International Hydrogen Ramp-up Programme – H2Uppp

Guide for the Development of Green Ammonia Projects in Mexico

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Mexico, April 2026

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Glossary

- AEM: Anion Exchange Membrane
- ASU: Air Separation Unit
- AWE: Alkaline Water Electrolysis
- BaU: Business as Usual
- BESS: Battery Energy Storage System
- BoP: Balance of Plant
- CRF: Capital Recovery Factor
- ESG: Environmental, Social and Governance
- EZ: Electrolyser
- DAP: Di-ammonium Phosphate
- GHG: Greenhouse Gases
- GHI: Global Horizontal Irradiation
- INAH: Instituto Nacional de Antropología e Historia (National Institute of Anthropology and History)
- KTPY: Kilotonnes per Year
- LCOA: Levelized Cost of Ammonia
- LCOE: Levelized Cost of Energy
- LCOH: Levelized Cost of Hydrogen
- LHV: Lower Heating Value
- MAP: Monoammonium Phosphate
- PEM: Proton Exchange Membrane
- CF: Capacity Factor
- PV: Photovoltaic
- RFNBO: Renewable Fuels of Non-Biological Origin
- RO: Reverse Osmosis
- SEMARNAT: Ministry of Environment and Natural Resources
- SENER: Ministry of Energy
- SOEC: Solid Oxide Electrolyser Cell
- SCT: Ministry of Infrastructure, Communications and Transportation
- TRL: Technology Readiness Level

Executive summary

Ammonia stands out as one of the most important chemical compounds worldwide. It plays a crucial role in the synthesis of fertilizers and in various applications in the chemical industry. Unfortunately, ammonia production is associated with the emission of approximately 500 megatons of carbon dioxide each year, representing 1% of total global emissions. This level of CO_2 emissions poses a challenge to achieving global decarbonization targets and combating climate change.

Unlike other sectors where greenhouse gas (GHG) emissions are linked to electricity generation, in ammonia synthesis these emissions result from the production of the essential raw material: hydrogen. Historically obtained from methane and accompanied by carbon dioxide emissions, renewable hydrogen has emerged as a promising alternative to produce ammonia in a sustainable manner.

Through the electrolysis process, which uses only water and electricity from renewable sources, hydrogen can be produced with virtually no direct associated GHG emissions. Cost reductions in renewable energy technologies, particularly solar and wind, together with expected reductions in electrolysis equipment costs in the near term, will make competitive production of renewable hydrogen possible.

This report begins by providing context for the role of ammonia in global decarbonization efforts. It then takes a comprehensive look at the ammonia production process, addressing all components in the value chain, from the production of renewable electricity to the transportation and distribution of the chemical. A comprehensive view of technical and economic aspects is provided, allowing a complete understanding of the technologies involved.

Additionally, a sizing example for a Power-to-Ammonia system is presented, illustrating the interaction between the key variables of this type of project. This example is accompanied by a financial-economic analysis that facilitates comparison among different system configurations and understanding of the associated cost structure. A methodology for refining cost estimation in green ammonia projects is also introduced.

Finally, the report addresses the regulatory framework applicable to these projects in Mexico, intending to provide quality information that will serve as a guide for renewable project developers in the country and contribute to the fight against climate change.

1. Overview of the Ammonia Production Process

Ammonia is currently a key global commodity. About 85% of ammonia is currently used to produce synthetic fertilisers such as urea and ammonium nitrate. It is also used in the chemical industry with specific applications in mining, pharmaceuticals, refrigerants, plastics, and textiles.

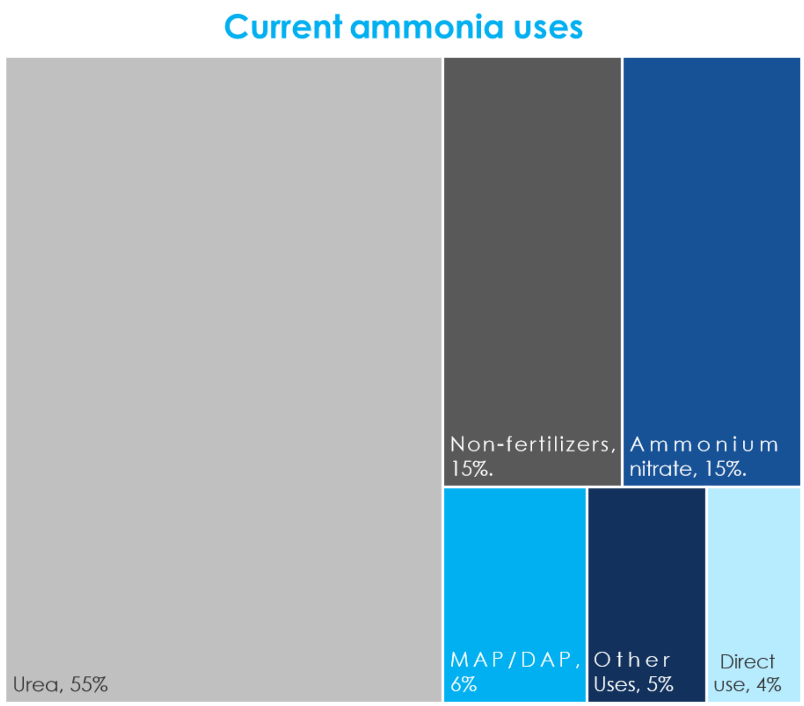

Figure 1. Current Ammonia Uses (AEA, 2022)

1.1. The Haber-Bosch Process: Conventional Production

The Haber-Bosch process remains the predominant method for the industrial production of ammonia. Discovered in the early 20th century, this process revolutionised agriculture by enabling the production of synthetic fertilisers at a large scale. The central chemical reaction of the Haber-Bosch process combines atmospheric nitrogen with hydrogen, traditionally obtained from natural gas, to produce ammonia (NH_3).

Haber-Bosch Reaction: $$N_{2(g)} + 3H_{2(g)} \leftrightarrow 2NH_{3(g)}$$

Nitrogen, which is naturally present in the atmosphere in large quantities (78% by volume), is captured by an air separation unit, while hydrogen can be produced in multiple ways. Currently, mostly natural gas is used as a feedstock along with the steam methane reforming process and the water-gas shift reaction. This process results in significant CO2 emissions.

Steam methane reforming reaction: $$CH_4 + H_2O \leftrightarrow CO + 3H_2$$

Water-gas shift reaction: $$CO + H_2O \leftrightarrow CO_2 + H_2$$

1.2. Hydrogen Production and Its Environmental Challenges

Hydrogen production for the Haber-Bosch process is performed by steam reforming methane, which generates significant CO_2 emissions, accounting for approximately 500 million tons of CO_2 per year and contributing between 15% and 20% of the chemical industry's emissions and 1% of global emissions. (AEA, 2022).

1.3. Sustainable Alternatives: Towards Renewable ("Green") Hydrogen

Another option for producing hydrogen is through the electrolysis process, which uses electricity to break down the water molecule into hydrogen and oxygen.

Electrolysis reaction: $$2H_2O_{(l)} \leftrightarrow 2H_{2(g)} + O_{2(g)}$$

If the electricity that powers the electrolyser is of renewable origin, it can be said that both the hydrogen and the ammonia for which it is used are green or renewable. Among the most common renewable energy sources are solar and wind, but it can also be hydro, geothermal, tidal or from biomass. In addition, there must be a continuous supply of water that, depending on its source and purity, must be treated to meet the requirements of the electrolyser (see Table 1 and Table 3). In any case, it is important to ensure a sustainable use of water that does not compromise the availability of the resource in areas of water stress.

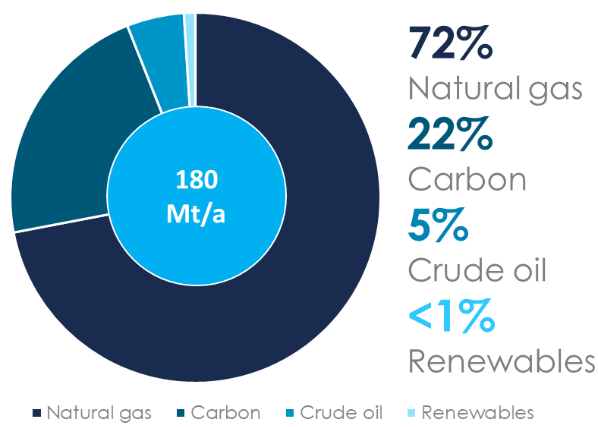

Figure 2. Ammonia production by source (AEA, 2022)

These emissions come from fossil fuels in the production of the hydrogen needed for ammonia synthesis. Once hydrogen starts to be produced by means of electrolysis using renewable energy technologies, new uses for ammonia are likely to appear in order to reduce emissions. One of the most relevant uses will be as fuel for ships, where it could play an important role in the decarbonization of the maritime transport sector. It will also be used as an energy vector to facilitate the transport and storage of hydrogen. Finally, although it will be an uncompetitive use compared to other decarbonization alternatives, ammonia also has the potential to be used as a fuel in boilers, turbines and engines to generate heat and electricity without direct greenhouse gas emissions[1] (NO_X will still be produced, which can be harmful to health). Use as a fuel for the shipping sector and as an energy vector for transporting and storing renewable

[1] For example: https://www.jera.co.jp/en/news/notice/20230616_1503

hydrogen will be of particular importance in limiting global warming to 1.5°C by mid-century (AEA, 2022). Thus, along with present uses, future uses will support the crucial role that green ammonia will play in the global energy transition.

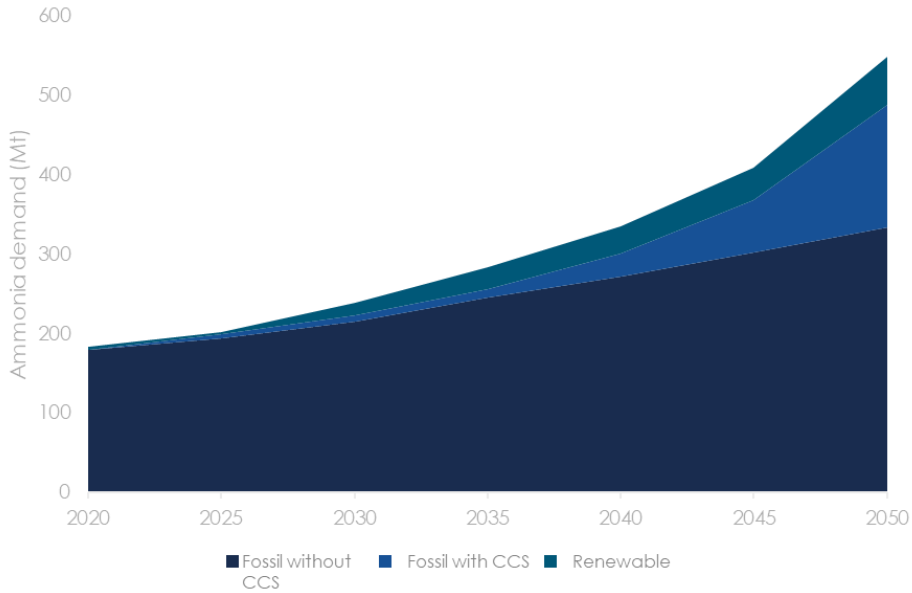

Figure 3. Expected ammonia production by feedstock in BaU scenario up to 2050 (AEA, 2022)

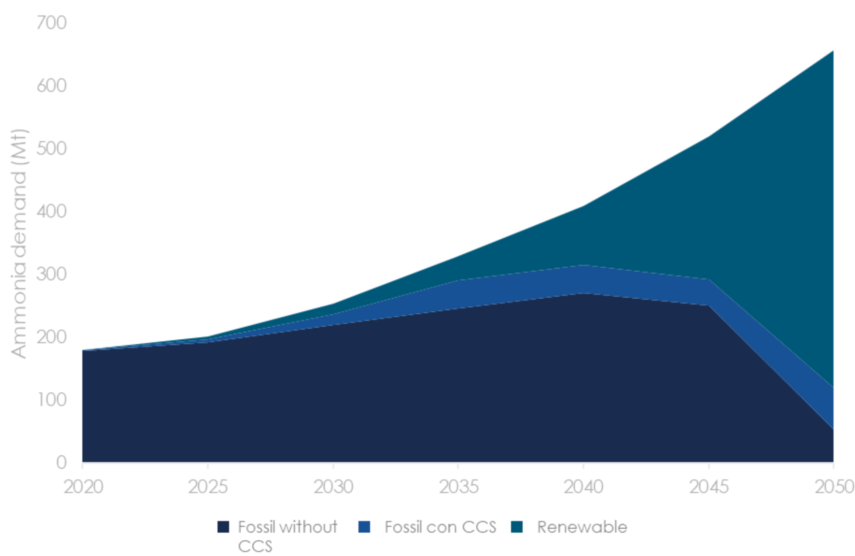

Figure 4. Expected ammonia production by feedstock in 1.5°C scenario up to 2050 (AEA, 2022)

The energy requirements and costs associated with ammonia production are critical factors for its economic viability. Traditional fossil fuel-based production has so far been more economical compared to renewable alternatives. However, technological advances and increased efficiency of renewables are closing this cost gap.

In the following section, each of the stages in its value chain will be described in more detail, including processes such as renewable energy generation, water supply, hydrogen production and storage, green ammonia synthesis and distribution. The description of each of these processes will be accompanied by a description of the different technologies, the necessary inputs, the products obtained, the energy requirements and the associated costs.

2. Detailed Process Description

Within the green ammonia production value chain, it is important to focus on the essential components of the process that dictate its technical and economic feasibility. Starting with the generation of renewable electricity, we move on to consider fundamental aspects such as water supply, the main input for the subsequent production of hydrogen. Once hydrogen is produced, it is imperative to consider its adequate and safe storage prior to its use in ammonia synthesis. Finally, logistics and transportation strategies also play an essential role in the viability of the system.

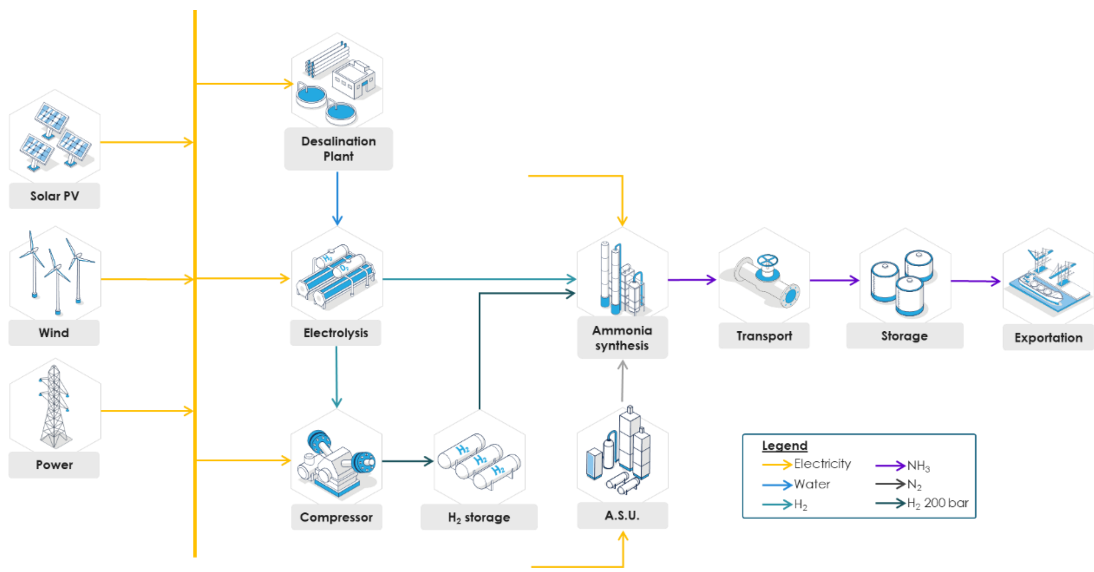

Figure 5. Green ammonia value chain

In the following sections, we will break down each of these components, focusing on their integration and applicability in the Mexican context.

2.1. Renewable Electricity Generation

Renewable electricity generation is the cornerstone of green ammonia production. It is essential to ensure that the electricity used comes from sustainable sources that have no associated greenhouse emissions. This will ensure that the ammonia produced does not have a negative impact on global warming.

2.1.1. Renewable Electricity Sources

Solar energy: Mexico has a higher average horizontal solar irradiation (GHI) than many regions of the world (5.73 kWh/m2), which positions it as an ideal candidate for large-scale solar energy projects (ESMAP, 2020). Photovoltaic technology, which converts sunlight directly into electricity, has experienced rapid cost reductions and has become competitive with traditional energy sources. According to the Centre for the Study of the Environment and Renewable Energy Technologies (CEMAER), in Mexico the price per installed watt ranges from $0.67 USD to $1.22 USD depending on the technology and power of the solar panels.

Wind energy: The coastal areas and the northern and southeastern regions of Mexico have significant wind energy potential. Wind energy consists of converting the kinetic energy of the wind into electricity using wind turbines.

Hydroelectric power: Although Mexico's hydroelectric generation capacity is already largely exploited, modernization and optimization of existing plants can help increase electricity production from this renewable source.

Geothermal energy: Given its volcanic activity, Mexico has vast geothermal potential, especially in the western region. This energy comes from heat stored beneath the earth's surface.

Biomass energy: Through gasification or fermentation processes, organic waste can be transformed into electricity. Mexico, with its robust agricultural industry, has considerable potential in this area.

2.1.2. Energy Storage

Due to the variable nature of renewable sources such as the sun and wind, energy storage solutions are essential to ensure a continuous supply of electricity for ammonia production. Batteries, hydroelectric pumping plants and thermal storage systems are some of the viable solutions to compensate for fluctuations in electricity generation.

2.2. Water Supply for Green Ammonia Projects

Water scarcity is a growing concern in many regions of the world, including Mexico. Desalination is a promising option for supplying potable water to regions facing water scarcity problems, especially in coastal areas. Reverse osmosis is considered the most suitable desalination process for Mexico, but possibilities of other water sources are also discussed.

2.2.1. Desalination

Reverse osmosis is a method of converting seawater into a reliable source of fresh water. In Mexico's geography, marked by long coastlines and freshwater supply challenges, this technology offers a particularly effective solution. Using semi-permeable membranes, reverse osmosis retains salts and contaminants, providing high-purity water suitable for electrolysis and other sensitive industrial uses.

Although this technology has advanced considerably, reducing costs and increasing efficiency, the electricity energy required for its operation is still considerable. Gravity-fed systems that could reduce the use of electricity energy also provide an alternative to conventional electricity-driven desalination. This poses the challenge of optimising energy consumption and sustainably managing the resulting brine to minimise its environmental impact. Mexico's renewable energy potential offers a viable pathway toward more sustainable and cost-effective reverse osmosis desalination.

2.2.2. Other Water Sources

1. **Rivers:** Mexico's river network offers potential for green hydrogen projects, where freshwater is a critical input for electrolysis. However, the challenges of overexploitation and pollution require decisive intervention. Sustainable management, including uses and advanced wastewater treatments regulations, would allow Mexican rivers to supply water for hydrogen production, aligning conservation efforts with renewable energy goals.
2. **Aquifers:** Underground aquifers are critical for hydrogen projects in coastal areas. Protection against overexploitation is essential to ensure that these reservoirs can continue to contribute to the water supply. Balanced extraction and recharge policies are required to maintain their long-term viability, which would allow for sustainable production of green hydrogen.
3. **Rainwater harvesting:** In regions with defined rainy seasons, rainwater harvesting is emerging as a complementary solution for supplying water to electrolysis plants. The implementation of adequate infrastructure to capture, store and treat rainwater can provide a constant flow of freshwater for continuous hydrogen production.

Given Mexico's varied climate and geography, a combined strategy using both desalination and sustainable management of other water sources could be the most effective solution to address the country's water challenges.

2.3 Green Hydrogen Production and Storage

Electrolysis is a process that uses electricity to break down water into hydrogen and oxygen. For each mass unit of hydrogen produced, approximately 10 to 20 volume units of water are required, slightly more than required by stoichiometry due to process inefficiencies. The equipment responsible for the electrolysis process is called an electrolyser and is composed of stacks (Figure 6), which in turn are composed of electrolytic cells. Each of these cells has two electrodes (anode and cathode) connected to a continuous electricity power source.

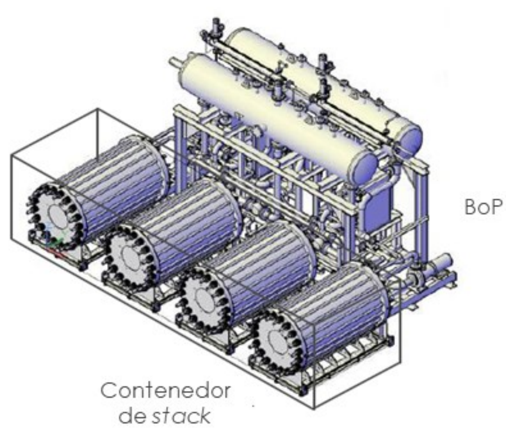

Figure 6. Electrolysis Plant

Depending on technology, the electrodes will be separated by an electrolytic solution or membrane to separate hydrogen from oxygen. By means of an electrochemical reaction, hydrogen is generated at the cathode, while oxygen is generated at the anode. Subsequently, the hydrogen will go through a purification and conditioning process that will allow it to be ready to be stored and/or used.

$$2H_2O \leftrightarrow 2H_2 + O_2$$

Depending on the physicochemical and electrochemical characteristics of the electrolyser cell, electrolysis can occur with multiple configurations. Alkaline electrolysers (AWE) have the highest level of maturity, with several industrial plants operating for decades. Proton exchange membrane electrolysers (PEM) are a relatively recent technology, less than 10 years old, but are already being scaled up and optimized. There are also solid oxide electrolysers (SOEC) and anion exchange membrane electrolysers (AEM), but these are still in the development stage and have not yet achieved technological and commercial maturity. Detailed descriptions of alkaline and PEM electrolysers are provided below.

2.2.3. Alkaline Electrolysers (AWE)

Alkaline electrolysers are the most mature electrolysis technology for producing hydrogen on an industrial scale of tens of MW. This technology has existed since 1850, had its first large-scale installations in the 1930s and already has a Technology Readiness Level (TRL) of 9.

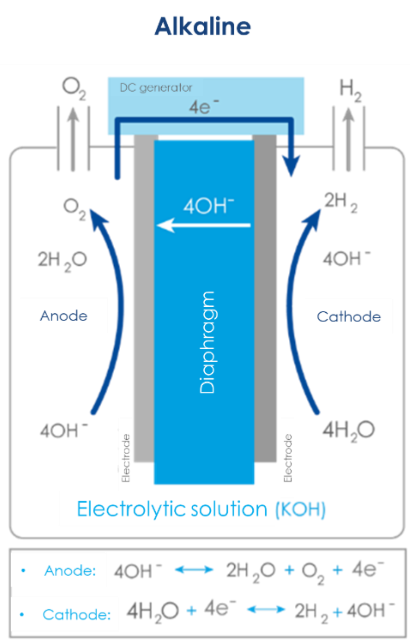

Figure 7. Diagram of an electrolysis reaction in an alkaline cell

Alkaline electrolysis is an electrochemical process (Figure 7) that uses an alkaline solution, usually potassium hydroxide (KOH), as the electrolyte. In this method, electric current is applied through an electrolytic cell consisting of an anode, a membrane, and the cathode to decompose water into hydrogen and oxygen.

In general, the costs of this technology are relatively low, due to its maturity, material costs and the large capacity of the stack modules, in addition to the useful life of the stack. However, it has technical weaknesses to address, such as the low current densities due to ohmic resistance of the electrolyte and diaphragm, since at high current densities the cross-gas diffusion of H_2 and O_2 is significantly increased. The partial charge range is limited by the ability of the diaphragm to prevent crossover, the electrolyte dynamics is low due to the inertness of the liquid electrolyte, and the large cell area limits the operating pressure since at high pressures more gas crossover is expected. In addition, the KOH electrolyte is corrosive and can damage piping and components, as well as affect externally through leakage, which can generate electricity hazards.

There are two types of alkaline electrolysis: atmospheric and pressurized. The first occurs at atmospheric pressure and the second at low pressures, between 15 and 30 barg. The main differences are that atmospheric alkaline electrolysis has a higher level of maturity and the complexity of the electrolyser design is lower, but it requires additional compression stages (typically between 20-30 barg is required for downstream processes) that generate an extra cost in compression, operation and maintenance. In addition, it has less flexibility to operate at variable loads and is less efficient in mechanical compression (higher mechanical compression losses) (IRENA, Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, 2020).

Pressurized alkaline electrolysis technology does not require mechanical compression, has lower space requirements because it operates with compressed gases and has greater operational flexibility. However, the electrolyser is more expensive because it needs to be reinforced to withstand the pressure at which the system operates. It also requires greater safety and maintenance control because the pressurized corrosive electrolyte (NaOH-KOH) can cause greater deterioration of plant equipment (IRENA, Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, 2020).

2.3.1.1 Atmospheric Alkaline Electrolysis (AWE atm)

Atmospheric alkaline electrolysis occurs at atmospheric pressure or low pressure, less than 10 barg. The electrolyte solution required (KOH or NaOH) must be 20-30% by mass and the hydrogen produced has a purity ranging from 98% to 99.9%. Currently, the stack of electrolysis cells in this technology has an average life of 70,000 hours. This is expected to increase to 85,000 hours by 2030 and to over 100,000 by 2040 (Nel, 2020).

In general, these electrolysers are composed of ZrO_2-based diaphragms and nickel-coated stainless-steel electrodes, avoiding the use of noble metals. The electrodes are immersed in the electrolyte solution, 20-30% NaOH or KOH, and the diaphragms used are thick and spaced to avoid mixing of the produced gases (H_2 and O_2) dissolved in the electrolyte. This results in high ohmic losses, which reduces the current density and overall cell efficiency. Work is currently underway to develop advanced designs using zero-gap electrodes, thinner diaphragms and different electrolyser concepts to increase current capacity and higher-pressure level operations.

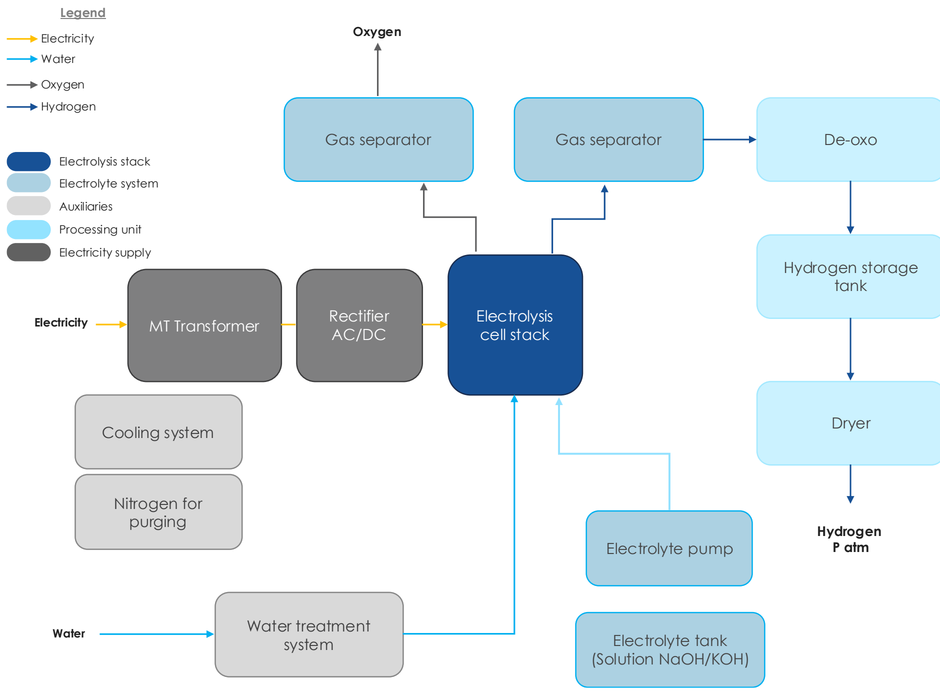

Figure 8. Simplified block diagram of stack and BoP of an atmospheric electrolysis plant (Hinicio)

In addition to the electrolyser, several pieces of equipment are required to be considered for the operation of an electrolysis plant (balance of plant, BoP), such as the following (Figure 8):

- Water purification plant.
- Electrolyte tank and pump.
- Transformers and rectifiers for the electrolyser.
- Cooling system for electrolysis.
- Gas-liquid separators.
- Hydrogen purification system (De-oxo and dryer).
- Nitrogen compressor

Typically, an atmospheric alkaline electrolysis plant requires an additional compression system (buffer tank, inter-stage and post compression cooling, etc.), because the required pressure is higher than atmospheric.

The efficiency of atmospheric alkaline electrolysis is between 56-70% of LHV, including BoP. The value is expected to increase to 65-71% by 2030 and 71% by 2040. The electricity consumption of the electrolysis stack is between 44.4 and 51.2 kWh/kgH2, and the electricity consumption of the electrolysis plant including the BoP is between 47.4 and 56 kWh/kgH2. Table 1 shows the technical specifications for alkaline electrolysis at atmospheric pressure.

Table 1. Technical specifications for alkaline electrolysis atm (Hinicio)

	Unit	Value
Operating pressure	barg	0
Operating temperature	°C	70-90
Current density	A/cm^2	0.2-0.8
Cold start-up time	Min	60
Mean time between failures (MTBF)	Year	< 2
Response time to dynamic stack load changes	s	0.02
Stack operating range	%	15-100
Stack lifetime	h	70,000-90,000
Electrolysis stack power consumption	kWh/kg H2	44.4-51.2
System power consumption	kWh/kg H2	47.4-56
Cooling water consumption	m3/kg H2	1.5-2
Demineralized feed water consumption	L/kg H2	9-13
Conductivity of demineralized feed water	µS/cm	< 1.0
Feed water pH	pH	5.5-8
Surface area per MW (whole plant)	m^2/MW	100-170

In terms of costs, in 2023, a 10 MW atmospheric alkaline electrolysis plant—comprising stacks and all the BoP required to deliver hydrogen under necessary conditions—costs between 580 and 1,010 USD/kW, with the stack accounting for 19% of the total cost. The overall cost distribution is shown in figure 9. The transformers and processing units required to process gases and fluids account for 38% and 32% of the cost, respectively. The remaining system components represent secondary cost contributions. Should the addition of a H_2 compressor unit be required to raise the pressure to 30 barg, the system cost increases to USD 655-1090/kW, where the cost of the compressor system represents 24% of the total.

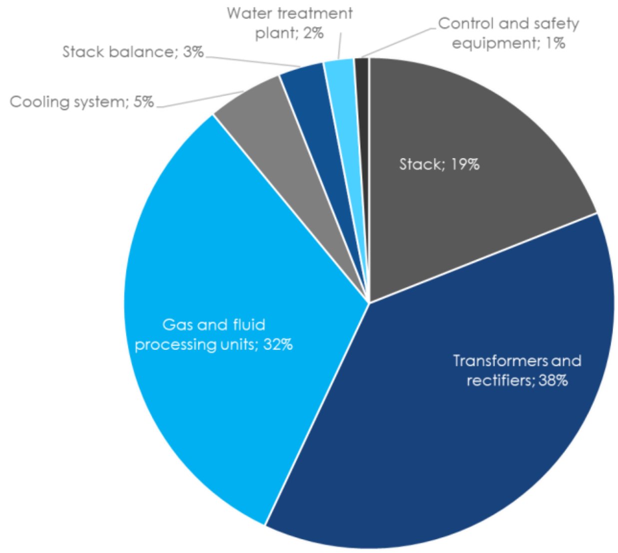

Figure 9. Alkaline Electrolysis Plant Costs

Additionally, the investment required for the development of an electrolysis plant depends on the capacity of the plant. In the case of alkaline electrolysis, as capacity increases, investment costs decrease (Figure 10). As an example, if the capacity of an alkaline electrolysis plant is ~2 MW the CAPEX is approximately 800 USD/kW, while the specific CAPEX decreases to approximately 400 USD/kW if the capacity of the electrolysis plant increases to 75 MW. It is important to note that when the alkaline electrolysis plant exceeds 50 MW, the specific investment cost (USD/kW) remains relatively constant. Finally, the fixed annual OPEX for an AWE plant is 2% of the initial CAPEX and includes operation and maintenance.

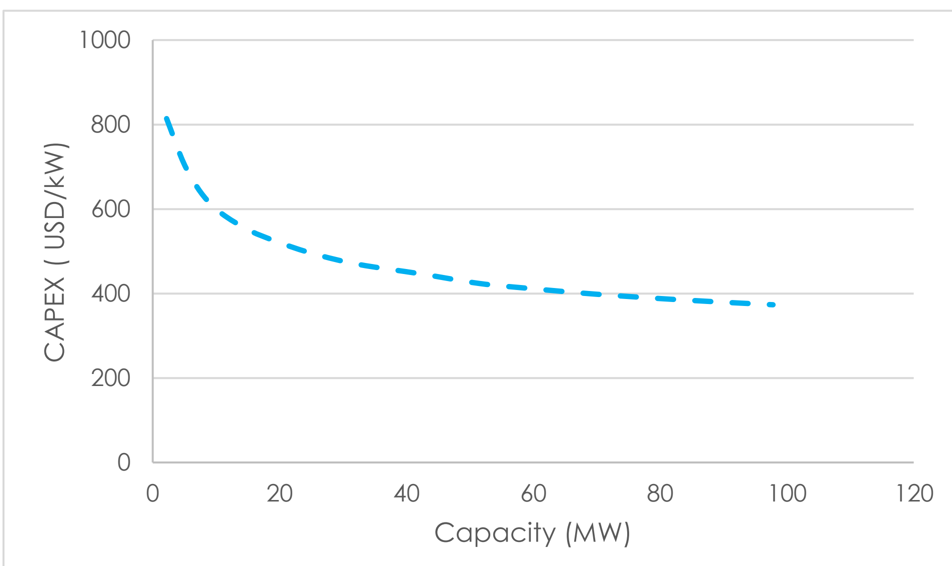

Figure 10. Specific CAPEX for alkaline electrolysis plant vs. capacity (multiple sources)

2.3.1.2 Alkaline Pressurized Electrolysis (AWE press)

Pressurized alkaline electrolysis occurs at pressures between 15 and 30 barg where both the electrolyte and the water must have the same pressure as the electrolyser. It has a similar maturity level to alkaline technology, with TRL equal to 9. The major difference between pressurized and atmospheric alkaline electrolysis is that pressurized alkaline electrolysis does not require the H_2 compression system. The materials used in this type of electrolysers are similar to those of atmospheric alkaline electrolysis but have a reinforced bipolar membrane design to cope with the higher pressure. The hydrogen produced with this electrolysis is 99.9% pure (Hanke-Rauschenbach, Bensmann, & Millet, 2015) (IRENA, Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, 2020).

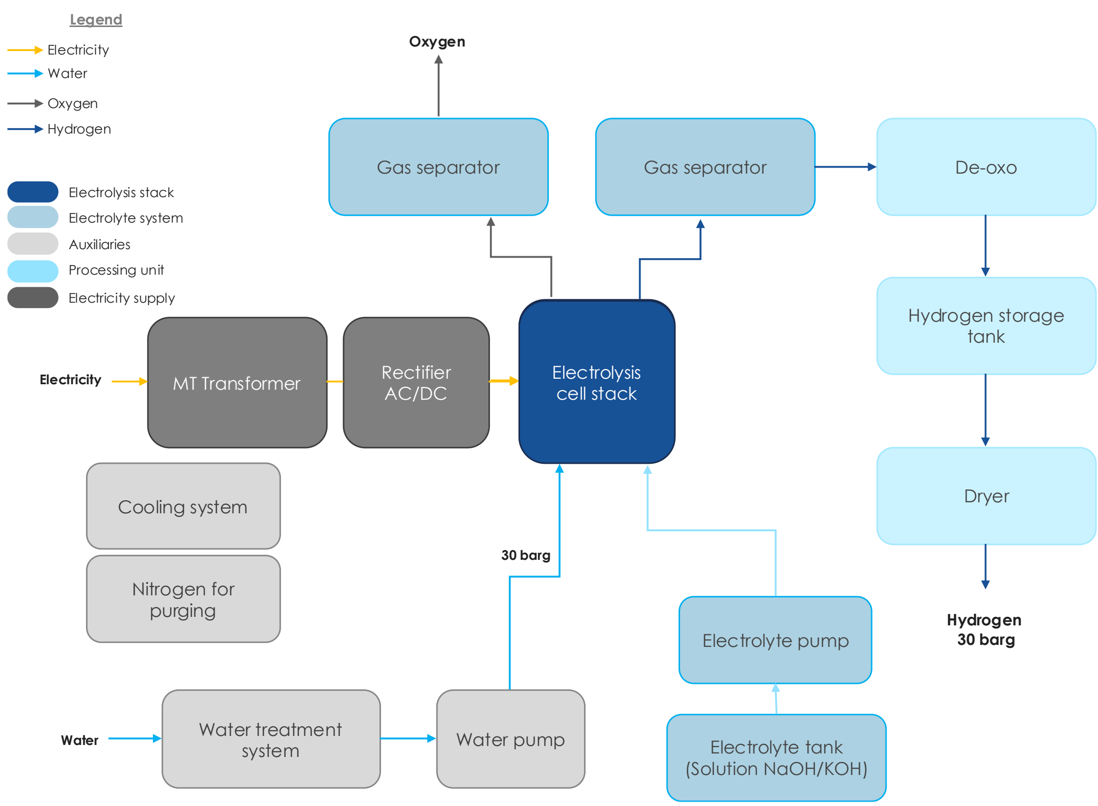

Figure 11. Simplified block diagram of stack and BoP of a pressurized electrolysis plant (Hinicio)

For pressurized alkaline electrolysis there is a simplification compared to what is required for the atmospheric alkaline electrolysis plant. In this case a H2 compressor is not required in the system upstream of the purification and drying unit to obtain H_2 at 30 barg, which translates directly into reduced costs and space requirements. To reach the pressure required by the system, a pump is used, which reduces the electricity consumption of the system, compared to those systems that require compressors, and gives greater operational flexibility of operation to the electrolysis plant, since by operating at pressure the cell better withstands fluctuations in operating flow (IRENA, Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, 2020).

In general, it matches the technical specifications of atmospheric alkaline electrolysis (Table 1). The difference is that it does not require a compressor to obtain hydrogen at 30 barg, since H_2 is obtained at the pressure at which the electrolyser operates (15 - 30 barg). Both the electrolyte circuit and the feed water to the system must have the same pressure as the electrolyser.

Table 2 shows the status of pressurized alkaline electrolysis technology along with future improvements that can be made.

Table 2. Current status and future improvements of alkaline electrolysis technology

Element	Current state of technology	Future enhancements to the technology
Stack - Electrodes	Nickel (Ni) coated stainless steel electrodes.	Develop suitable material ($Ni(OH)_2$ or $NiCo_2O_4$-$NiCoS_4$), which allows to increase the current density due to its high activity and stability.
Stack - Diaphragm	Thick diaphragm based on ZrO_2.	Develop corrosion resistant electrodes.
Stack - Electrolyte	Uses 20%-30% NaOH or KOH solution.	Develop thinner diaphragms to increase current density but avoid mixing dissolved gases in the electrolyte.
Stack - Size	Mature stack technology in the MW range.	Develop a new electrolyte for high temperature operations. Example: molten salts.
Stack - Design	Traditional alkaline electrolysis design.	Increase stack size to have multi-MW stacks, leading to a decrease in technology-specific costs.
BoP	Pre-electrolyser water purification system.	"Zero Gap" design: This design considers that the porous electrodes are only separated by the diaphragm, which causes an increase in current density due to the lower internal resistance inside the cell.

In terms of cost, the pressurized electrolysis stack is, on average, 10% higher than atmospheric alkaline electrolysis and the total cost of the pressurized electrolysis plant is 650 - 1,100 USD/kW. The cost breakdown of a 10 MW plant is similar to that of atmospheric alkaline electrolysis (Figure 9). The difference in the cost of the stack is because it needs to be reinforced to withstand the pressure at which the system operates. In this case, the costs related to the subsequent compression of H_2 to the desired pressure are avoided. Like atmospheric alkaline electrolysis, pressurized electrolysis has a fixed annual OPEX corresponding to 2% of the initial CAPEX.

2.3.2 PEM Electrolysers

Proton exchange membrane electrolysis (PEM) is a mature technology with a TRL equal to 9 and is characterized by its proton-conducting solid electrolyte. PEM electrolysers are a relatively recent technology that has rapidly achieved commercial and technological maturity. Although their costs are currently higher than alkaline electrolysers, they are promising in terms of current density, operational flexibility, and land footprint.

In this type of technology, the H^+ protons produced by the electrolysis reaction are transported through a solid electrolyte from the anode to the cathode, as shown in Figure 12. The cell area can be reduced due to the high achievable current densities and can tolerate differential pressure, which allow PEM stacks to operate under pressure. Currently the typical operating pressure is 30 barg and this type of electrolysis produces H_2 with a purity of 99.99% (IRENA, 2020).

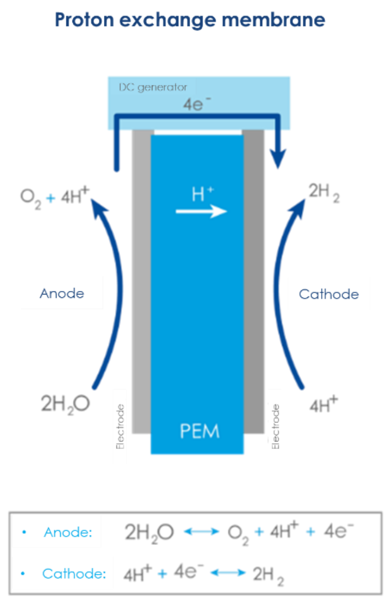

Figure 12. Diagram of an electrolysis reaction in a PEM cell

This type of electrolysis has a high current density, between 1 to 2.2 A/cm², so the cooling system must operate efficiently and uniformly across the cell area. The electrolysis cell stack for this type of electrolyser has an average lifetime of 50,000 hours, which is expected to increase to 75,000 in 2030 and to more than 100,000 by 2040 (IRENA, 2020).

In terms of characteristics and materials, PEM electrolysis cells use a perfluorosulfonic acid (PFSA) membrane or a fluorinated membrane that is chemically and mechanically robust, allowing for higher efficiencies (lower ohmic resistance) and high-pressure differentials, because the lateral pressures of the anode and cathode must not be balanced. To provide optimum electron conductivity, high efficiency and long-term stability of the components of a PEM cell, titanium-based materials, catalysts made of noble metals (usually iridium- and platinum-based) and protective coatings are used. These requirements have made PEM electrolysis cells more expensive than alkaline cells. Moreover, PEM cells are sensitive to impurities in the water, such as iron, copper, chromium and sodium, and can suffer from contamination and degradation, so high feedwater purity is essential to maintain a high lifetime of the electrolysis cell.

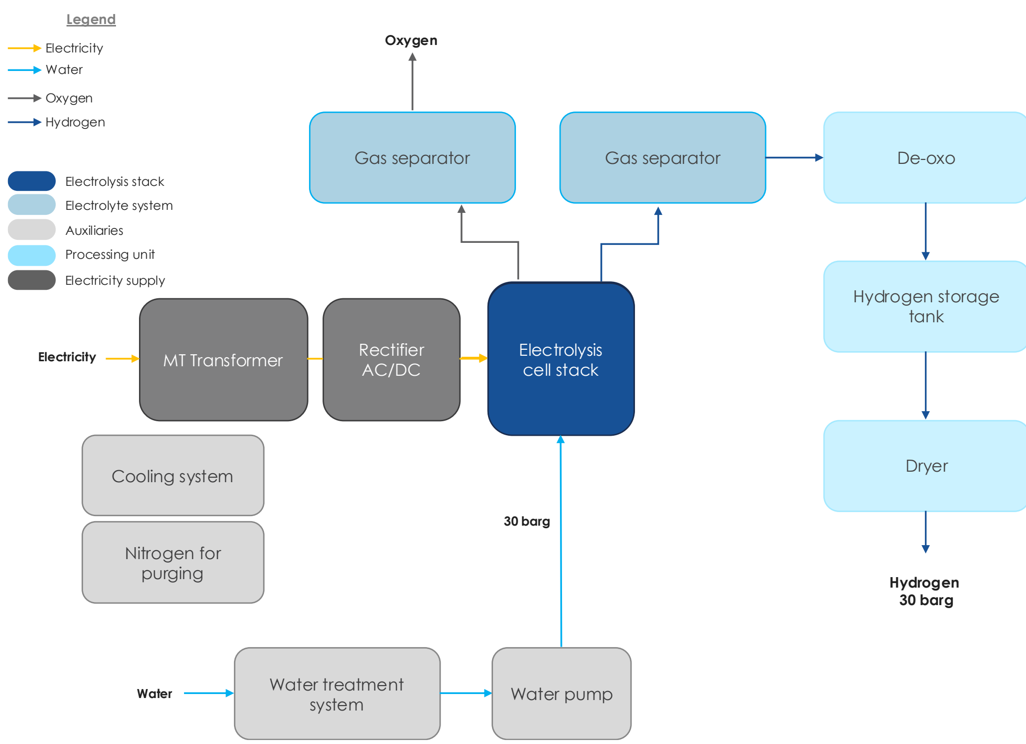

Figure 13. Simplified block diagram of stack and BoP of a PEM electrolysis plant (Hinicio)

In addition to the electrolyser, there is a series of equipment that must be considered for the operation of the electrolysis plant (BoP), they are the following (Figure 13):

- Water treatment system.
- Transformers and rectifiers.
- Cooling system for electrolysis.
- Gas-liquid separators.
- H_2 purification system (De-oxo and dryer).
- Nitrogen compressor.

A H_2 compression and storage system can be added if it is required to have a higher pressure than the electrolyser operating pressure. The PEM electrolysis plant typically operates at 30 barg, so it requires a pump to drive the water to the electrolyser at the desired pressure.

PEM electrolysis stacks take up less space than alkaline electrolysis stacks because their design is more compressed as they do not require the circulation of a liquid electrolyte through the electrolyser. For this reason, the total land requirement of these systems is equal to or less that of alkaline electrolysis plants. The BoP for this type of electrolysis is simplified compared to that required by the atmospheric alkaline electrolysis plant, as the H_2 compression system downstream of the electrolyser is optional (Siemens Energy, 2020).

The main strength of PEM electrolysis is the ability to operate at high current density and pressure, thereby decreasing the land requirement of the system and the compression work required downstream. In addition, it has a wide operating range due to the low membrane gas crossover rate of the polymer electrolyte and the transport of protons across the membrane responds quickly to energy input due to the lower system inertia compared to liquid-electrolyte systems. Thanks to the use of a polymer electrolyte, water is the only impurity that must be removed, reducing the risk of deviations in product purity. Finally, PEM technology uses a thin polymer membrane that allows compact cells compared to alkaline electrolysis technology.

As for weaknesses, since the process is based on proton (H^+) exchange, specific materials need to be used in the stack such as, for example, titanium. On the other hand, between 20,000 and 90,000 hours of stack life have been reported, with an average of 50,000 h of operation. In terms of scale, commercial systems have only recently become available at the MW scale. Finally, the costs of the stack materials are high: PFSA membrane, catalyst and electrodes based on noble metals (iridium, platinum).

Table 3 shows the technical specifications of PEM electrolysis. The efficiency of PEM electrolysis is between 42-66% of the LHV. The value is expected to increase to 63-68% by 2030 and 68% by 2040. The electricity consumption of the electrolysis stack is between 47.8 and 52.3 kWh/kg H2, and the electricity consumption of the electrolysis plant including the BoP is between 49.9 and 60 kWh/kg H2.

Table 3. PEM electrolysis technical specifications (Hinicio)

	Unit	Value
Operating pressure	Barg	1-70
Operating temperature	°C	40-80
Current density	A/cm^2	1-2.2
Cold start-up time	min	30
Mean time between failures (MTBF)	years	2-3
Response time to dynamic stack load changes	s	0.01
Stack operating range	%	5-100
Stack lifetime	h	30,000-90,000
Electrolysis stack power consumption	kWh/kg H2	47.8-52.3
System power consumption	kWh/kg H2	49.9-60
Cooling water consumption	m3/kg H2	0.93-1.8
Demineralized feed water consumption	L/kg H2	10-13
Conductivity of demineralized feed water	µS/cm	< 0.75
Surface area per MW (whole plant)	m^2/MW	80-130

Table 4 describes the current status of the technology along with future improvements for it.

Table 4. Current status and future improvements of PEM electrolysis technology

Element	Current state of technology	Future enhancements to the technology
Stack - Catalyst / Electrodes	Iridium-based catalyst at the anode and platinum-based at the cathode.	Reduction of IrO_2 loading on the anode and Pt on the cathode.
Stack - Membrane	Perfluorosulfonic acid (PFSA) or fluorinated membrane.	Improve stability and activity of the catalyst at the anode. Development of Ru-based materials to increase stability.
Stack - Bipolar plates	Bipolar plates with titanium-based materials.	Development of alternative inorganic materials for the cathode (sulphides, phosphides, carbides and nitrides).
Stack - Size	Stack technology matures in the MW range.	Improve or develop new catalysts: development of nanostructures that minimize noble metal loading by optimizing the contact area.
Stack - Operation	Currently operating at 60-80°C.	Develop thinner membranes to increase current density.
BoP	Water purification system upstream of the electrolyser.	Develop membrane reinforcement as the size of the electrolysis cell increases.

The cost of a 10 MW plant, including the BoP, is between 700 - 1,200 USD/kW, where the stack corresponds to 29% of the total. Figure 14 shows the general cost distribution for the PEM electrolysis plant. At the process unit level, the PEM cell represents a larger share of the overall cost than an alkaline cell. In addition, the transformers and processing equipment needed to process gases and fluids represent a significant cost over the total cost of the PEM electrolysis plant: 31% and 28%, respectively. Finally, the water treatment plant, cooling system and safety equipment are secondary costs within the system.

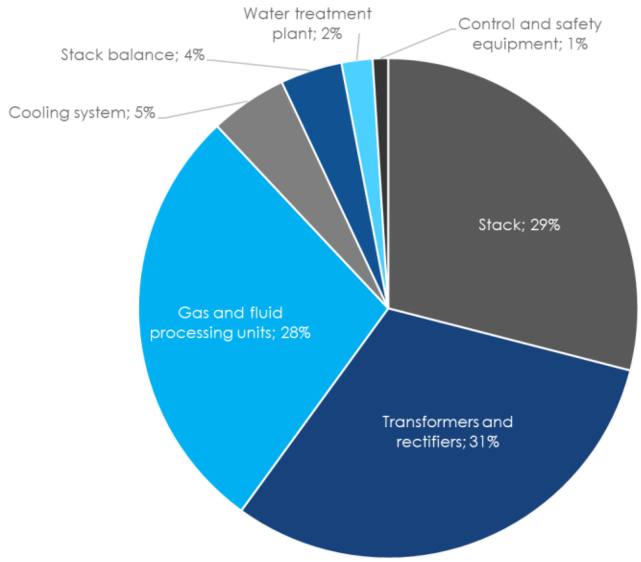

Figure 14. Costs for PEM electrolysis plant

On the other hand, the investment required for the development of an electrolysis plant depends on its capacity. In the case of PEM electrolysis, similar to alkaline electrolysis, as capacity increases, investment costs decrease (Figure 15). For example, if the capacity of a PEM electrolysis plant is 20 MW the CAPEX is greater than 600 USD/kW, while the cost decreases to 480 USD/kW if the module capacity increases to 75 MW. Similarly, as with alkaline electrolysis, above a certain capacity (~50 MW) the specific investment cost remains relatively constant as the plant capacity increases. Finally, the fixed annual OPEX for a PEM electrolysis plant is 2% of the initial CAPEX and includes operation and maintenance.

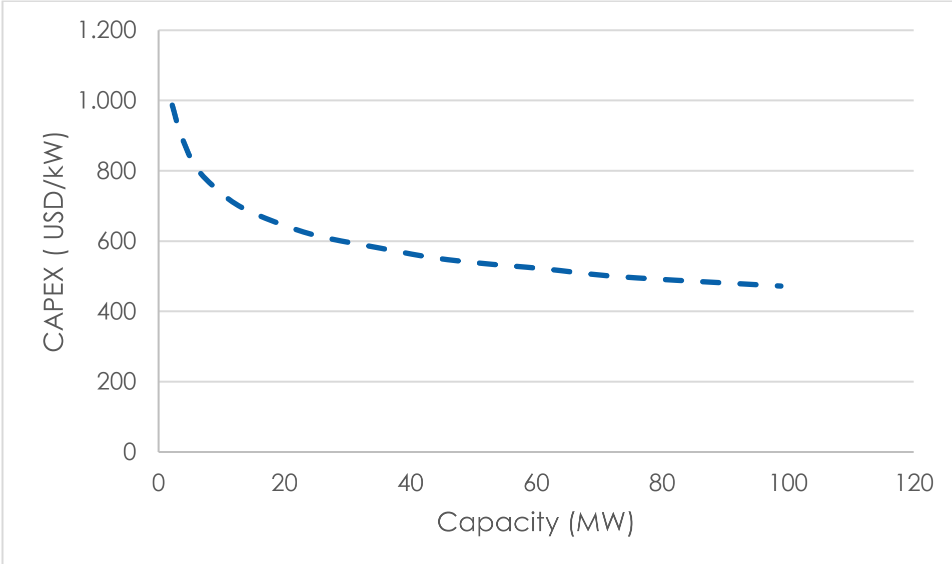

Figure 15. Specific CAPEX for PEM electrolysis plant vs. capacity (multiple sources)

To conclude the section on renewable hydrogen production technologies, Table 5 provides a summary of advantages and disadvantages for the described electrolysis technologies.

Table 5. Advantages and disadvantages of alkaline and PEM electrolysis

Technology	Advantages	Disadvantages
AWE	• Mature technology • Catalyst does not require noble metals. • Mature cell technology in the MW range • Comparatively low costs • Comparatively long lifetime	• Low current densities • Gas crossover between H2 and O2 • Partial load range limited by diaphragm capacity to avoid crossovers. • Low dynamics • Low operating pressures • Corrosive liquid electrolyte
PEM	• High rated current density • Operating pressure decreases the need for downstream compression. • Wide operating range • Dynamic response • High peak power densities • High hydrogen purity • Compact system design	• Corrosive liquid electrolyte • Corrosive acidic environment inside the stack • Average stack operating lifetime of 50,000 h • Stack capacity in the recent MW scale. • High cost of stack materials

2.3.3 Hydrogen Storage

Storing compressed hydrogen in a gaseous state is usually the best option. It requires a compression system, a pressurized tank, and an adequate safety system. The main disadvantage is the low storage capacity due to the low density of the gas. For this reason, hydrogen is compressed to pressures of up to 1,000 barg for storage. Depending on the application and pressure needed, there are 4 storage options:

1. Type I: metal tank, usually steel, used for stationary industrial applications. For hydrogen, a pressure of 200 barg is used and is the most economical type of storage. At this pressure, the density of hydrogen is approximately 14.5 kg/m3.
2. Type II: tank made of metal lining coated in composite fibre resin used for stationary industrial applications with pressures between 200 and 350 barg, which represents a density between 14.5 and 23.3 kg/m3.
3. Type III: tank made of metal lining coated in composite fibre resin used for mobile applications with pressures between 350 and 700 barg. At this pressure, the density of the stored gas is approximately between 23.3 and 39.4 kg/m3.
4. Type IV: tank made of polymeric lining coated in composite fibre resin used for mobile applications with pressures between 700 and 1,000 barg. This type of tank has a longer service life than type III due to its fatigue resistance and can store hydrogen at a density between 39.4 and 49 kg/m3.

For the specific case of Power-to-Ammonia projects, the tanks commonly used are type I and type II and cost approximately 600 USD/kg.

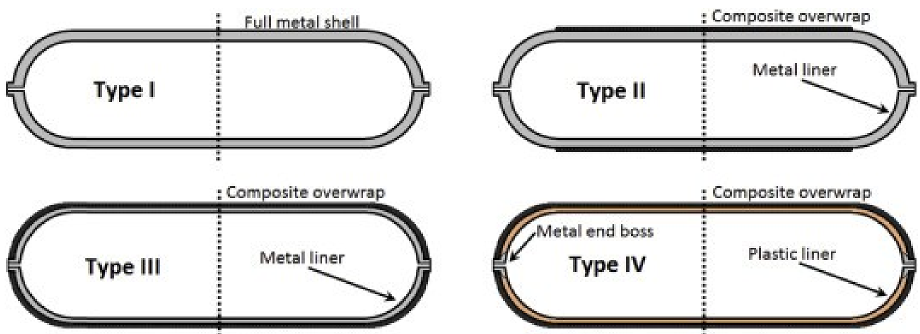

Figure 16. Types of hydrogen storage tanks

It is important to note that a certain amount of gas remains in the tank at the end of the discharge cycle. In small containers, this amount may be negligible, but in large containers it can be significant. Liquid, such as brine, is commonly used to displace the gas inside the tank so that it can be extracted in its entirety.

2.4 Green Ammonia Synthesis

On an industrial scale, the Haber-Bosch synthesis process is used to synthesise ammonia. This process is based on the exothermic and reversible reaction between hydrogen and nitrogen:

$$N_{2(g)} + 3H_{2(g)} \leftrightarrow 2NH_{3(g)}$$

The reaction requires a ferrous catalyst and operates in a temperature range of 350-550 °C and a pressure range of 100-300 barg. In the following, the process of nitrogen capture from air will be described first, followed by the Haber-Bosch synthesis process.

2.4.1 Nitrogen Capture

To obtain the nitrogen needed for ammonia synthesis, air separation units (ASU) are used. This equipment is responsible for separating nitrogen from the other components of atmospheric air. Oxygen and argon are also obtained from this process. There are three main technologies for air separation: cryogenic distillation, membrane separation and pressure swing adsorption (PSA). Each technology has different production capacities and purities of the products obtained, but all of them have reached industrial and commercial maturity so that the differences in costs are not significant. Among these alternatives, cryogenic distillation makes up approximately 90% of air separation worldwide since it is the only commercially practical method for large-scale production. For this reason, only the operation of cryogenic distillation will be described.

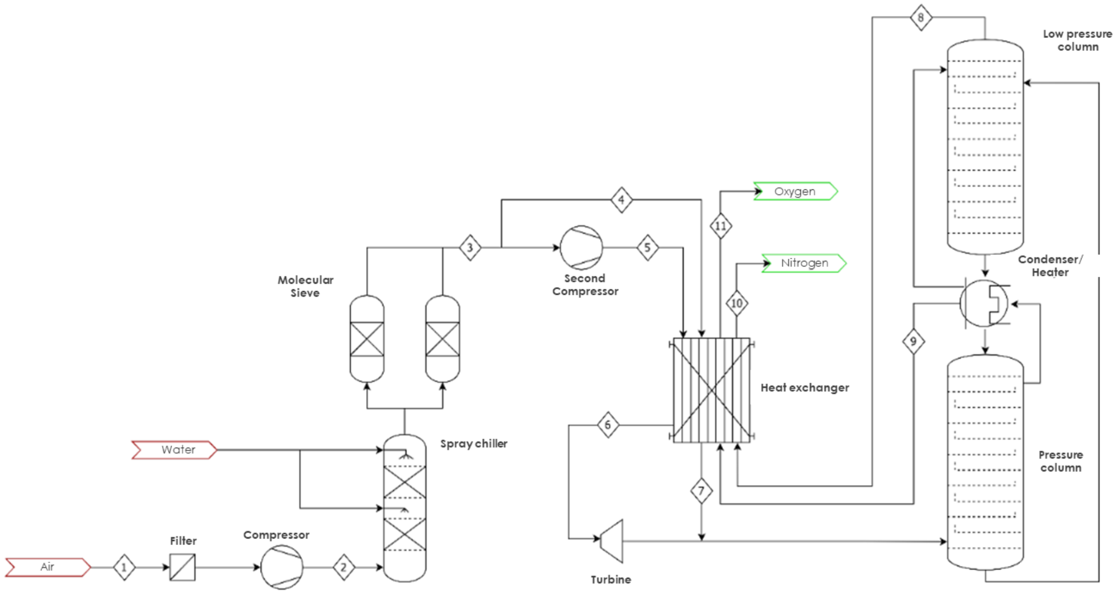

Figure 17. Simplified diagram of air separation unit (ASU)

The operation of the ASU (Figure 17) involves 3 main stages: air compression and purification, heat exchange, and cryogenic distillation. Initially, atmospheric air (1) is filtered to remove dust particles and compressed to 6 barg. It is then cooled to room temperature in a spray chiller (2) and passed through a molecular sieve that removes water and carbon dioxide (CO_2), which prevents the formation of ice and solid carbon dioxide (CO_2) in subsequent cryogenic stages. Once purified (3), the air flow is divided into two streams. The larger stream (4) is cooled and liquefied in a multi-stream heat exchanger using the oxygen and nitrogen product streams. The smaller stream (5) is compressed again, cooled in a heat exchanger and expanded in a turbine. Then, the two streams (6-7) are merged and passed to the distillation system, where the different boiling temperatures of nitrogen and oxygen (-196°C and -185°C at 10 barg for nitrogen and oxygen, respectively) are finally used to obtain the nitrogen needed in the ammonia synthesis. The distillation section consists of two columns, the high-high-pressure column and the low-high-pressure column. The high-high-pressure column operates at 0.5-0.6 MPa and receives cold air from the multi-stream heat exchanger. Two streams are obtained from this column: an upper stream consisting mainly of nitrogen (the lighter compound) and a lower product which is a mixture of nitrogen, oxygen and argon. The nitrogen stream is sent to the condenser/heater that connects the two columns. This equipment and the pressure difference between the columns allow them to be energetically integrated, letting the heat exchanger to function as a condenser for the high-high-pressure column and as a heater for the low-high-pressure column. A fraction of the liquid nitrogen obtained is used as reflux from the high-pressure column, and the rest is sent to feed the low-high-pressure column together with the lower product from the high-pressure column. From the low-pressure column (0.13-0.15 MPa), pure nitrogen (upper) and oxygen (lower) products are obtained. These two streams are used in the multi-stream heat exchanger for air cooling. The air separation unit typically consumes about 100 kWh/tN2.

As for other stages in the value chain, the unit cost of the air separation unit decreases as its capacity increases. In the case of cryogenic distillation, costs vary with respect to production capacity as shown in Figure 18. From a capacity of 750 tpd of N_2, the cost begins to stabilise at 133,000 USD/tpdN_2. Above a capacity of 1,000 tpd N_2 the cost stabilises at 114,500 USD/tpdN_2, and any further increase in capacity marginally reduces the unit cost.

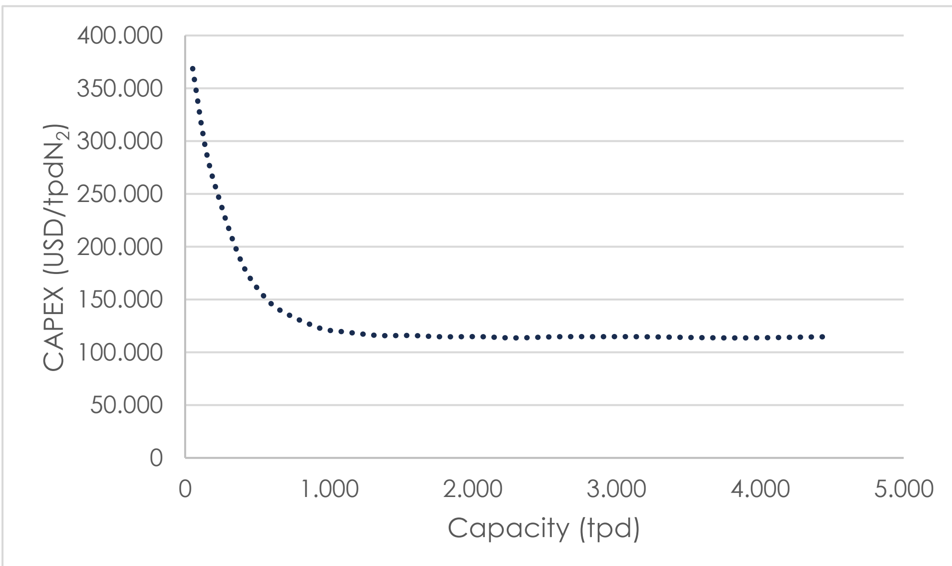

Figure 18. Cryogenic distillation unit cost vs. capacity (multiple sources)

2.4.2 Haber-Bosch Synthesis Process

The Haber-Bosch process is composed of five main stages:

1. Synthesis feed gas (nitrogen and hydrogen mixture) compression
2. Conversion of syngas into ammonia
3. Waste heat recovery, cooling and condensation of the converted gas.
4. Compression of recirculated gas (unconverted syngas).
5. Separation of the ammonia product

It is a peculiarity of this process that the conversion rate of each pass through the reactor is only 15%-20%. For this reason, an internal recirculation system is required to achieve a high overall conversion rate (up to 98%). A simplified diagram of the process can be seen in Figure 19.

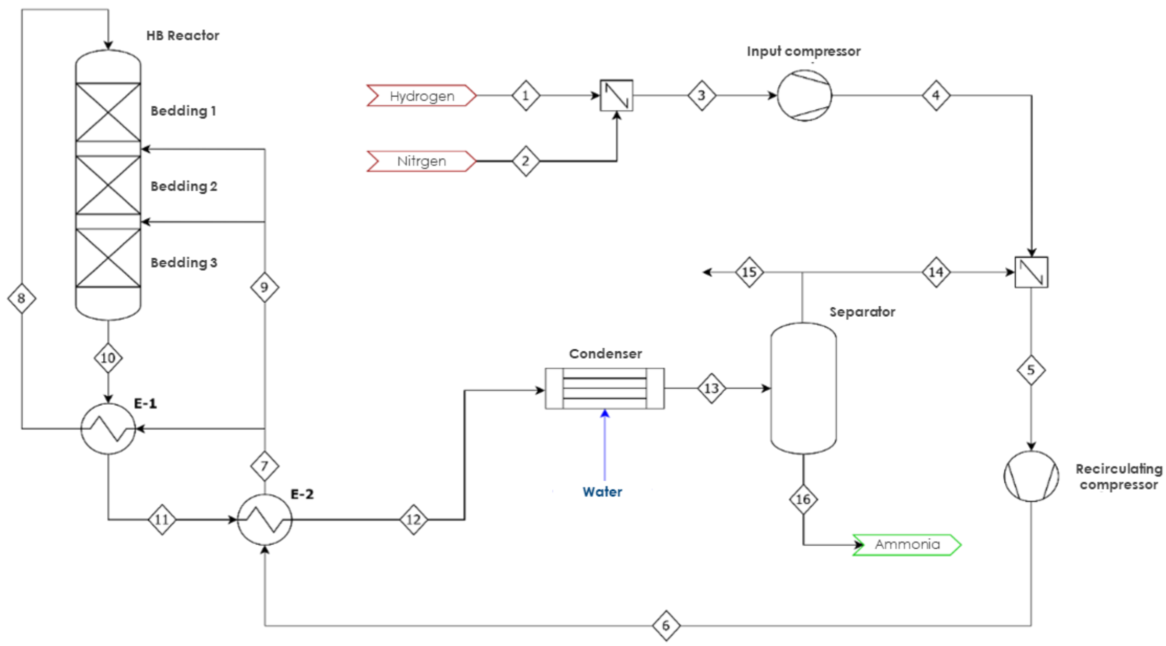

Figure 19. Simplified Haber-Bosch process diagram

First, nitrogen is mixed with hydrogen (syngas) at 30 barg. This syngas (3) feeds the multi-stage compressor (4), which compresses and mixes with the recirculation stream (14) containing the unconverted gas. Once the fresh feed and recirculation are mixed, the resulting stream (5) is compressed to syngas pressure ≈ 150 barg. Before entering the reaction section, the feed stream (6) is preheated through the E-2 heat exchanger and then split into a mainstream (8) and a cooled stream (9). The mainstream is heated in heat exchanger E-1 using reactor product (10), then enters the reaction section. It should be noted that the reaction step is composed of three beds. This is done in order to handle the exothermic behaviour of the reaction and increase the conversion of the process. Consequently, the products of beds 1 and 2 are cooled and diluted by mixing with a fraction of the cooled stream. The product from the reaction section is used to preheat the feed by heat exchangers E-1 and E-2 (heat integration). Subsequently, the product is cooled and condensed before entering the separation step (13), where liquid ammonia (≈99 wt%) and unconverted gases are separated. Finally, it is important to mention that it is not advisable to completely shut down a Haber-Bosch reactor in order to maintain its efficiency, avoid thermal stress of the equipment, preserve catalyst stability and prolong its useful life. For this reason, the reactor capacity cannot go below the minimum stable operating load, which is usually between 10% and 30% of its nominal capacity.

The efficiency of the Haber-Bosch process is approximately 98% H_2 conversion. The energy consumption of an ammonia production plant is variable and is between 0.5-2 MWh/tNH_3. Currently, there are plant designs with production capacities of between 4 - 6,000 tpd, and typical capacities of grey hydrogen-fuelled ammonia plants are 2,000 - 3,500 tpd (IRENA, Global Trade Hydrogen, 2022).

Table 6. Technical specifications Haber-Bosch process

	Unit	Value
Operating pressure	barg	80-250
Operating temperature	°C	350-550
Synthesis conversion	%	< 98
Power consumption	kWh/tNH_3	440
Molar ratio of syngas (H_2/N_2)	-	3
Syngas inlet pressure	barg	30
Hydrogen consumption	kgH_2/tNH_3	177
Nitrogen consumption	kgN_2/tNH_3	823
Turndown ratio	%	30
Heat generation	GJ/tNH_3	3.1
Lifetime	Years	30

Current developments are focused on increasing "flexibility" in new green ammonia plants. Several technology licenses are even offering reduction rates of 5-10% of nominal load while minimising the need for pressurised hydrogen storage.

Table 7. Current status of Haber-Bosch process and future improvements

Element	Current technology status	Future technology improvements
Ammonia Reactor	Exothermic process without requiring external heating to maintain temperature.	Electric heaters (resistors) to maintain the temperature in the ammonia synthesis reactor at low operating loads.
Ammonia Reactor	-	Use of surplus nitrogen as inert to maintain flow rates and pressure within the ammonia loop.
Ammonia Reactor	Fe catalyst	New catalysts such as ruthenium to reduce reactor operating pressure.
Synthesis and recycling compressor	Centrifugal compressors	Variable load compressors to reduce operating capacity.

Finally, the CAPEX of conventional ammonia production plants based on the Haber-Bosch process is strongly linked to plant capacity. Plants that have a typical current capacity (2,000 - 3,500 tpd) have approximate investment costs of between 87,000 - 152,000 USD/tpdNH_3 from what has been reported from literature. These costs include both the production unit and the auxiliary equipment necessary for plant operation. (IRENA, Global Trade Hydrogen, 2022).

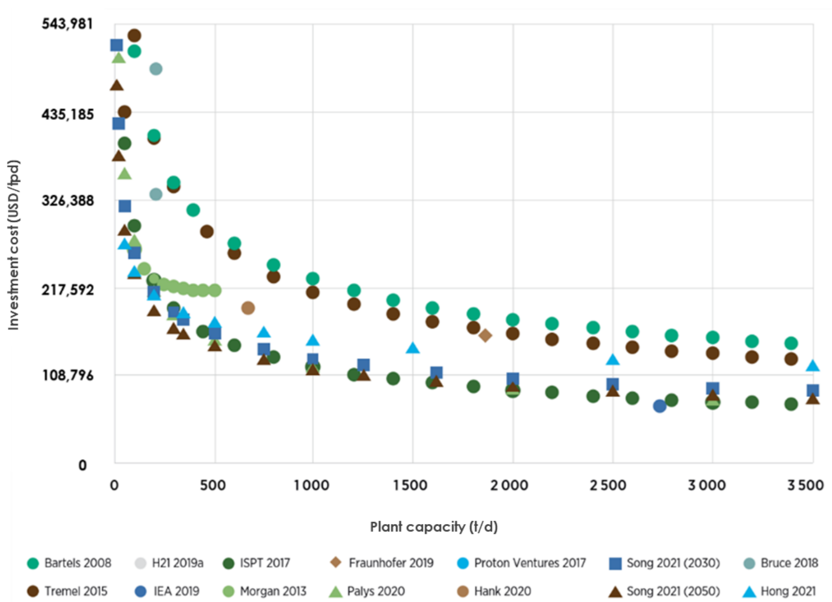

Figure 20. Specific CAPEX for Haber-Bosch plant (IRENA, Global Trade Hydrogen, 2022)

The specific CAPEX of a Haber Bosch plant is shown in Figure 20. When the capacity is greater than 500 tpd NH_3 the specific CAPEX drops from 218,000 USD/tpd NH_3. Above a capacity of 2,000 tpd NH_3 the specific CAPEX stabilises around 108,000 USD/tpd NH_3. This cost also contemplates all the equipment required to operate the plant.

2.5 Green Ammonia Distribution

Efficient transport and distribution of green ammonia are vital to maximise its positive environmental impact and economic viability. It is essential to consider both emerging technologies and international regulations, especially in Europe, where strict emission limits could affect the supply chain.

2.5.1. Current and Emerging Distribution Technologies

- **Traditional infrastructure:** Current networks of pipelines, terminals and storage tanks are essential for ammonia distribution. However, they must be inspected and adapted if necessary.

- **Specialised vessels:** There are vessels specifically designed for the transport of ammonia. Innovation in this sector could include ammonia or hydrogen-powered vessels, which would offer a zero-emission transport solution.

- **Land transport:** Conventional tanker trucks are used for land transport. Transitioning to electric or hydrogen-powered trucks could provide a viable decarbonization pathway for Mexico, taking advantage of its growth in electric vehicle production.

- **High-pressure container technology:** These containers allow the transportation of ammonia in liquid form at high pressure, which could facilitate its distribution and reduce the need for storage infrastructure.

2.5.2. Impact of distribution and transport emissions under EU Renewable Energy Directives

For ammonia produced in Mexico to be considered "renewable" under European directives, not only the net emissions from its production must be considered, but also the emissions associated with its distribution and transportation to its point of use in Europe.

Factors to consider:

1. Means of transport: the choice between ships, trucks and railroads, and the efficiency and technology of these, has a major impact on total emissions**.**

2. Distance: The transatlantic transport of ammonia from Mexico to Europe is a considerable distance that can add up to significant CO_2 emissions.

3. Storage and transhipment infrastructure: Emissions associated with intermediate storage and transhipment must also be considered.

4. Propulsion technology: If shipping uses conventional fossil fuels for propulsion, this will add significant emissions. Alternatively, ships using cleaner technologies or even ammonia as fuel could reduce this impact.

RED and RED II guidelines:

- EU directives set specific reductions for greenhouse gas (GHG) emissions from RFNBOs (Renewable Fuels of Non-Biological Origin). According to Article 25a of Directive (EU) 2018/2001[2], the reduction in emissions must be at least 70% compared to conventional fossil fuels. For ammonia, the associated emissions must be less than 720 $gCO_2eq/kgNH_3$ to be considered RFNBO.
- Any ammonia to be marketed in the EU as "green" or renewable must demonstrate that it meets these thresholds, considering the entire life cycle of the fuel, from production to consumption.

Recommendations for the Mexican sector:

1. Emissions transparency: It is essential to have a clear and verifiable record of emissions associated with the distribution and transportation of ammonia.

[2] https://eur-lex.europa.eu/legal-content/ES/TXT/HTML/?uri=CELEX:32018L2001#d1e3465-82-1

2. Innovation in transportation: Consider investments in ammonia-powered ships or clean technologies to reduce emissions associated with maritime transportation.

3. Strategic collaborations: Establish partnerships with European stakeholders to ensure that green ammonia produced in Mexico meets EU (end consumer) requirements and expectations.

For Mexico to be a leading exporter of green ammonia to Europe, it is imperative to consider not only production emissions, but also those associated with transportation and distribution. European directives on renewable energy technologies set high standards, and to meet them, careful planning and management along the entire supply chain are needed.

3. Power-to-X Project Optimisation: A Case Study in the Planning of a Green Ammonia Plant

Power-to-X projects are inherently complex, and establishing an optimal sizing process can be challenging. In these projects, it is essential to coordinate and fine-tune the interaction between the renewable energy plant, the electrolysis unit and the ammonia production facility. Each of these stages has an interconnected set of variables; the selection of any one of them can significantly alter the final system configuration.

Given the complexity of this process, some heuristic rules will be described that allow a very general estimation of the sizing of a Power-to-Ammonia project. The results obtained from these heuristic rules provide a CAPEX class 5 estimate according to the AACE[3] (Association for the Advancement of Cost Engineering) classification, which implies a deviation of the final cost of the project that is between -50% and -20%, at the lower limit, and +30% and +100% at the upper limit. Subsequently, the necessary steps to improve cost estimation and increase accuracy will be described.

The exercise to be carried out next will consider a plant with an annual production of 350 kilotonnes per year of green ammonia. Three configurations for the renewable energy plant will be considered: (1) solar photovoltaic only, (2) wind only and (3) hybrid. Additionally, the analysis will be complemented with a system where the electricity is supplied by the grid.

The general methodology to be followed is described in Figure 21. This methodology follows a bottom-up logic since it starts by finding the final demand of ammonia to be produced and from there goes backwards to estimate the required inputs and capacities needed to obtain that production. Each of the steps described in Figure 21 will be described in detail below.

[3] https://web.aacei.org/docs/default-source/toc/toc_18r-97.pdf?sfvrsn=4

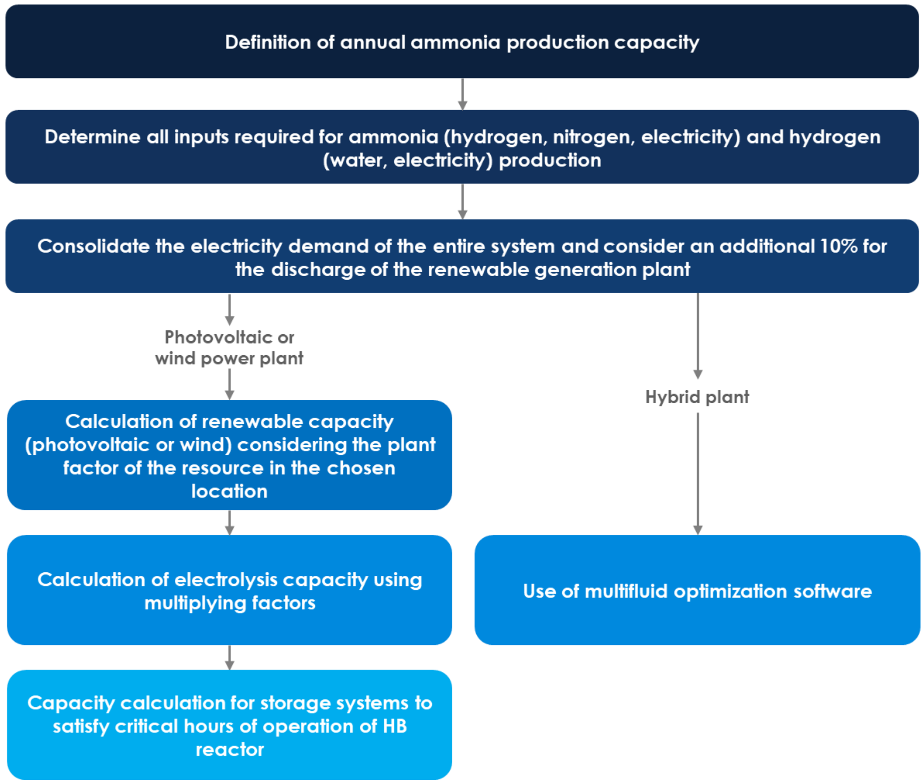

Figure 21. General methodology for Power-to-Ammonia system sizing

Ammonia synthesis plant

Typically, a conventional ammonia plant has a capacity factor of approximately 95%, operating 350 days per year. However, ammonia plants fuelled by renewable hydrogen and renewable electricity typically have a capacity factor of 80% because green ammonia plants are oversized to take advantage of peak times in renewable energy production. In addition, since ammonia plants are less CAPEX intensive than renewable energy plants, this oversizing strategy can reduce overall production costs.

$$Nominal\ capacity = \frac{Annual\ production}{80\%}$$

Considering the amount of ammonia to be produced and the capacity factor for the renewable case, the nominal capacity of the plant would be 438 kilotonnes per year.

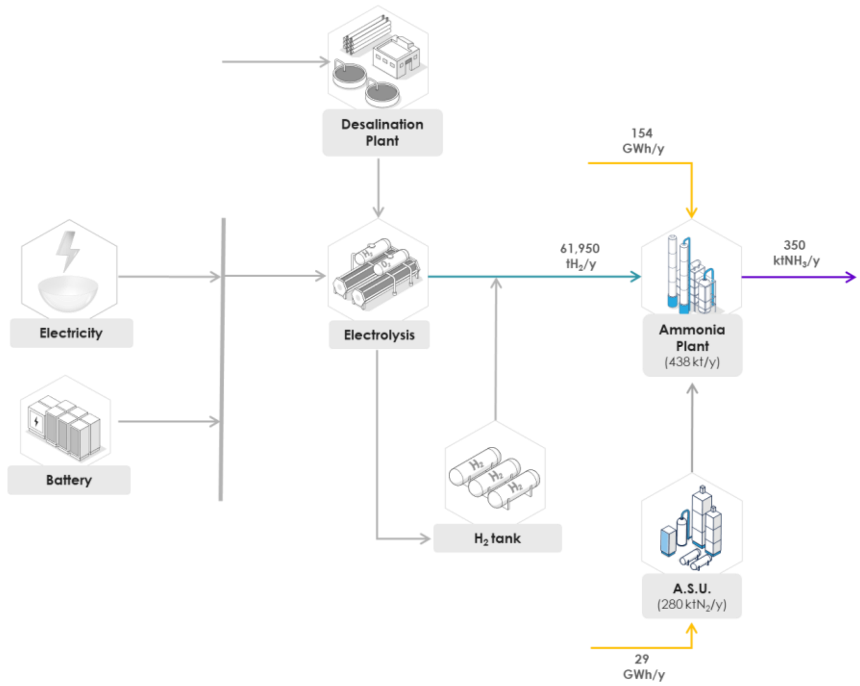

Figure 22. Ammonia synthesis plant capacities and operation

Based on the unit consumptions described in the previous section and the defined annual production, the Haber-Bosch synthesis plant requires 61,950 tons of hydrogen, 288,050 tons of nitrogen and 154,000 MWh of electricity each year. Additionally, 28,805 MWh of electricity are needed to operate the air separation unit, reaching a total electricity requirement of approximately 182,805 MWh per year. Table 8 summarizes the operational parameters of the ammonia synthesis.

Table 8. Operation of Haber-Bosch plant

	Unit	Value
Nominal Capacity	tNH_3/y	438,000
Capacity Factor	%	80
Annual production	tNH_3/y	350,000
Hydrogen consumption	tH_2/y	61,950
Nitrogen consumption	tN_2/y	288,050
Haber Bosch electricity consumption	MWh/y	154,000
Electric consumption ASU	MWh/y	28,805

Although the ammonia plant has relatively constant operating parameters in most Power-to-Ammonia projects, the same cannot be said for the other components in the value chain. The operation of the electrolyser and the renewable energy plant, as well as the storage systems, will depend largely on the characteristics of the available renewable resource and the type of plant configuration (PV, wind or hybrid). For this reason, the capacity factor for hydrogen production can vary greatly and be between 30% and 70%.

Figure 23. Location of the state of Tamaulipas in Mexico

To avoid the difficulty that implies the difference of the renewable resource in different locations, the sizing example below will take as a reference a representative location in the state of Tamaulipas. This state has the advantage of having both a good solar and wind resource (Figure 24). Multiple considerations can be used to make a high-level estimate of the renewable energy plant and the electrolysis plant. In addition, for electricity and hydrogen storage, the period in the typical year with the highest unavailability of renewable resources will be considered. The sizing criteria for these two components allows maintaining the operation of the Haber-Bosch plant at its technical limit (30%) as long as there is no availability of renewable resources.

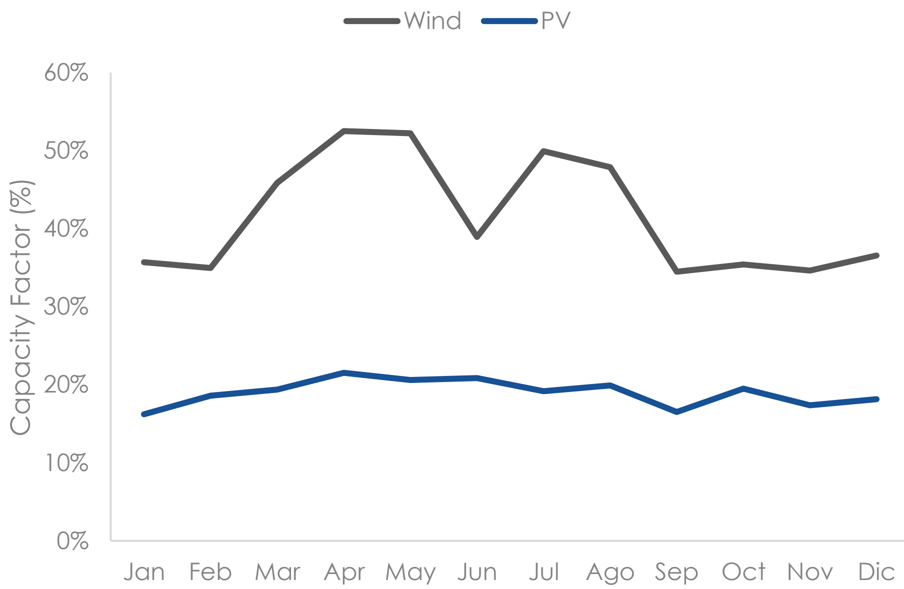

Figure 24. Capacity factor for wind and solar PV resource at an arbitrary point in the state of Tamaulipas

Although the following example considers factors specific to the state of Tamaulipas to illustrate how to perform a high-level estimation, it is essential to emphasise that the detailed sizing of a Power-to-Ammonia project must consider the characteristics of the renewable resource at the site where the project is to be developed. It is helpful to have renewable resource data that represent a typical year and have hourly resolution. The steps necessary to achieve a more accurate estimation of project costs will be detailed later in Chapter 4.1.

Electricity Consumption

The first step in sizing a Power-to-Ammonia system is to calculate the power consumption of the entire system. In addition to the electricity consumption of the ammonia synthesis plant (including ASU), the electricity consumption of the electrolyser and the desalination plant must be considered:

$$Electricity\ consumption\left(\frac{MWh}{y}\right) = Consumption_{HB} + Consumption_{ASU} + Consumption_{EZ} + Consumption_{Desal.}$$

For the electricity consumption of the electrolyser, an efficiency of 63% is considered, which corresponds to an energy consumption of 53 kWh for each kilogram of hydrogen produced. In addition, the electricity consumption of the desalination plant is 3.5 kWh per cubic meter of water. If it is considered that for each ton of hydrogen 15 cubic meters of water are required and that the hydrogen requirement is 61,950 tons per year, the annual electricity consumption of the system is 3,470 GWh/year. This value will be the starting point for sizing the remaining components of the system.

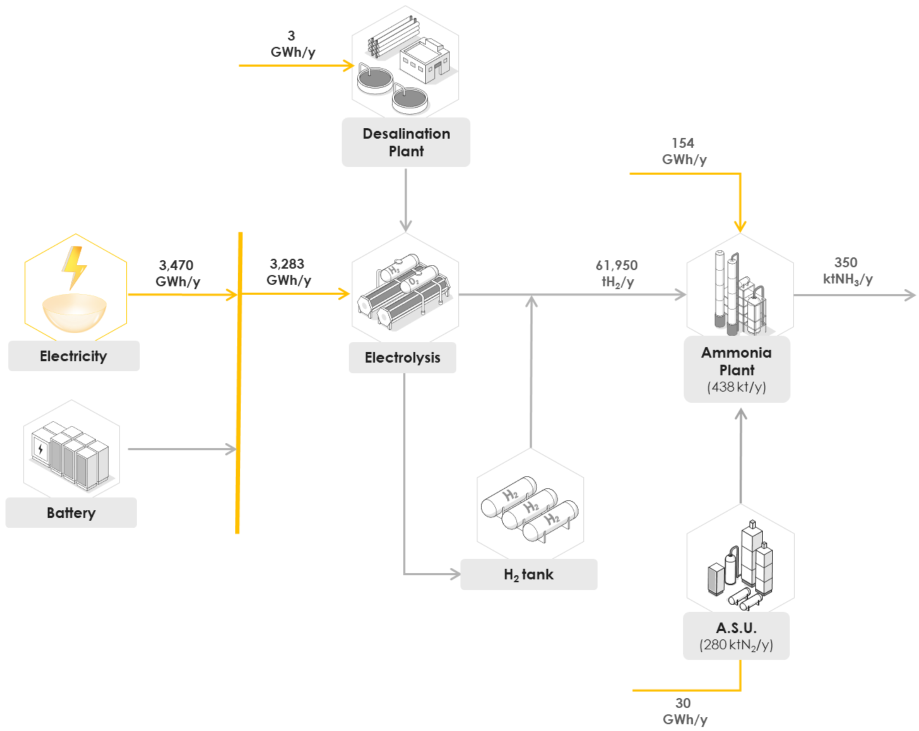

Figure 25. Power demand of the Power-to-Ammonia system

Photovoltaic power plant

After analysing the resource in the chosen location, it has been found that the typical Capacity Factor for photovoltaic installations in the state of Tamaulipas is approximately 20%. Additionally, it should be considered that these plants have curtailment, since they usually produce more energy than the one demanded by the system. Curtailment levels depend on the specific project configuration, but for the sizing example, a reference value of 10% of the system demand will be taken. Considering the capacity factor, the electricity demand and the discharge, the capacity of the photovoltaic plant can be estimated with the following equation:

$$Capacity_{PV}(MW_P) = \frac{1.1 \times Electricity\ demand\ (MWh)}{FP_{PV} \times 8769\ (h)}$$

For the present case, the PV capacity is 2.18 GW. Once this value is obtained, a multiplicative factor can be used to find the electrolyser capacity. This factor considers that the renewable energy plant will not be producing electricity constantly (in the solar case, only during the day) and sizes the electrolyser considering this constraint. For the selected location in the state of Tamaulipas, this factor has a value of 1.7 but can be between 1.5 and 1.9 for other locations with a different solar resource.

$$\frac{Capacity_{PV}}{Capacity_{EZ}} = 1.7$$

With this relationship, it is found that an electrolysis capacity of approximately 1.28 GW is required. Furthermore, knowing the electrolysis capacity and the hydrogen to be produced, the expected annual capacity factor for the electrolyser can be calculated:

$$FC_{EZ} = \frac{Hydrogen\ mass\ (kg) \times LHV \left(\frac{kWh}{kg}\right)}{Electrolysis\ capacity\ (MW) \times Efficiency \times 1{,}000 \times 8760(h)}$$

In this case, considering that the lower heating value (LHV) of hydrogen is 33.33 kWh/kg, the equation allows calculating a capacity factor of 29%.

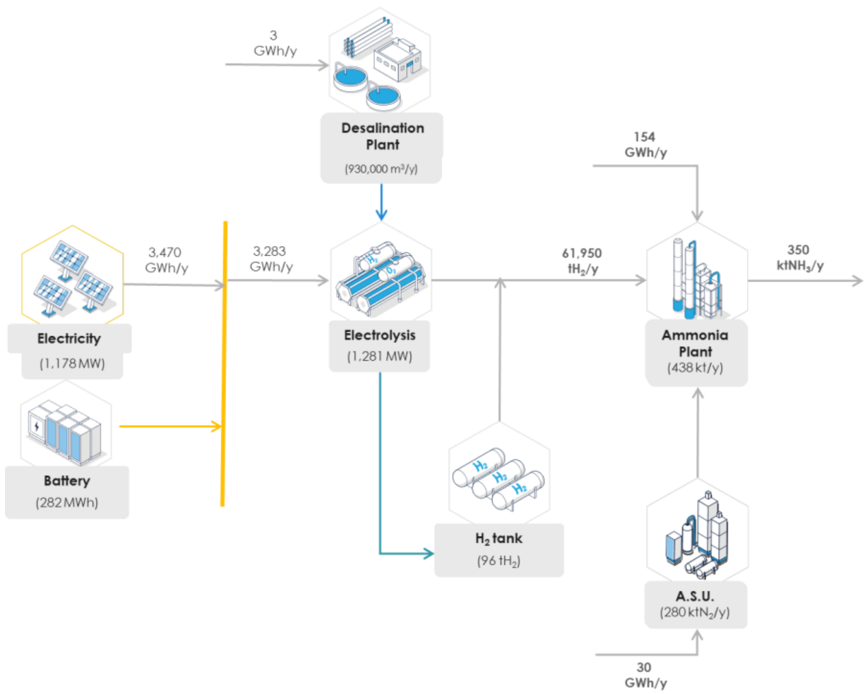

Figure 26. Capacities for photovoltaic configuration

To complement the system, a battery system and a hydrogen storage tank are required to allow the ammonia plant to operate at its technical limit during the hours when renewable generation is not sufficient. Based on the typical year for the point in the state of Tamaulipas, it has been found that there is a period of approximately 3 days with insufficient solar resources. To simplify the calculation, it has been considered that the storage systems should be able to keep the ammonia plant operating for three days. Under this simplification, a battery system and a hydrogen storage tank capable of keeping the plant producing for approximately 36 hours would be required. Considering the minimum stable operating load of 30%, which corresponds to 15 tNH_3/h for the present example, the 36-hour period and the unit consumption of electricity and hydrogen, the following equations can be used to estimate the size of the corresponding energy and hydrogen storage.

$$BESS\ capacity\ (MWh) = HB\ technical\ minimum \left(\frac{tNH_3}{h}\right) \times Time(h) \times Unit\ electricity\ consumption \left(\frac{MWh}{tNH_3}\right)$$

$$H_2\ Tank\ capacity\ (tH_2) = HB\ technical\ minimum\ \left(\frac{tNH_3}{h}\right) \times Time(h) \times Unit\ electricity\ consumption\left(\frac{tH_2}{tNH_3}\right)$$

This allows estimating a battery system of 282 MWh and a hydrogen storage tank of 96 tons. Table 9 shows a summary of the capacities, efficiencies, capacity factors and productions for the case where there is only one photovoltaic power plant.

Table 9. Dimensions for photovoltaic configuration

	Unit	Value
PV Capacity Factor	%	20
PV Capacity	MW	2,178
PV Plant Discharge	MWh/y	347
PV Capacity/EZ Capacity	-	1.7
Electrolyser capacity	MW	1,281
Electrolyser Capacity Factor	%	29
BESS Capacity	MWh	282
H2 tank capacity	tH_2	96
Hydrogen production	tH_2/y	61,950
Electrolyser electricity consumption	MWh/y	3,283,350
Water consumption	m^3	929,250

Wind Power Plant

After analysing the resource in the chosen location, it has been found that the typical capacity factor for photovoltaic installations in the state of Tamaulipas is approximately 35%. Like the solar case, a discharge of 10% of the electricity demand of the system is considered in the wind case. Thus, considering the capacity factor, the electricity demand, and the discharge, the capacity of the wind plant can be estimated with the following equation:

$$Capacity_{PV}(MW_P) = \frac{1.1 \times Electricity\ demand\ (MWh)}{FP_{WIND} \times 8769\ (h)}$$

For the present case, it is obtained that the wind capacity is 1.24 GW. Once this value is obtained, a multiplicative factor can be used to find the electrolyser capacity. Similar to the photovoltaic case, in the wind case this factor takes into account the variability in renewable resources. For the selected location in the state of Tamaulipas this factor has a value of 1.6 using a wind renewable plant but may range from 1.4 to 1.8 for other locations with a different wind regime.

$$\frac{Capacity_{WIND}}{Capacity_{EZ}} = 1.6$$

With this relationship, it is found that an electrolysis capacity of approximately 778 MW is required. Furthermore, knowing the electrolysis capacity and the hydrogen to be produced, the expected annual capacity factor for the electrolyser can be calculated with the same equation used in the solar case. In the case of a wind-only renewable plant, the capacity factor for the electrolyser will be 48%.

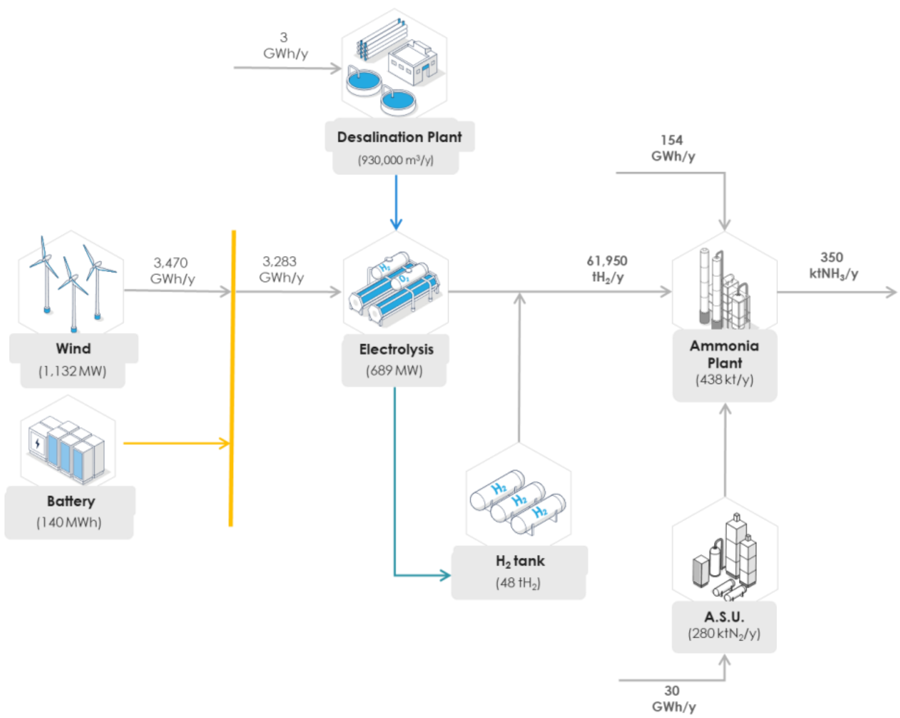

Figure 27. Capacities for wind configuration

Additionally, from an analysis like the one presented in the photovoltaic configuration section, the typical year of the wind resource shows that storage systems are required to keep the ammonia plant in operation for approximately 18 hours. Using the same equations presented in the previous section, a 140 MWh battery system and a 48 ton hydrogen storage tank are obtained. Table 10 shows a summary of the capacities, efficiencies, capacity factors, and productions for the case where there is only one photovoltaic power plant.

Table 10. Dimensioning for wind configuration

	Unit	Value
Wind Capacity Factor	%	35
Wind capacity	MW	1,132
Wind plant discharge	MWh/y	347
Wind capacity/EZ capacity	-	1.6
Electrolyser capacity	MW	689
Electrolyser Capacity Factor	%	54
BESS capacity	MWh	140
H2 tank capacity	tH_2	48
Hydrogen production	tH_2/y	61,950
Electrolyser electricity consumption	MWh/y	3,283,350
Water consumption	m^3	929,250

Hybrid power plant

Unlike plants that rely solely on solar or wind energy, Power-to-X installations that harness a combination of renewable energy technologies present significantly greater complexity. This complexity is due to the need to manage and optimise multiple energy and material flows, which makes it unfeasible to apply simple approximate factors typical in simpler systems. To reach an optimal solution, it is necessary to consider a wide range of factors, both technical and economic. The interaction between continuous and discrete variables, the integration of intermittent renewable energy sources, variability in product demand and the need to comply with environmental constraints add additional layers of complexity. Therefore, the use of specialised multifluid system optimisation software capable of handling this complexity through advanced optimisation techniques becomes essential. In this context, and to illustrate these concepts practically, the sizing of the hybrid plant described below is based on the results obtained using the specific software developed internally by Hinicio, called ANDREA. This approach makes it possible to effectively address the optimisation challenges inherent to Power to X projects, ensuring solutions that maximise system efficiency.

For the renewable resource specific to the considered location in the state of Tamaulipas (see assumptions in preceding sections on PV and wind configuration sizing), the electrolyser size was found to be 575 MW after optimisation. For each equipment, technical-economic parameters were determined, ranging from costs and discount rates to operational aspects, such as minimum production capacities of the plants.

An operational profile was used for each equipment represented through time series with 8760 data points corresponding to the hours of the typical meteorological year. Factors considered include equipment sizes, equipment utilization, production, consumption and discharge, storage usage, as well as equipment CAPEX and OPEX.

This detailed approach allows optimising the sizes of the complete project value chain, ensuring an efficient operation of green hydrogen production considering the intermittency of renewable sources and demand needs throughout the year.

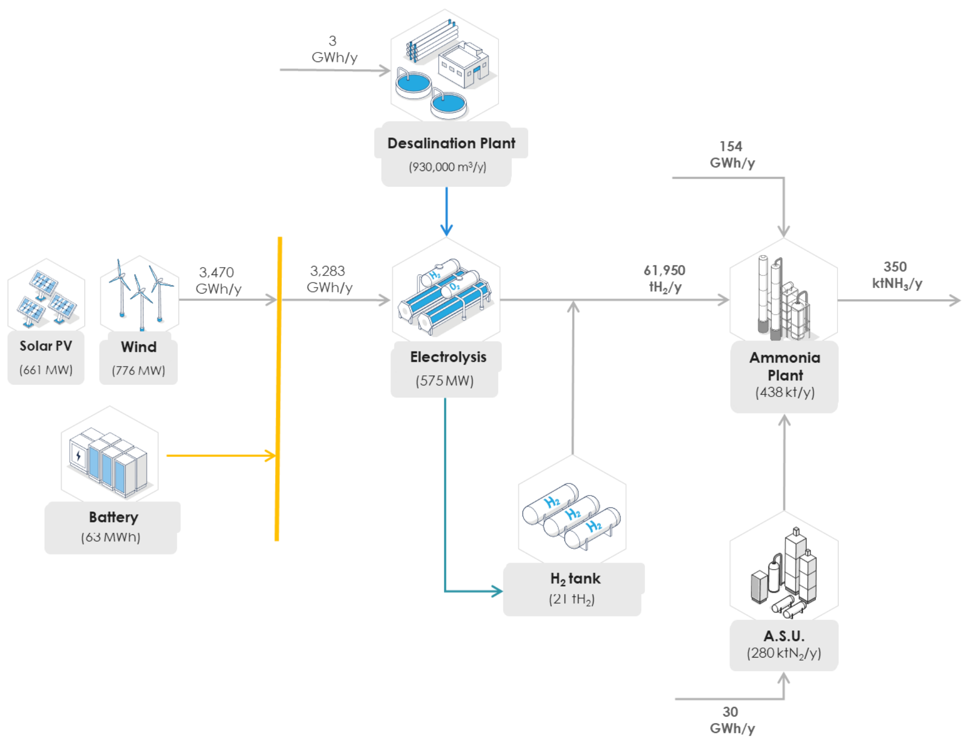

Figure 28. Capabilities for hybrid configuration

Using the same equation used in the preceding sections, the capacity factor can be calculated, and a value of 65% can be obtained. In general, the capacity factor of an electrolyser powered by a hybrid renewable plant is higher than that powered by a solar or wind only plant. In addition, the following relationships between renewable plant capacity and electrolysis capacity were found:

$$\frac{Capacity_{PV}}{Capacity_{EZ}} = 1.15 \qquad \frac{Capacity_{WIND}}{Capacity_{EZ}} = 1.35$$

With the calculated values, a total renewable energy capacity of 1.44 GW is obtained, divided into a photovoltaic farm of 660 MW and a wind farm of 780 MW. Additionally, the same analysis that was carried out in the previous sections was performed in this case to size the different system storages. It was found that the mix of solar and wind generation further reduces the period of electric power unavailability and that the battery and hydrogen storage system should be sufficient to keep the ammonia plant operating at its minimum stable operating load for 8 hours. From the equations presented in the photovoltaic sizing section, it is obtained that the hybrid plant requires a battery system of 63 MWh and a hydrogen tank of 21 tons. Table 11 shows a summary of the capacities, efficiencies, capacity factors and productions for the case where only one photovoltaic power plant is available.

Table 11. Sizing for hybrid configuration

	Unit	Value
Wind Capacity Factor	%	35
PV Capacity Factor	%	20
Renewable plant discharge	MWh/y	70
Electrolyser capacity	MW	575
Capacity factor electrolyser	%	65
Wind capacity/EZ capacity	-	1.35
Wind capacity	MW	776
PV Capacity/EZ Capacity	-	1.15
PV capacity	MW	661
BESS Capacity	MWh	63
H2 tank capacity	tH_2	21
Hydrogen production	tH_2/y	61,950
Electricity consumption	MWh/y	3,283,350
Water consumption	m^3	929,250

The first two exercises, which address the use of solar and wind resources independently, provide an initial overview using heuristic rules that simplify the analysis. These preliminary approaches are useful for gaining a basic understanding of the feasibility and challenges associated with each renewable energy source separately. However, the approach taken in the third exercise, involving system optimisation, represents the most appropriate methodology for these initial phases of development.

This optimisation approach considers the inherent complexity of integrating multiple renewable energy sources, allowing for a more accurate and holistic assessment of the project. By employing optimisation models, optimal configurations that maximise system efficiency and profitability can be identified, considering factors such as variability of power generation, production demand, and interactions between different components of the value chain.

To better understand the effect of renewable resources and the interaction between the different components of the green ammonia value chain, the following graphs illustrating an average day of operation are presented. Figure 29 shows the behaviour of a renewable energy plant with a high complementarity between solar and wind resources, allowing a relatively constant electricity supply throughout the day. It is also possible to identify two hours where there are minimums in the energy supply: 8:00 and 17:00. These hours correspond, respectively, to sunrise, when solar production increases and wind production decreases, and sunset, when the opposite occurs.

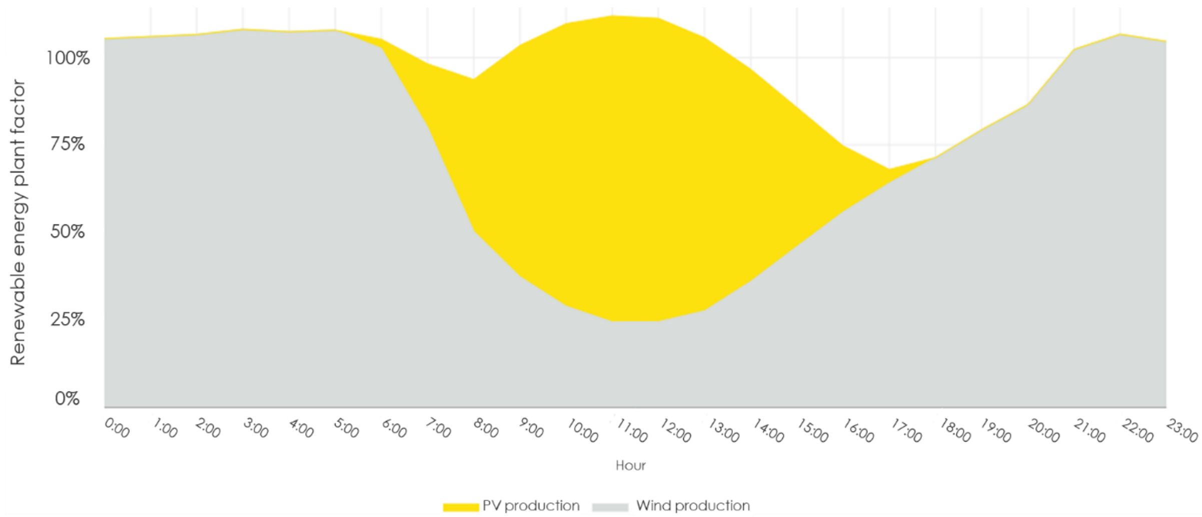

Figure 29. Renewable Energy Capacity Factor for typical operating day[4]

These two baselines for renewable energy supply correspond to the baselines for hydrogen production (Figure 30) and ammonia production (Figure 31). The result of these production minima is that in the immediately subsequent hour there is a considerable reduction in the state of charge of the hydrogen tank (Figure 30) and the battery system (Figure 31). Additionally, the storage systems take advantage of the energy available in the hours before the two indicated minimums, reaching their maximum state of charge to support the reduction in renewable energy production.

[4] Figures 29, 30, and 31 obtained from ANDREA software (Advanced Energy System Modelling and Analytics)

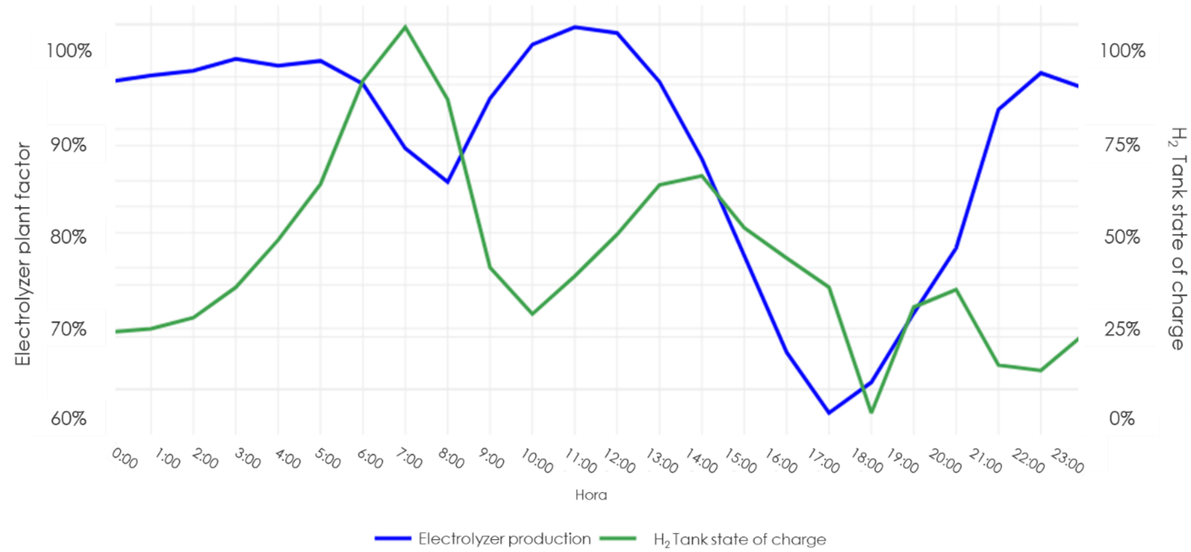

Figure 30. Electrolyser Capacity Factor and hydrogen storage state of charge for typical operating day

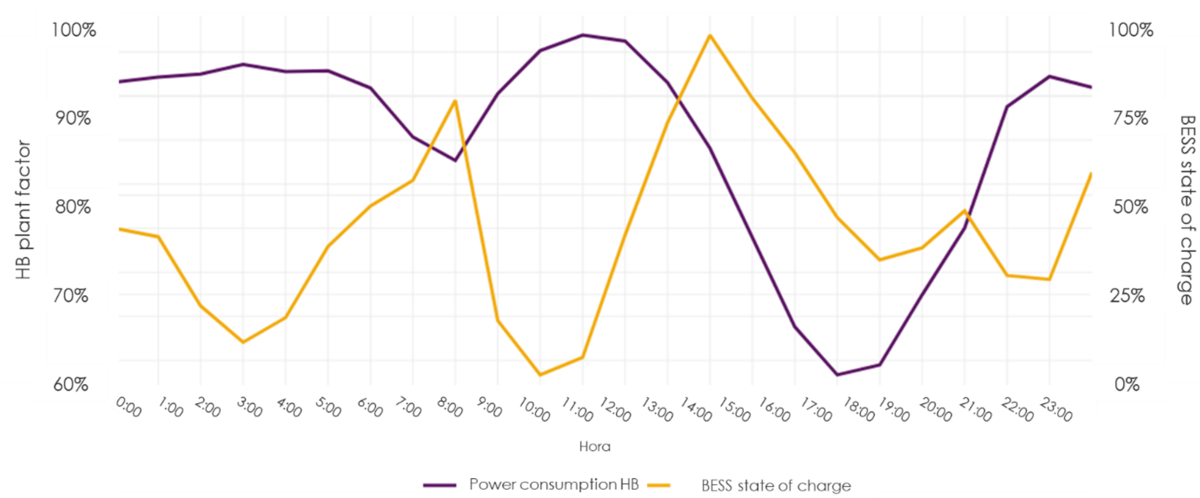

Figure 31. HB Capacity Factor and BESS state of charge for typical operating day

In addition, it is important to note that on the typical day the capacity factor of both the electrolyser and the ammonia reactor does not go below 60%. This indicates that the storage can be relatively small due to the high complementarity between solar and wind resources. Thus, a good complementarity between the solar and wind resource will allow an efficient operation of the entire value chain and will significantly reduce the costs associated with the project.

Plant supplied by electricity from the grid.

Lastly, an example of sizing for an ammonia production system from electrolytic hydrogen with electricity supplied from the grid will be presented. The result obtained will be strongly influenced by the price at which this electricity is purchased. For different locations in Mexico, the price of electricity for industrial consumption can vary between 1,200 MXN/MWh and 2,400 MXN/MWh (66 USD/MWh and 133 USD/MWh) depending on the location and the month being considered (CFE, 2023). For the example below, a price at the lower limit of 65 USD/MWh will be considered.

Considering that this configuration does not depend on the intermittency of the renewable resource, capacity factors of 100% are assumed for both the electrolyser and the ammonia synthesis plant. With this assumption, a Haber-Bosch reactor with a capacity of 350,000 tpa and an electrolyser with a capacity of 374 MW can be obtained. The capacities, specifically those of the electrolyser, are considerably lower than for the cases fed with renewable energy. However, the economic analysis in the next section will allow us to check if this reduction implies lower levelized ammonia costs.

Table 12. Assumptions and sizing for mains powered configuration.

	Unit	Value
Electricity cost	USD/MWh	65
Electrolyser capacity	MW	374
Ammonia synthesis plant capacity	tNH_3/y	350,000

Desalination plant

To size the desalination plant, capacities are considered that can supply the demand of each of the electrolysers calculated above when they are working at their nominal capacity. To calculate the water consumption required for hydrogen production for one hour, the following equation can be used:

$$Water\ consumption\left(\frac{m^3}{h}\right) = \frac{Capacity_{EZ}(MW_e) \times Efficiency_{EZ} \times Unit\ water\ consumption\left(\frac{m^3}{tH_2}\right)}{LHV\left(\frac{MWh}{tH_2}\right)}$$

Additionally, the electricity consumption of a desalination plant is considered to be approximately 3.5 kWh/m3. Table 13 shows the capacity of the desalination plant for each of the four cases previously considered.

Table 13. Desalination plant sizing

Electricity configuration	PV	Wind	Hybrid	Power grid
Electrolysis capacity (MW)	1,281	778	575	374
Desalination plant capacity (m3/h)	330	195	165	105
Hydrogen production (tH2/year)	61,950			
Electrolysis water production (m3/year)	929,250			
Electricity consumption (MWh/year)	3,250			

At this point, it is worth noting that most of the electricity consumption in the entire value chain is represented by the electrolysis plant. For the present example, the electrolysis plant consumes approximately 3,300 GWh in a year, which implies a consumption 20 times higher than the ammonia synthesis plant and 1,000 times higher than the consumption of the desalination plant.

Finally, Table 14 shows a summary of the results obtained in the sizing of the different configurations. These results show that the ammonia plant with smaller equipment and higher Capacity Factors is the one powered by a hybrid renewable energy plant.

Table 14. Sizing summary for different configurations

Capacity	PV	Wind	Hybrid	Power grid
Renewable plant (MW)	2,178	1,245	1,440	-
Battery system (MWh)	282	140	63	-
Desalination plant (m3/h)	330	195	165	105
Electrolyser (MWe)	1,281	778	575	374
EZ Capacity Factor (%)	32	54	65	100
Hydrogen tank (tH2)	96	48	21	-
Ammonia synthesis plant (KTPY)	437.5	437.5	437.5	350

Alternatively, the configuration with a solar plant requires further oversizing to compensate for the scarcity of the resource during non-solar hours. Finally, the sizing of a grid-connected non-green ammonia plant is shown for reference. These sizes will have an important effect on project costs, as will be seen in the next section.

4. Economic Analysis of the Project

From the capacities calculated in the previous section, the costs of the project examples considered can be estimated. The following financial assumptions were considered for this economic analysis:

Table 15. Financial assumptions

	Unit	Value
Discount rate	%	8
Useful life	years	30
Indirect costs[5]	%	20
Indirect costs electrolyser	%	30

[5] This component includes additional costs associated with engineering, integration and project development contingencies.

Table 16 summarises the unit costs assumed for the different equipment for the economic analysis of the example project.

Table 16. Techno-economic assumptions for economic analysis[6]

Photovoltaic plant		
CAPEX	kUSD/MW	650
OPEX	% CAPEX	1.5
Wind power plant		
CAPEX	kUSD/MW	1,100
OPEX	% CAPEX	3
Battery System (BESS)		
CAPEX	kUSD/MWh	350
OPEX	%CAPEX	3
Desalination plant		
CAPEX	kUSD/m^3/h	30
OPEX	%CAPEX	3
Electrolysis plant		
CAPEX	kUSD/MW	800
OPEX	% CAPEX	3
Hydrogen storage tank		
CAPEX	kUSD/tH_2	600
OPEX	%CAPEX	4
Ammonia plant		
CAPEX	kUSD/tph	4,500
OPEX	% CAPEX	5

[6] CAPEX refers to installed CAPEX.

The unit costs for CAPEX and OPEX, as well as the calculated capacities, allow the calculation of the levelized cost (LCOX) for electricity (LCOE), hydrogen (LCOH) and ammonia (LCOA) using the following equations:

$$LCOE = \frac{\sum_{t=0}^{t} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=0}^{t} \frac{MWh_t}{(1+r)^t}} \quad LCOH = \frac{\sum_{t=0}^{t} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=0}^{t} \frac{kgH2_t}{(1+r)^t}} \quad LCOA = \frac{\sum_{t=0}^{t} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{t=0}^{t} \frac{tNH3_t}{(1+r)^t}}$$

Where:

$CAPEX_t = investment\ cost\ year\ t$
$OPEX_t = O\&M\ cost\ year\ t$
$t = year$
$r = discount\ rate$
$MWh_t = electricity\ production\ year\ t$
$kgH2_t = hydrogen\ production\ year\ t$
$tNH3_t = ammonia\ production\ year\ t$

It should be noted that the battery system costs are included in the LCOE and the hydrogen storage costs in the LCOH. Based on the estimated sizes, techno-economic assumptions and the levelized cost equations, the following results are obtained for each of the 4 configurations.

Table 17 shows the costs considered to calculate the levelized cost of energy (LCOE) for the PV plant, the wind plant, the hybrid plant and the grid electricity.

Table 17. Levelized cost of energy (LCOE)

		PV	Wind	Hybrid	Power grid
	Unit	Value			
CAPEX	MUSD	1,514	1,418	1,306	-
Indirect costs	MUSD	303	284	261	
OPEX	MUSD/y	24.2	42.6	32.7	
Electricity production	MWh/y	3,820,000	3,820,000	3,540,000	3,470,000
LCOE	USD/MWh	48.6	50.8	48.6	65

Table 18 shows the costs considered to calculate the levelized cost of water for the photovoltaic plant, the wind plant, the hybrid plant and the grid electricity.

Table 18. Water levelized cost

		PV	Wind	Hybrid	Power grid
	Unit	Value			
CAPEX	MUSD	9.9	5.9	4.9	3.2
Indirect Costs	MUSD	2	1.2	1	0.6
OPEX	kUSD/y	298	176	147	95
Electricity	kUSD/y	159	166	158	211
Water production	m^3/y	929,250			
Water levelized cost	USD/ m^3	1.6	1.0	0.9	0.7

From the levelized cost of energy and water, the levelized cost of hydrogen (LCOH) can be calculated by taking the corresponding costs for the electrolysis plant as shown in Table 19.

Table 19. Levelized Cost of Hydrogen (LCOH)

		PV	Wind	Hybrid	Power grid
	Unit	Value			
CAPEX[7]	MUSD	1,082	623	473	299
Indirect costs	MUSD	325	187	142	90
OPEX	MUSD/year	33	19.8	14.3	9
Electricity	MUSD/year	160	167	160	213
Water	MUSD/year	1.5	0.9	0.8	0.6
Hydrogen production	tH_2/year	61,950			
LCOH	USD/kgH_2	4.7	3.7	3.7	4.2

Finally, the levelized cost of ammonia (LCOA) can be calculated from the corresponding ammonia plant costs and the levelized hydrogen and energy costs, as shown in Table 20.

Table 20. Levelized cost of ammonia (LCOA)

		PV	Wind	Hybrid	Power grid
	Unit	Value			
CAPEX Haber Bosch	MUSD	225			180
Indirect costs	MUSD	45			2.7
OPEX	MUSD/y	11.2			9
Electricity	MUSD/y	8.9	9.3	8.9	11.9
Hydrogen	MUSD/y	319	259	229	258
Hydrogen production	tNH_3/y	350,000			
LCOA	USD/tNH_3	≈ 1,040	≈ 870	≈ 780	≈ 840

[7] Includes electrolyser and hydrogen storage tank.

When evaluating the levelized costs of energy (LCOE), hydrogen (LCOH) and ammonia (LCOA) for the different plant configurations (photovoltaic, wind, hybrid and grid), the hybrid configuration emerges as the most cost-effective, evidencing the synergy between solar and wind energy in the production of green ammonia.

Detailed analyses reveal that CAPEX represents a substantial portion of the total cost, approximately 75%, for all configurations. This finding reinforces the need for innovative financing strategies to mitigate the initial impact of investment in Power-to-X projects. On the other hand, OPEX, although lower in comparison, remains a crucial factor for the long-term economic sustainability of these technologies.

The detailed analysis of the Levelized Cost of Ammonia (LCOA) reveals significant differences in the costs associated with ammonia production in each of the scenarios evaluated, underlining the decisive influence of the energy source on the cost structure. It is observed that the configuration that relies exclusively on solar photovoltaic energy incurs the highest production costs due, in part, to the inherent variability of this energy source and the need for storage or backup systems that increase the initial (CAPEX) and operating (OPEX) expenditure. On the other hand, the hybrid configuration, which combines solar and wind energy, manages to minimise ammonia production costs, taking advantage of the complementarity of these renewable sources to ensure a more stable and efficient energy generation. **It is crucial to note that the data presented is based on a hypothetical study designed to illustrate a calculation methodology and the impact of different energy configurations on ammonia production costs. Therefore, these results should not be interpreted as absolute cost references for the region analysed.**

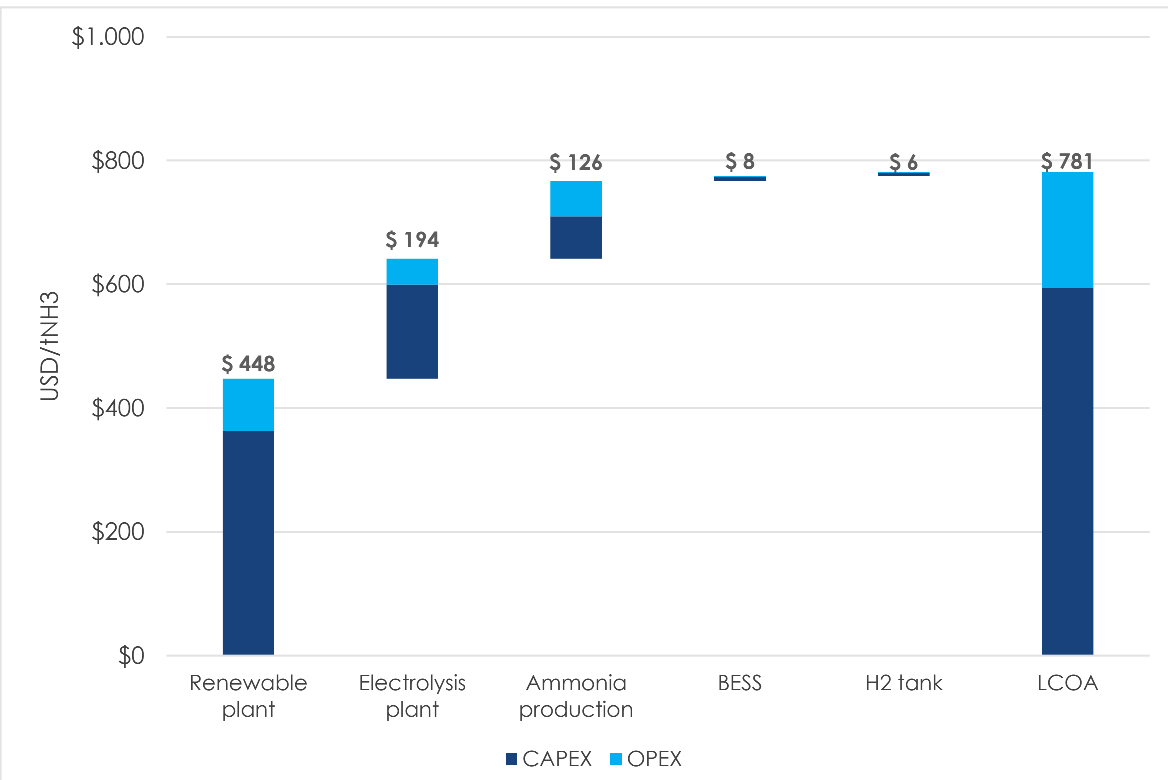

Figure 32. Waterfall plot for hybrid configuration

Figure 32 illustrates how the different components of the levelized cost of ammonia are distributed. The figure shown takes the values of the hybrid configuration, but the other two configurations fed with renewable energy present a very similar behaviour. The graph shows that the component with the greatest weight in the levelized cost of ammonia is the renewable energy plant, which represents approximately 57% of the total cost. In contrast, the ammonia synthesis plant has a considerably lower contribution and represents only 16% of the total cost. In addition, the CAPEX component contributes approximately 75% of the total cost, evidencing how the Power-to-X projects are capital intensive.

Finally, the results in Table 20 show that the wind-powered configuration has almost the same costs as the grid-powered configuration. In the previous section, it was seen how grid supply allows equipment with lower capacities and, therefore, reduces the investment costs of the project. However, even using a relatively low cost of electricity for Mexico (65 USD/MWh), the levelized cost of energy with renewable plants is lower (Table 17). For the grid-fired configuration to reach a price comparable to the hybrid configuration, an LCOE of 59 USD/MWh is required. The fact that renewable energy can achieve competitive prices demonstrates the virtues of developing this type of project with clean energy. On the other hand, the carbon intensity of the electricity matrix in Mexico is relatively high (300 gCO_2eq/kWh[8]) and would imply a footprint of 16 $kgCO_2/kgH2$ for electrolytic hydrogen produced with grid electricity (this would be higher than the 9 $kgCO_2/kgH2$ emitted with traditional steam methane reforming production). For this reason, the use of grid electricity would imply, in addition to higher CO_2 emissions, an increase in costs when considering federal or state carbon taxes, as well as those applicable to products for export.

4.1. Development of a Detailed Cost Estimation Methodology

The key to more accurate and reliable cost estimating lies in the detailed breakdown of the project into manageable subsystems and components. This approach allows the complexities and interactions between different elements of the project to be addressed more effectively. According to the Association for the Advancement of Cost Engineering (AACE), achieving a level of accuracy that is within a range of -15% to +30% for new projects requires a thorough and comprehensive understanding of every aspect of the project.

Development of Essential Engineering Deliverables

To achieve this degree of accuracy, it is imperative to develop and utilise several engineering deliverables, including:

- Site plans and process flow diagrams, which offer a clear view of the project layout and operation.
- Mass and energy balances, process equipment lists and general equipment layout diagrams, essential for understanding the project's technical requirements and specifications.
- Project schedules and work breakdown structures, which facilitate efficient planning and resource allocation.

Systematic Cost Estimating Methodology

To move from a preliminary estimate to a more accurate estimate, a systematic method is proposed that includes the following steps:

[8] Climate Transparency Report 2022

1. Location and Resource Assessment: Select potential sites and evaluate renewable resources, land suitability, and proximity to consumption centres. This initial phase is crucial to identify project requirements and constraints.

2. Define Technical Assumptions: Technically specify and obtain quotes for critical equipment. This step improves accuracy by focusing on the components with the greatest impact on CAPEX.

3. Preliminary Analysis and Scenario Selection: Use simulation tools to evaluate and improve project scenarios, enabling informed selection of the most viable configuration.

4. Sensitivity Study: Modify key variables to understand their impact on the project configuration, providing a basis for adjustments and optimisations.

5. Determination of the Optimal Configuration: Iterate on options to minimise the total annualised cost, ensuring the technical and economic feasibility of the project.

This methodology, which integrates the preparation of engineering documents, allows not only a more accurate cost estimate, but also a better understanding and management of project risks.

Figure 33. Methodology for obtaining an optimal Power-to-X plant design and sizing.

Adopting this methodological approach and developing engineering deliverables is critical to improving the accuracy of project cost estimates. By integrating comprehensive analysis with advanced optimisation tools, a solid foundation is established for informed decisions, effective risk management, and successful project execution. This approach not only ensures more accurate cost estimates but also contributes to the long-term sustainability and viability of complex projects, such as those in the field of Power-to-X technologies.

5. Regulatory Framework

A fundamental part of the development of green ammonia projects is compliance with all legal requirements at both regional and national levels for each of the components and links in the project's value chain, from the production of renewable electricity to the final use of green ammonia or its transportation to the final consumption destination, in the case of an export-oriented project.

In the specific case of Mexico, each of these stages of the project must comply with federal, state and municipal legislation. If a project complies with and obtains the permits indicated by the applicable regulatory framework, it will avoid risks related to delays or postponements in its activities.

According to the analysis conducted for the preparation of this guide, the legal timeframe for preparing the relevant permit applications for a green ammonia project in Mexico, including the timeframe for resolution by the authorities to obtain all required permits, is approximately 12 months. However, in practice, it has been determined that on average it can take between 24 and 30 months to obtain a response to permit applications.

In order to analyse in detail the permits required for a green ammonia production and export project, the value chain will be divided into three large blocks, and for each of these the permits required at three different levels will be presented: federal, state and municipal.

5.1. Electricity Generation

As presented throughout the document, the production of green ammonia requires the implementation of one or more renewable energy generation and energy storage projects. The critical permitting path that will be presented will apply to Power-to-Ammonia projects that are not interconnected to the National Grid, i.e., are supplied by completely isolated power generation and supply projects. It is important to keep in mind that, in case it is planned to develop several power generation projects, for example, a solar plant and a wind plant, it is possible to apply for the necessary permits for each project independently or process the necessary permits as a single power generation package.

Requirements at the federal level:

At the federal level, electricity generation projects such as photovoltaic plants and wind power plants must consider the following permits:

- **Social Impact Authorisation:** This authorisation deals with an evaluation that allows identifying and characterising the possible impacts, both negative and positive, that could originate due to the development of the project and that could have effects on the towns and communities with interests in the areas of influence of the project.
  In addition, a social management plan must be established that involves all the parties interested in the project and allows them to reach agreements and the consent of the communities to the development of the project. The study, which must be conducted by an independent third party, must be submitted for evaluation to the Directorate of Social Impact and Territorial Occupation of the Secretariat of Energy - SENER[9]. Occasionally, it is possible that the need for a Prior Consultation process could be determined, due to the identification of direct and significant impacts on indigenous communities. This process must be concluded prior to the issuance of licenses, permits and authorisations for the project.
- **Environmental Impact Authorisation:** For the development of any activity that has environmental impacts, an environmental impact assessment must be prepared, anticipating the possible environmental impacts that the project may have on the environment and the health and safety of people. In addition, an environmental management plan must be established in which environmental protection measures are defined. Like the social impact authorisation, this study must be conducted independently and be submitted for evaluation by the General Directorate of Environmental Impact and Risk of the Secretariat of the

[9] https://www.gob.mx/sener

Environment and Natural Resources - SEMARNAT[10], to obtain the corresponding authorisation.

- **Land Use Change Authorisation for Forest Lands**: A permit allowing the partial removal of forest cover in a given area. For this, it is necessary to demonstrate that (1) the biodiversity of the ecosystems will not be affected; (2) there will be no soil erosion; (3) the carbon storage capacity will not be compromised; and (4) there will be no deterioration in water quality or decrease in water catchment. This study must be conducted by qualified independent third parties and subsequently submitted for evaluation by SEMARNAT's General Directorate of Sustainable Forestry Development.
- **Electric power generation permit:** This applies to generation plants with a capacity greater than 0.5 MW and must be requested from the CRE (Energy Regulatory Commission) regardless of whether they will be connected to the National Electric System or not. In the case of being connected to the grid, CENACE (National Energy Control Centre) will oversee determining the necessary infrastructure to interconnect the project.
- **Authorisation from the INAH (National Institute of Anthropology and History):** The project must obtain INAH clearance[11], indicating that there are no records of archaeological remains. Interventions in the area will not be allowed until the site has been cleared by INAH. Regardless of whether the site has been released, if archaeological remains are found, the work must be stopped.
- **Accesses, decelerations on public roads and use of Federal right-of-way:** A permit must be obtained from the SICT (*Ministry of Infrastructure, Communications and Transportation*[12]), specifically for the construction stage of the project where intensive use of public roads is foreseen.

With respect to energy storage projects, at the federal level, the same requirements previously presented for electric generation projects must be met, except for the power generation permit.

State level requirements:

At the state level, the requirements may vary from state to state. However, in general terms, the following permits must be considered for the development of the project:

- **Environmental Impact Assessment**: At the state level, an Environmental Impact Assessment must be processed only in reference to the construction of internal roads within the project.
- **Civil protection feasibility:** Being one of the most technical and complex permits required, it must be processed before the State Civil Protection Secretariat to obtain the municipal construction permit. It must clearly state the complexity of the project, possible risks, key health and safety aspects, and the mitigation strategies that will be applied.
- **Special waste:** At the state level, permits must be obtained for the integrated management of non-hazardous waste.

State-level requirements:

[10] https://www.gob.mx/semarnat
[11] https://www.inah.gob.mx/
[12] https://www.gob.mx/sct

All projects, works, construction and/or activities, regardless of their sector or volume, must comply with municipal legislation, regardless of federal and state obligations and requirements, i.e., they are independent, and municipalities may require permits, feasibility or environmental approvals, urban development, civil protection, among others. The most relevant are presented below:

- **Land Use Feasibility:** The municipality must issue the Land Use license, which allows us to identify the feasibility or not of the project on each property.
- **Municipal civil protection feasibility**: Approval from the Municipal Directorate of Civil Protection, specifically regarding the operation of the plant.
- **Land Use License and Official Alignment and Numbering Certificate:** can be processed jointly, representing compliance with the provisions on land use, construction, and operation of works within the municipality.
- **Construction License:** It is required to obtain a Construction License for the works, infrastructure, and earthworks necessary for the construction of the project.

5.2. Ammonia Production Plant

For practical purposes of this guide and the presentation of the critical path of permits and legal requirements for the implementation of a green ammonia project, the process of hydrogen production through electrolysis is included in the section called Ammonia Production Plant. Due to the above, this section will present the permits related to: (1) water use and desalination, (2) ammonia generation, and (3) Onshore Ammonia Pipeline. As presented in section 7.1 Electricity generation, the required permits will be listed at three levels: federal, state and municipal.

5.2.1. Water use and desalination.

When an industrial activity requires the use of a body of water or water source, various permits must be obtained for both the construction and operation phases of the equipment and/or systems that draw from or utilise water resources.

Federal level requirements:

As in the case of electricity generation, the water use stage must be included in the Environmental Impact Authorisation that is processed at the federal level. It is important to clarify that it is mandatory to apply for a single Environmental Impact Authorisation that covers all stages of the project. The same applies to the Land Use Change Authorisation for Forest Lands, the Authorisation by the INAH and the permit for access, decelerations in public roads and use of federal right of way.

Additionally, and specifically for the use of water and desalination, it is necessary to have the following permits:

- **National Water Use Title:** A concession title is required for the use and exploitation of water from federal bodies of water, which must be granted by the National Water Commission (CONAGUA[13]), if there is water availability in the basin where the water is to be extracted.

[13] https://www.gob.mx/conagua

- **Waterworks permit:** A permit from CONAGUA is required for the installation of waterworks. The safety of groundwater and water bodies under federal jurisdiction must be guaranteed.

Requirements at the State level:

At the state level, the water utilisation and desalination stage must be included within the Civil Protection Feasibility and permits related to special handling waste.

Municipal Requirements:

At the municipal level, the water use and desalination stage must be included within all municipal permits presented in the previous section, corresponding to electricity generation.

5.2.2. Ammonia Generation

The generation of green ammonia involves technical, chemical, and industrial processes that will result in the production of low-emission fuel. In this sense, it is necessary to comply with different permits for both the construction stage and the operation stage of the ammonia production plant within the different levels of government, as presented below.

At the federal level, requirements like those that apply to electricity generation must be complied with. Specifically:

- Environmental Impact Authorisation.
- Land Use Change Authorisation for Forest Lands
- Authorisation from the INAH (National Institute of Anthropology and History)
- Access, deceleration on public roads, and use of federal right-of-way.

At the state and municipal levels, the same requirements that apply to water use and desalination must be met.

5.3. Onshore Ammonia Pipeline

Regarding the requirements necessary to transport ammonia by means of a land pipeline, in addition to the permits already presented for the other stages of the project, at the federal level a Maritime Land Zone Concession must also be processed, since the 20-meter strip from the maximum high tide, as well as any surface temporarily covered by maritime waters, is considered a federal maritime land zone. The maritime zone concession enables the transportation of ammonia through the surface of federal jurisdiction.

At the state level, permits such as civil protection feasibility and permits for the integrated management of non-hazardous waste must be considered. At the municipal level, land use and municipal civil protection permits are required.

5.4. Maritime Infrastructure

At this stage of the value chain, two components are considered necessary for the export of green ammonia: (1) the offshore ammonia pipeline and (2) the marine terminal. For these two components, permits must be obtained at the federal and state levels.

5.4.1. Offshore Ammonia Pipeline

This pipeline will allow the transport of the green ammonia molecule to the location of the marine terminal, where it will be supplied to vessels. If the pipeline is required to be located on the seabed, the following permits must be considered:

At the federal level, as in all other stages of the project, Environmental Impact Authorisation must be processed, and authorisation must be obtained from INAH. In addition, the following permits must be considered:

- **Concession for the Use of Inland Marine Waters, Territorial Sea and Exclusive Economic Zone:** issued by the Marine Secretary[14] for the occupation and use of the seabed of inland marine waters, the territorial sea and the exclusive economic zone.
- **Dredging Authorisation:** To conduct dredging or seabed levelling activities, authorisation is required from the Merchant Marine Directorate of the SCT.
- **Dumping Permit:** Any infiltration or dumping (substance, matter, infrastructure, etc.) made into the ocean, necessary for dredging or seabed levelling activities, as well as the performance of any work, requires a permit issued by the SCT. This permit is essential for the construction stage of the marine pipeline.

Since the facilities are in the ocean, which is federal property, state requirements are limited to those related to the integrated management of non-hazardous waste. There are no municipal requirements for this link in the project's value chain.

5.4.2. Maritime Terminal

This refers to the point of supply of ammonia to the vessels, from a naval device that is not self-propelled. All the requirements described for the offshore ammonia pipeline apply to the marine terminal. In addition, permission must be requested at the federal level from the Port Captain's Office to fix and position elements at sea. These elements must be registered and flagged to generate a maritime registry and maritime marking and thus avoid accidents on the shipping lanes, especially in the case of ammonia.

5.5. Chronological order of obtaining permits.

Figure 34 below shows the chronological order for obtaining permits for all stages of the project, indicating the approximate time that, in practice, it has been determined that it may take to obtain a response from the relevant authorities. Assuming that the documents mentioned above were obtained for the Construction and Operation stages, in the same process and authorisation, only the necessary plans, programs and monitoring will have to be followed up.

[14] https://www.gob.mx/semar

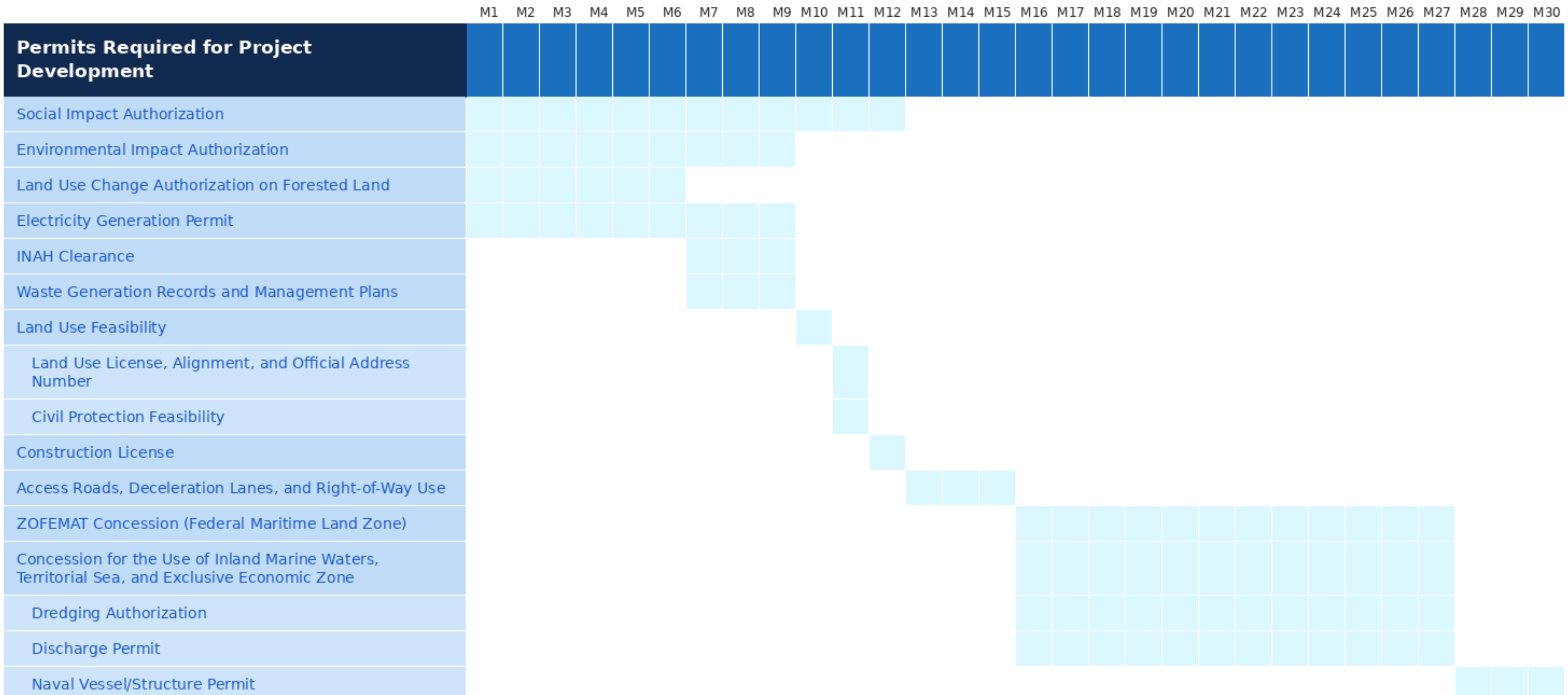

Figure 34. Chronological order and approximate duration of permits obtained

6. Socio-environmental critical path for the development of green ammonia projects

This section will focus on presenting the main aspects that should be considered in relation to socio-environmental issues to identify the main impacts that a green ammonia project may have and to implement the necessary measures to mitigate the negative impacts that may affect the communities and the environment.

A fundamental first step in identifying and mitigating potential impacts is to conduct an environmental impact assessment. The following is a general description of the main characteristics for this type of study to contribute to the success of the project.

Evaluation and mitigation of environmental impacts:

A high-level environmental impact assessment for a green ammonia project can be composed of the following steps:

1) **Analysis and description of the ecological land use and land use programs that apply to the property to be evaluated:** as a first step, the compatibility of the land to be occupied with respect to the vocation of land use in the region should be studied, considering the existing ecological land use programs in place. In addition, the study should consider sites of environmental interest that could be affected by the project. For example, areas of interest for bird conservation or wetland conservation.

2) **Determination of impact radii by type of project:** According to the type of project to be implemented, a detailed study must be carried out to determine the impact radii and the magnitude of the consequences or damages that could cause accidents or related events, for example, to the release or emission of hydrogen and ammonia. This type of HAZOP requires detailed technical descriptive information about the project, such as engineering calculations, capacities to be installed, energy consumption of the equipment, and estimated production of the green ammonia plant. Ideally, this type of analysis uses digital tools specially designed for this purpose, which allow the determination of gas dispersion, evaporation of substances, determination of heat radiation in case of fire, and determination of overpressure levels in case of explosions of flammable and/or explosive gas vapour clouds. For the type of project analysed, the estimation of the radii of affectation should be conducted for:
    - **a.** The green hydrogen generation plant.
    - **b.** The ammonia synthesis plant.
    - **c.** If there is pipeline transport of ammonia:
        - i. Onshore ammonia pipeline.
        - ii. Offshore ammonia pipeline.

3) **Analysis and determination of areas of influence and areas affected by the project:** The analysis of areas of influence is based on the previously determined radius of influence and the superimposition with layers of geographic information, such as bodies of water, vegetation, areas of ecological interest, among others that are available in the area of interest. At this point, no impact prevention or mitigation measures have been considered. As prevention, mitigation and

compensation measures that are technically and economically feasible are determined, adjustments may be made to the established area of influence.

4) **Compliance with laws and regulations**: It is pertinent to conduct a detailed review of the linkage of the proposed project with the relevant laws and regulations. The review should determine, for the applicable laws and regulations, the legal instrument that applies to a given environmental issue or factor and specify the stage or activity of the project in which the instrument applies, understanding by stages, the activities that will be carried out consecutively for the development of the project, such as Site Preparation, Construction, Operation, Closure and Abandonment.

5) **Environmental considerations for the development of the project and development of the environmental impact matrix:** Once all the activities to be carried out within the framework of the project have been identified, understood as the works that encompass the intended tasks for four common project phases: Site Preparation, Construction, Operation and Closure and Abandonment, the environmental factors impacted are determined within each environmental component for the Abiotic, Biotic, Landscape and Environmental Services environments. The following table presents an example of possible environmental factors.

Mean	Environmental component	Environmental factors
Abiotic	Air	F01. Air quality
		F02. Noise
	Soil	F03. Use
		F04. Erosive processes
		F05. Stability
	Water surface	F06. Quality
		F07. Availability

Next, a checklist is developed to guide the interaction matrix of potential impacts. This list evaluates each environmental factor in reference to the effects that may arise as a result of the project. From this, the matrix of potential environmental impacts is developed, where it is possible to identify the interactions between environmental factors and project activities.

As a final step, and with the intention of facilitating the evaluation of each impact, these are weighted according to their intensity, extent, persistence and effect, among other parameters. Based on the results obtained, an Environmental Surveillance Plan (PVA) is developed, which allows us to bring together impact prevention measures simply and concretely, assigning performance indicators to each measure.

Evaluation and mitigation of social impacts:

For the evaluation and mitigation of social impacts, it is also necessary to conduct a series of activities to ensure that the project will have a minimal impact on the people and communities that may be located in the vicinity of the intervention area. This procedure is known as a Social Impact Assessment (SIA).

The following is a list of the main activities that contribute to a successful identification and assessment of the social impacts of the project.

1) **Delimitation of the areas of influence:** These are the physical spaces that are likely to be impacted by the project during all its stages. Typically, three zones of influence will be identified: core area, area of direct influence, area of indirect influence. The classification given will depend on the degree of exposure to the impacts generated, which can be positive or negative. The intensity of the impacts, the degree of exposure and the perception of the population are the criteria that allow the delimitation of these three areas of influence, under the assumption that the closer the proximity, the more susceptible the communities will be to being affected. It is important to point out that proximity is not exclusively from the dimension of physical distance; it is also important to consider the social, cultural, and economic relationship between the population and the project.
2) **Social baseline:** Consists of the identification of communities and human settlements within the limits established for the project's area of influence. Once the identification has been made, the population within the area of influence must be characterised. This characterisation may involve identifying age groups, gender, culture, access to health, access to education, sources of employment, housing and welfare conditions, economic conditions and any other criteria considered relevant to identify the level of impact that will be caused by the different stages of the project.
3) **Social impacts:** Identification of the repercussions that may occur in the impacted communities. For this purpose, it is recommended to establish impact indicators and relate them to the possible effects that could occur under a project scenario. Based on the above, it will be possible to establish the level of impact that each of the identified impacts could have within the project's area of influence.
4) **Analysis of key social actors:** It is important to recognise the level of incidence of different actors in decision-making with respect to the territory where each of the links in the project's value chain will be carried out, recognising their objectives, actions, interests, and level of influence in relation to the project's development. For this purpose, it is recommended to start by identifying the social actors that have some kind of relationship with the project involving land use or with the maritime territory, if it is part of the project. This identification will also make it possible to establish a network of relationships between stakeholders, which may be positive relationships, such as alliances or mutual collaboration links between stakeholders or, on the other hand, negative relationships, such as conflict relationships between stakeholders, which could cause potential social problems.
5) **Recommendations:** Based on the findings of the previous steps, the necessary procedures for mitigating the possible negative social impacts of the project should be established. For example, if indigenous communities are identified within the project's area of influence, the need for an Indigenous Consultation should be determined. As a result of the established procedures, the identified communities should be entitled to share benefits from the implementation of the project. Finally, it is important to keep in mind that when conducting the Social Impact Assessment (SIA) it will be possible to measure the degree of occurrence and degree of impact of the impacts that have been identified in the early stages of the project, for example, at the prefeasibility level, as well as to identify new impacts and discard some of them.

Working together with the communities is one of the success factors for the development of the project, either through workshops and various activities that allow understanding the dynamics of the communities, their relationship with the territory and the main repercussions and impacts on their way of life from the development of the project.

7. Success Factors

7.1. Factors controlled by the project developer:

For the successful development of a green ammonia plant in Mexico, factors controlled by the project developer play a crucial role. These elements range from maximising the capture of renewable energy technologies, taking advantage of optimal conditions in certain regions, to specific technological adaptation to local conditions. The construction of an efficient infrastructure for ammonia transport and storage is indispensable, as well as continued investment in research and development (R&D) in collaboration with national institutions such as the Mexican Petroleum Institute (IMP) and the National Council of Humanities, Sciences and Technologies (CONAHCYT). Strategic alliances with dominant energy actors, such as PEMEX and the Federal Electricity Commission (CFE), and effective community management that respects the Indigenous Consultation Law and fosters genuine dialogues are fundamental. Attention to and proper management of these factors by the developer can minimise logistical costs, avoid legal and community conflicts, and ensure the harmonious integration of the project into the economic and social fabric of the country. Table 21 shows a description of the factors that can be controlled by the developer and the possible impacts if they are not properly addressed.

Table 21. Factors that can be controlled by the project developer

Focus	Description	Challenge if ignored
Renewable Energy	Maximise the capture of complementary renewable energy technologies in optimal regions.	Increased costs.
Technological Efficiency	Adapt technologies to Mexico's regional specificities.	Malfunctioning or reduced equipment life.
Water Supply	Perform a correct evaluation of the quality of the water supply for the electrolysis process.	Reduced useful life and possible malfunctioning of the electrolyser.
Water Supply	Perform an adequate analysis of the availability of the resource and the possible environmental impacts derived from its long-term exploitation.	Environmental impacts on ecosystems and/or water tributaries that could generate possible limitation in water supply.
Infrastructure	Create adequate transportation and storage networks.	Increased logistics costs and possible interruptions.
R&D	Cooperate with national entities such as IMP and CONAHCYT.	Use of technologies that are not optimised for Mexico.
Partnerships	Synergies with energy entities such as PEMEX or CFE.	Loss of opportunities and shared resources.
Community Management	Comply with the Indigenous Consultation Law and genuine dialogues.	Legal conflicts and community rejection.

7.2. External Factors: Socioeconomic and International Trade Factors

As for external factors, these are equally critical to the success of a green ammonia plant in Mexico's socioeconomic and commercial context. Navigating through the regulatory landscape and maintaining close collaboration with the Ministry of Energy (SENER) and other regulatory agencies is essential to avoid penalties and to capitalise on available incentives. Obtaining financing through institutions such as BANOBRAS and BANCOMEXT is a pillar of the project's economic viability. Understanding and anticipating local market dynamics to ensure solid penetration and return on investment is critical, along with gaining social support through cooperation with community leaders and organisations. Educational programs and alignment with government green transition initiatives not only position the project to coordinate with national sustainability goals, but also promote community buy-in and support. Complying with consultation and consent protocols and seeking mutual benefit through community investment programs solidifies long-term relationships and ensures a firm foundation for sustainable plant development. Ignoring these external factors could result in a range of challenges, from legal disputes to unfavourable market position and deterioration of the project's public image.

Table 22. External factors influencing the development of the project.

Approach	Description	Challenge if ignored
Regulation	Adapt and collaborate with SENER and regulatory agencies.	Penalties or lack of access to incentives.
Financing	Support from multilaterals and other funds that require ESG compliance.	Lack of capital and unfavourable interest rates.
Market	Identify national demand and connect with industries. Identify countries and industries willing to pay the high cost of green ammonia.	Limited market penetration and lower ROI.
Social Support	Cooperate with community organisations and leaders.	Lack of social support and poor public image.
Education	Promote educational programs with relevant institutions.	Public misinformation and lack of interest.
Green Transition	Integrate into government sustainability programs.	Misalignment with national objectives.
Consultation and Consent	Adhere to the consultation and consent protocol.	Legal conflicts and community opposition.
Mutual Benefit	Generate community investment programs.	Dissatisfaction and lack of local support.
Environmental Impact	Cooperate with SEMARNAT and respect protected areas.	Sanctions and damage to biodiversity.
Transparency	Establish committees and effective communication channels.	Disinformation and mistrust.
International Harmonization	Comply with international standards and certifications.	Trade barriers and international rejection.
Bilateral Agreements	Facilitate exports through the T-MEC.	Unfavourable tariffs and trade complexities.

One of the factors that has gained relevance to ensure the success of project development is access to sustainable financing, which refers to the process of considering environmental, social and governance (ESG) criteria when making investment decisions in the financial sector, seeking to encourage investments in sustainable projects and economic activities. Below are some areas commonly considered as ESG aspects, in each of their dimensions (GIZ, 2022):

- **Environmental:** mitigation and adaptation to climate change, preservation of biodiversity, reduction of environmental pollution, sustainable use of water sources and marine resources, and transition to circular economies.

- **Social:** Compliance with regulations related to occupational health and safety, fair working conditions, diversity, training and development opportunities, investment in human capital and in the communities influenced by the project, as well as everything related to human rights.
- **Governance:** Having management structures, fiscal honesty, anti-corruption measures, considering sustainability criteria in the company's management decisions, guaranteeing employees' rights, data protection and information disclosure guarantees.

In this sense, companies and/or project developers interested in applying for loans or sustainable financing should take ESG criteria into account in the different stages of the project. In addition, timely recognition of these criteria can also contribute to understanding and preventing potential risks that may arise from non-compliance with sustainability criteria, and which may ultimately translate into material or significant financial risks. Examples include:

- Physical risks: Damage to infrastructure due to extreme weather events.
- Reputational risks: Due to the increasing importance given to issues such as climate change, human rights, among others.
- Transitional risks: which may result from the economic cost of moving towards a more sustainable economy and/or not complying with environmental and/or climate regulations from the outset.

8. Conclusions

- Ammonia is one of the most important chemicals worldwide and plays a fundamental role in the production of fertilisers. Its production is currently associated with 1% of all global emissions, making it essential to seek alternatives for its decarbonization.
- Emissions associated with the ammonia production process can be considerably reduced if hydrogen, which together with nitrogen constitutes the raw materials of ammonia, can be obtained cleanly. Water electrolysis powered by electricity from renewable sources offers a significant opportunity to obtain hydrogen without associated GHG emissions.
- The two main electrolysis technologies that have reached technological maturity are alkaline and PEM. Both have advantages and disadvantages that will make the choice of one or the other dependent on the characteristics of the project being developed. Although their costs are still high, a significant reduction is expected in the short term, as well as large-scale deployment of the technology.
- Although electrolysis is a process that consumes large quantities of water, large-scale deployment of technology would not pose a threat to the availability of water resources. The implementation of desalination plants makes it possible to take and purify seawater for use in electrolysers without incurring additional costs over and above their contribution to the levelized cost. In addition, it can be presented as a great opportunity to provide potable water to communities currently living under high water stress.
- A high-level estimation of the size of the various components of the Power-to-Ammonia system can be conducted using multiplicative factors and coarse assumptions about the availability of the renewable resources to be relied upon. However, this type of procedure has large uncertainties and only serves to illustrate how the orders of magnitude of a potential Power-to-Ammonia system would turn out. To accurately size this type of project, it is essential to use optimisation models capable of overseeing a large number of variables and minimising the cost of the system.

- In particular, the variability of renewable resources and the complementarity between the wind and solar resource for hybrid plant configurations represent a challenge in finding the optimal sizing and operation. In any case, the specific behaviour of the renewable resource in the locations where green ammonia production projects are to be developed must always be considered.
- The economic-financial analysis presented evidence that a Power-to-Ammonia system powered by a hybrid renewable energy plant can achieve a lower levelized cost of ammonia (LCOA) than even those that would be achieved using the electric grid. Most of this cost is attributed to the electricity required to produce the green hydrogen, so ensuring a good renewable resource is crucial for the development of such projects.
- Compliance with all legal requirements at the municipal, state, and national levels at every stage of project development, including planning, construction, operation and dismantling, is one of the most relevant aspects to ensure the success of a green ammonia project. By processing, obtaining, and complying with the permits indicated in the applicable regulatory framework, risks related to delays, postponements, and conflicts with relevant stakeholders such as the communities will be avoided.
- In line with the above, working together with the communities is one of the success factors for the development of the project, either through workshops and various activities to understand the dynamics of the communities, their relationship with the territory and the main repercussions and impacts on their way of life from the development of the project.

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