , while the PEM electrolyser stack is a 10 MW stack with 310 cells. It has a current density of  $3.5 \text{ A cm}^{-2}$  and uses improved membrane and electrode materials and low-iridium anodes.

## 11. Hydrogen Health and Safety

Hydrogen is considered hazardous due to several unique properties that increase its risk of causing fires and explosions compared to other fuels (Table 6). Firstly, hydrogen has a wide flammability range (4–75% in air) and a very low ignition energy, which means it can easily ignite and sustain combustion over a wide range of concentrations [29]. Additionally, its flame is nearly invisible, making it difficult to detect a fire [30].

Hydrogen also presents a high risk of explosion. It has a high deflagration index and can create significant overpressure during explosions, increasing the severity of potential explosions compared to other fuels like gasoline or natural gas. Its rapid diffusion rate and low energy requirements for ignition further contribute to this hazard [31].

**Table 6.** Hydrogen leak hazard summary.

| Hazard Type  | Description                                                                                                                        | Potential Impact                                                                                             |
|--------------|------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|
| Explosion    | Hydrogen can form explosive mixtures with air, and the lower explosive limit (LEL) is very low [32].                               | Severe damage to infrastructure, potential loss of life, and widespread disruption.                          |
| Fire         | Hydrogen is highly flammable and can ignite even in very low concentrations and with minimal ignition energy [33].                 | Fires can spread rapidly and be difficult to detect initially, posing a high risk to personnel and property. |
| Asphyxiation | Hydrogen can displace oxygen in confined spaces, leading to oxygen-deficient environments and causing asphyxiation [34].           | Risk to human health in confined environments such as industrial settings, submarines, and spacecraft.       |
| Detonation   | In certain conditions, hydrogen can cause detonation, which is a more violent form of explosion with a supersonic shock wave [35]. | Catastrophic damage with much more severe impact compared to typical explosions.                             |

As such, hydrogen farms need integrated safety systems because of hydrogen's properties. These safety systems should meet legal requirements for maintaining hydrogen safety, incorporate safety management procedures to prevent and mitigate events connected to these processes, and include hydrogen safety equipment to ensure the safe handling of hydrogen.

### 11.1. Legal Requirements for Hydrogen Safety

Table 7 contains general rules for maintaining safety at hydrogen storage and transfer sites. Such a facility should have enough lighting, lightning protection, alarm systems, and gas detection and sampling equipment, and include more comprehensive safety regulations about safety policy, safety in the building and test chambers used for hydrogen service, and security in the operation, maintenance, and disposal of the hydrogen facility.

**Table 7.** Legal requirements for hydrogen safety.

|                                                       |                                                                                                                                                                                      |
|-------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Electrical Considerations                             | Use intrinsically safe electrical equipment to prevent fires and make sure all electrical systems adhere to applicable standards (such as IEC 60079 for explosive atmospheres) [36]. |
| Bonding and Grounding                                 | Use appropriate bonding and grounding techniques to stop the accumulation and release of static electricity [37].                                                                    |
| Hydrogen Transmission Lines                           | Adhere to norms like ASME B31.12 for hydrogen piping and use materials resistant to hydrogen embrittlement [38].                                                                     |
| Removing Ignition Sources                             | Where appropriate, use explosion-proof equipment and remove or regulate potential ignition sources close to hydrogen storage and usage areas [39].                                   |
| Flames, Hot Items, and Flame Arrestors                | Integrate flame arrestors into pipe systems to stop the spread of flames and keep hot surfaces away from areas that are high in hydrogen [40].                                       |
| Building Design and Construction                      | Use non-combustible materials and design structures to minimise hydrogen accumulation. Design buildings to permit the safe venting of hydrogen in the event of leakage [41].         |
| Hanging Control Placards and Signs in Exclusion Zones | Ensure that areas used for processing and storing hydrogen are properly marked with signage and that safety sign regulations like ISO 3864 and OSHA are followed [42].               |

### 11.2. Safety Management Systems

A crucial engineering instrument for industrial applications is a management system that is appropriate for the specific risks under consideration, encompassing process safety, occupational safety, health, environmental concerns, and asset integrity. These safety management systems are universally acknowledged and accepted as optimal approaches for risk management.

The safe operation, handling, and use of hydrogen and related systems necessitate comprehensive safety management, which is why the hydrogen industry needs to apply a safety management system approach. Safety management systems work best when they are specifically designed to address the risks and hazards that are of concern [43].

To prevent process-related events and injuries (such as fires and explosions), process safety management focuses on identifying, comprehending, and controlling process dangers by considering the processes listed in Table 8.

**Table 8.** Safety management systems.

|                                              |                                                                                                                                                                                              |
|----------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Accountability                               | Encourage a strong safety culture and risk awareness throughout all organisational levels. Leadership should demonstrate a commitment to this effort [44].                                   |
| Process Knowledge and Documentation          | Keep current process documentation, such as operating manuals and safety data sheets (SDSs), and conduct frequent audits and reviews of process knowledge [45].                              |
| Capital Project Review and Design Procedures | Make sure designs adhere to applicable codes and best practices, and incorporate safety evaluations into all stages of project design and execution [46].                                    |
| Process Risk Management                      | Put in place a framework for risk management that identifies hazards and periodically reviews and updates risk assessments [47].                                                             |
| Management of Change                         | Create a thorough management of change (MoC) protocol to oversee modifications to staff, equipment, or processes. Make sure that every change is examined for any safety ramifications [48]. |
| Process and Equipment Integrity              | Use non-destructive testing (NDT) techniques to identify any problems, and perform routine equipment maintenance and inspections to guarantee integrity [49].                                |
| Human Factors                                | Create procedures and systems that take into consideration the limitations and capacities of people, encourage ergonomic designs, and reduce the likelihood of human mistakes [50].          |
| Training and Performance                     | Provide all staff members with thorough training programmes, and hold frequent drills and performance reviews [51].                                                                          |
| Incident Investigation                       | Create a system for the in-depth examination of events and near-misses; then, put the corrective measures into practice and communicate the lessons discovered [52].                         |

### 11.3. Equipment for Hydrogen Safety

Because hydrogen is flammable and potentially explosive, handling it demands close attention to safety. To ensure the safe handling, storage, and transportation of hydrogen, a variety of safety tools and procedures are used. Some essential safety equipment and practices are detailed in Table 9.

**Table 9.** Equipment for hydrogen safety.

|   |                                                  |
|---|--------------------------------------------------|
| 1 | Gas Leak Detectors and Sensors                   |
| 2 | Hydrogen Ventilation Systems                     |
| 3 | Emergency Shutdown Systems                       |
| 4 | Gas Detection System Control Panels              |
| 5 | Pressure-Relief Valves (PRVs)                    |
| 6 | Flame Detectors                                  |
| 7 | Fire Suppression Systems                         |
| 8 | Hydrogen Storage Safety Valves and Rupture Discs |
| 9 | Alarm and Warning Systems                        |

### 11.4. Safety Distances

A safety distance in a hydrogen farm is the minimum separation distance needed between various parts of the facilities for producing, storing, and distributing hydrogen to minimise the harmful effects of potential hydrogen hazards. Storage tanks, pipelines, personnel areas, equipment, and hydrogen generators are some of these components. Given how highly flammable and reactive hydrogen is, keeping this distance is intended to reduce the possibility of fires, explosions, or other mishaps [53].

An adequate safety distance is very important to reduce the risk of fire and explosion. When combined with air, hydrogen, which is highly flammable, can ignite or explode. When hydrogen storage locations are kept at a safe distance from other equipment (such as electrical components or heat sources), the possibility of an unintentional ignition that could result in devastating fires or explosions is decreased [54].

Safety distances also ensure that any hydrogen gas leaks have enough space to safely dissipate into the atmosphere because hydrogen is lighter than air and disperses quickly. This keeps gas mixtures that could explode in small spaces from forming, and also safeguards people and equipment. The safety distance acts as a buffer zone to shield personnel and vital equipment from the direct effects of any potential accidents in the case of a leak or system failure.

These delineate the essential minimum safe distances for various components associated with hydrogen. In the case of compressed hydrogen storage, the requisite distance spans from 15 to 30 m, whereas for liquid hydrogen storage, it is prescribed to be between 30 and 50 m. Hydrogen compressors necessitate a clearance of 5 to 10 m, and hydrogen piping mandates a separation of 3 to 5 m. Ultimately, edifices and public spaces ought to be situated at a distance of 15 to 25 m from these hydrogen systems [55].

The requisite safety distances for the storage of hydrogen are contingent upon both the storage capacity and the prevailing pressure conditions. In scenarios involving storage capacities of up to 50 kg at pressures reaching 350 bar, the stipulated minimum distances are 1.5 m from buildings, 3 m from property lines, and 7.5 m from areas accessible to the public. In cases where the storage capacity ranges from 51 to 300 kg, the requisite distances are increased to 3 m, 7.5 m, and 15 m, respectively. For storage capacities between 301 and 1000 kg, the mandated minimum distances are 7.5 m from buildings, 15 m from property lines, and 22.5 m from public areas. Finally, for capacities ranging from 1001 to 5000 kg, the required distances are 15 m, 22.5 m, and 30 m, accordingly [56].

The minimum safe distances established for hydrogen compression systems are contingent upon their operational capacity. For small-scale compressors (up to 300 kg/day), the requisite distances are 7.5 m from edifices, 15 m from property boundaries, and 22.5 m from communal spaces. Medium-scale compressors (ranging from 300 to 1000 kg/day) necessitate a distance of 15 m from buildings, 22.5 m from property demarcations, and 30 m from public zones. Large-scale compressors (exceeding 1000 kg/day) mandate a separation of 22.5 m from structures, 30 m from property lines, and 37.5 m from areas accessible to the public [57].

Applying safety distances to hydrogen systems requires the following actions to be performed:

1. List the elements of a hydrogen farm and any possible risks they pose.
  - Alkaline Electrolyser: Creates oxygen and hydrogen, which could perhaps cause an explosion or fire.
  - Desalination Plant: Mostly a low-risk water-processing facility, but because it is close to hydrogen systems, this may affect its general safety.
  - H<sub>2</sub>CCGTs: These fuel-using devices run the risk of exploding, catching fire, and experiencing mechanical failure.
  - Storage Facilities: Because hydrogen has a large volume when under pressure, storing it poses serious dangers.

2. Establish safety distances between every element:

Alkaline Electrolyser: The hub for productive hydrogen generation.

Hydrogen Storage Site: Depending on the amount and pressure of the hydrogen, it should be placed 50 metres or more away from the electrolyser, according to Aziz [55].

H<sub>2</sub>CCGTs: Positioned to provide a safe operating distance (e.g., 100 metres from storage) between the electrolyser and storage site.

Desalination Plant: Situated at a safe distance (30 m, for example, from the electrolyser) from hydrogen systems.

However, there are important elements that impact safety distances:

Hydrogen Storage Capacity and Pressure: Greater separation distances are necessary for higher volumes and pressures.

Type of Equipment and Level of Hazard: Diverse equipment presents varying degrees of risk.

Example Layout Plan:

Below is an illustrative example layout plan incorporating the safety distances, as shown in Figures 8 and 9:

Electrolyser: Maintained at a central place, 22.5 m from compressors and more than 37.5 m from hydrogen storage site.

Hydrogen Storage Sites: Gaseous storage is 30 m from public places, 15 m from building openings, and 22.5 m from the property line.

Compressors for Hydrogen: Kept 22.5 m away from other parts.

H<sub>2</sub>CCGTs: Kept 30 m away from the electrolyser and compressors, and 37.5 m from the hydrogen storage site.

Desalination Plant: Kept 15 m away from systems that use hydrogen.

#### 11.5. Application of Health and Safety on Hydrogen Farms

Developing a thorough plan for the implementation of health and safety precautions on a hydrogen farm, particularly one with a group of proton exchange membrane (PEM) electrolyzers and alkaline electrolyzers, entails taking care of many important issues. The amount of hydrogen that a 1 GW electrolyser would likely produce is 90 ktonne of hydrogen per year. This is based on 1 GW power input, so this farm containing a 20 GW electrolyser would produce 1800 ktonne. Moreover, storage systems typically operate at pressures from 350 to 700 bar, and hydrogen might be compressed to around 100 bar for pipeline transport. An extensive summary of the equipment required for hydrogen safety, safety management

systems, and the legal requirements which must be implemented in cooperation with safety engineers and other staff is provided in Table 10.

To prevent or reduce the likelihood of hydrogen leaks, high-quality materials should be used such as stainless steel for pipelines to minimise corrosion and leaks. Proper sealing and double-walled piping in critical areas should also be implemented. Moreover, regular inspection and maintenance schedules are required to detect early signs of wear.

Regarding ignition source control, important requirements include installing intrinsically safe electrical systems, eliminating spark-generating activities (such as welding) near hydrogen systems, and using explosion-proof equipment in hazardous zones.

Concerning rapid detection and shutdown systems, several automated shutdown valves are activated in the event of a detected leak or fire, and remote monitoring systems with instant alerts to control room personnel should be installed to avoid consequences.

Furthermore, burst discs and devices for relieving pressure should be used to avoid overpressure, with pressure-relief valves installed on pipes and storage tanks and burst discs used to release excess pressure quickly.

To mitigate hydrogen leaks and reduce hazardous consequences, controlled vent systems should be used, so that leaking hydrogen is immediately vented to the atmosphere. Materials and coatings that are fireproof should be used for equipment that is susceptible to leaks. When a leak is detected, automatic isolation valves should close.

Blast walls should be implemented to separate high-risk areas such as hydrogen storage sites from other operational areas.

Other important points that need to be considered are ensuring wide access roads and open space for firefighting vehicle access and including water supplies and hydrants close to hydrogen storage and production areas.

#### 11.6. Hydrogen Farm Design Considerations

The following general safety design factors should be considered:

1. Site Layout and Selection:

Pick a place that is sufficiently removed from crowded regions.

Arrange the design to reduce the possibility of hydrogen build-up and to make it simple for emergency personnel to access.

2. Safety and Exclusion Zones:

Define safety zones surrounding places used for the production, handling, and storage of hydrogen.

Only allow access to qualified individuals.

3. Monitoring and Control Systems:

Set up real-time temperature, pressure, and hydrogen level monitoring systems.

When anomalies are found, use automated control mechanisms to stop the process.

4. Emergency Response Plan:

Create and carry out a plan for handling emergencies.

Organise routine emergency exercises and training sessions.

Table 10. Safety systems.

| Safety System                                    | Description                                                                                                                          | Estimated Number/Coverage                                                    |
|--------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Hydrogen Detectors and Sensors                   | Monitor hydrogen leaks in key areas such as the electrolyser, storage tanks, pipelines, and distribution areas.                      | 2000–4000 units distributed across critical areas.                           |
| Gas Detection System Control Panels              | Provide centralised systems for processing hydrogen detection alerts and triggering alarms or emergency shutdown procedures.         | 100–200 centralised control panels.                                          |
| Ventilation Systems                              | Ensure safe dispersion of hydrogen gas in case of leaks by maintaining adequate airflow in confined spaces.                          | Multiple units for each critical room (electrolyser, storage, etc.).         |
| Emergency Shutdown (ESS) Systems                 | Automatically shut down electrolysers and related systems in case of hydrogen leaks, pressure anomalies, or other failures.          | Several, typically (20ESS); 1 per major electrolyser unit.                   |
| Pressure-Relief Valves (PRVs)                    | Release excess hydrogen or oxygen to prevent overpressurisation of pipes and storage tanks.                                          | Dozens across all piping, electrolyser units, and storage tanks.             |
| Explosion-Proof Electrical Systems               | Enable electrical components, especially in hazardous areas, to be explosion-proof to prevent sparks that could ignite hydrogen gas. | Installed across all electrical equipment in hydrogen zones.                 |
| Flame Detectors                                  | Detect the presence of a hydrogen flame (which burns invisibly) in critical areas.                                                   | An estimated 50 units in high-risk areas, such as near storage or pipelines. |
| Hydrogen Purge Systems                           | Purge hydrogen safely from electrolysers, pipelines, and storage vessels during maintenance or emergencies.                          | Multiple systems for each hydrogen-processing unit.                          |
| Fire Suppression Systems                         | Offer specialised fire suppression systems, such as inert gas systems (CO <sub>2</sub> or nitrogen), to smother hydrogen fires.      | Fire suppression units for all critical hydrogen areas.                      |
| Blast-proof Walls or Barriers                    | Provide physical barriers to contain explosions and prevent the spread of damage to other parts of the facility.                     | Typically required around storage tanks and electrolysers.                   |
| Hydrogen Storage Safety Valves and Rupture Discs | Prevent overpressurisation and ensure safe operation of hydrogen storage tanks.                                                      | Each storage tank is typically equipped with multiple valves and discs.      |
| Alarm and Warning Systems                        | Provide visual and audible alarms to alert personnel of hydrogen leaks, fires, or other hazardous situations.                        | Distributed across the facility, 1000–2000 in number.                        |
| Emergency Venting Systems                        | Allow safe hydrogen to vent into the atmosphere in case of emergencies.                                                              | Several, typically 1–2 for each major storage or production unit.            |
| Inert Gas Systems (Nitrogen Purge)               | Inject inert gas like nitrogen into hydrogen systems to prevent oxygen–hydrogen mixtures from becoming flammable.                    | Required for all hydrogen-containing vessels and pipelines.                  |
| Explosion Suppression Systems                    | Suppress explosions in their early stages to minimise damage.                                                                        | Few systems are installed in critical sections like storage.                 |
| Hydrogen Embrittlement Monitoring Systems        | Monitor the structural integrity of equipment that could become brittle due to exposure to hydrogen.                                 | Installed on all pipelines and pressure vessels.                             |
| Automated Pressure Control Systems               | Maintain safe pressure levels in hydrogen pipelines and storage vessels.                                                             | Integrated control systems across the plant.                                 |
| Lighting Systems with Intrinsic Safety           | Lighting designed to prevent ignition in potentially explosive atmospheres.                                                          | All lighting systems in hydrogen-prone areas.                                |

## 12. Conclusions

Numerous conclusions are drawn from this study, which is provided as an example of a foundation-level investigation. The first is that significant infrastructural requirements have been identified. The layout of the hydrogen farm illustrates the massive facility and equipment requirements.

Another significant conclusion is that, given the intermittent and seasonal nature of sunlight illumination or wind availability, the overall utilisation of the equipment would not be too high for application in the country's decarbonisation project, which will rely on solar farms and wind farms to supply energy. For instance, combined-cycle gas turbines will be operated alone when there is no sunshine. Demand management, enhanced technology, the deployment of advanced maintenance methods, and other strategies can all help to some extent. The amount of hydrogen that will need to be produced by the electrolyzers has been identified.

While the scale of the decarbonisation expenditure is not anticipated to change significantly, the hydrogen farm idea offers meaningful cost savings. Efficient integration of the various components will also result in cost savings. The health and safety measures that will be required for the hydrogen farm have been identified. The farm has a significant capacity as it includes a group of PEM electrolyzers and alkaline electrolyzers with a capacity of 1 GW each; the implementation of such a design is multifaceted and requires diligent attention to legal requirements, safety management systems, and advanced safety equipment. The number of safety systems that will be required on hydrogen farms have been estimated such as hydrogen detectors and sensors, gas detection systems, emergency shutdown systems, alarm and warning systems, emergency venting systems, etc.

Moreover, the safety distances that will be required for the hydrogen farm have been defined. The layouts of the hydrogen farms have been set out to provide good access to all facilities during maintenance or in case of an emergency incident. By fostering a strong safety culture, maintaining detailed process documentation, implementing comprehensive risk management strategies, and ensuring continuous training and improvement, the hydrogen farm can operate safely and efficiently, minimizing risks to personnel and infrastructure. Moreover, during the operation of the farm, the strict health and safety regulations necessary for hydrogen operations will need to be applied to designated places.

Large-scale electricity requirements have been defined, which is necessary to complete the greening process. The research and development, investment, and political agenda required at the outset of the decarbonisation journey can all begin with this foundational analysis.

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## Nomenclature

|                     |                                     |
|---------------------|-------------------------------------|
| H <sub>2</sub>      | Hydrogen                            |
| CO <sub>2</sub>     | Carbon dioxide                      |
| AE                  | Alkaline electrolyser               |
| PEM                 | Proton exchange membrane            |
| SOE                 | Solid oxide electrolyser            |
| H <sub>2</sub> CCGT | Hydrogen combined-cycle gas turbine |
| Nm <sup>3</sup> /h  | Normal cubic meters per hour        |

|     |                     |
|-----|---------------------|
| LHV | Lower heating value |
| MW  | Megawatt            |
| GW  | Gigawatt            |

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## **Preliminary assessment of a hydrogen farm including health and safety and capacity needs**

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