Grey-to-Green ammonia as a decarbonisation pathway: market assessment and techno-economic analysis

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I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Abstract

NH_3 is an essential commodity representing 2% of global energy consumption and 1.3% of global CO_2 emissions, as more than 99% of its production relies on fossil fuels by 2023, especially from NG (72% - grey NH_3). Green NH_3 (renewable energy and green H_2-based) is expected to substitute grey in current uses and surges as zero-CO_2 emissions fuel to decarbonise sectors such as shipping. Therefore, the thesis aim is to develop a techno-economic analysis to assess grey-to-green potential as decarbonisation pathway. Brazil, specifically Ceará state, has been the geography analysed due to its high renewable energy potential, high-voltage grid access and planned port infrastructure to export NH_3 to the EU. The methodology developed to define renewable resource identified onshore wind as a promising option to produce green NH_3, with >65% capacity factors. Green NH_3 LCOA resulted in 831$/ton$NH_{3\text{-green}}$, including production costs and shipping to EU, with associated LCOE of 34.1$/MWh and LCOH of 3.7$/kgH_2. EU Grey NH_3 production relies on variable NG prices and potential carbon taxes, thus Brazil imported green NH_3 is to be competitive with grey when NG and carbon taxes prices reach 50$/MWh and 150$/tonCO_2 respectively, values expected in the short-medium term. If considering a 30% CAPEX reduction in wind turbines and electrolyzers, an optimistic LCOA 654$/ton$NH_{3\text{-green}}$ would be competitive with current grey NH_3 prices. Both production pathways lead to similar energy consumptions (36.5 GJ/ton$NH_{3\text{-green}}$, 38 GJ/ton$NH_{3\text{-grey}}$) while green NH_3 provides a 90% emissions reduction with 0.22 tonCO_2-eq/ton$NH_{3\text{-green}}$ versus 1.92 tonCO_2-eq/ton$NH_{3\text{-grey}}$

Keywords: green ammonia; green hydrogen; decarbonisation; techno-economic analysis; LCOA (Levelized Cost of Ammonia); sustainability

Resumo

O NH_3, representando 2% do consumo global de energia e 1.3% das emissões globais de CO_2, depende em mais de 99% de combustíveis fósseis para a sua produção até 2023, principalmente GN (72% - NH_3 cinza). Espera-se que o NH_3 verde (baseado em energia renovável e H_2 verde) substitua o cinza em usos atuais e surja como um combustível sustentável. O objetivo da tese é desenvolver uma análise técnico-económica para avaliar o potencial cinza-a-verde como caminho de descarbonização. O estado do Ceará, no Brasil, foi a geografia analisada devido ao seu alto potencial renovável, rede de alta voltagem e infraestrutura portuária. A energia eólica terrestre foi identificada como uma opção promissora para produzir NH_3 verde, com fatores de capacidade >65%. O LCOA do NH_3 verde resultou em 831$/ton$NH_{3\text{-verde}}$, incluindo custos de produção e transporte para a UE, com um LCOE associado de 34.1$/MWh e um LCOH de 3.7$/kgH_2. A produção de NH_3 cinza da UE depende dos preços do GN e potenciais impostos sobre o carbono. A NH_3 verde importada pelo Brasil será competitiva com a cinza quando os preços do GN e dos impostos sobre o carbono atingirem 50$/MWh e 150$/tonCO_2, respetivamente, valores esperados no curto-médio prazo. Se considerarmos uma redução de 30% no CAPEX em aerogeradores e eletrolisadores, um LCOA otimista de 654$/ton$NH_{3\text{-verde}}$ seria competitivo com o cinza atualmente.. Ambas as vias de produção têm consumos de energia semelhantes (36.5GJ/ton$NH_{3\text{-verde}}$, 38GJ/ton$NH_{3\text{-cinza}}$), enquanto o NH_3 verde proporciona 90% de redução de emissões com 0.22 ton$CO_{2\text{-eq}}$/ton$NH_{3\text{-verde}}$ versus 1.92 tonCO_2- eq/ton$NH_{3\text{-cinza}}$

Palavras-chave: amoníaco verde; hidrogénio verde; descarbonização; análise técnico-económica; LCOA (Custo Nivelado de Amoníaco); sustentabilidade

Table of Contents

List of Figures

List of Tables

Acronyms

ASU – Air Separation Unit

CAPEX – Capital Expenditures

CO_2 – Carbon dioxide

COD – Commercial Operation Date

EU – European Union

H_2 – Hydrogen

KPI – Key Performance Indicator

LCOA – Levelized Cost of Ammonia

LCOE – Levelized Cost of Energy

LCOH – Levelized Cost of Hydrogen

Mton – Million tons (1 ton = 1,000 kg)

N_2 - Nitrogen

NG – Natural Gas

NO_x – Nitrogen oxides

NH_3 – Ammonia

OPEX – Operational Expenditures

PEM – Proton Exchange Membrane

R&D – Research and Development

SWRO – Seawater Reverse Osmosis

TRL – Technology Readiness Level

US – United States

WACC – Weighted Average Cost of Capital

1. Introduction

1.1 Motivation and Background

Ammonia (NH_3) is mainly used as a feedstock to produce nitrogen-based fertilizers, which are crucial for agricultural productivity and food security. NH_3 global production accounts for 185 Mton/year (million tonnes per annum) and currently relies more than 99% on fossil fuels, being considered an energy and carbon-intensive industry which accounts for around 2% of total final energy consumption and 1.3% of CO_2 emissions from the energy system [1].

NH_3 is produced by the combination of hydrogen (H_2) and nitrogen (N_2) at high temperatures, and it is the second largest H_2 consuming industry in the world with 33 Mton/year in 2020 [2]. With commitments to meet CO_2 emission targets, green H_2 produced from renewable energy sources and its derived fuels such as green NH_3 will be needed to decarbonize energy-intensive sectors.

Green NH_3 can be widely deployed leveraging on technological maturity and existing infrastructure, and it is expected to become competitive in the short to medium term in high-renewable energy potential locations.

Integrated energy companies such as oil and gas companies are one of the most active players investing in green H_2 to reduce their CO_2 footprint, as they widely use H_2 as feedstock for their refining processes. Therefore, the expertise on H_2 operations and commodities trading from these players alongside the need of diversifying their business into renewable energy and zero-carbon fuels is a key advantage that could propel a leading position in this field.

As the largest H_2 producer and consumer in Portugal, Galp is actively developing green H_2 projects to decarbonize its refinery. In this context, the possibility of developing businesses in other parts of the green H_2 value chain such as green NH_3 are being analysed.

1.1.1 Green Hydrogen

Green H_2 has been gaining momentum in recent years as a potential solution to decarbonize the energy system and address climate change. It is seen as a key component of the energy transition as it provides an effective alternative to reduce dependence on fossil fuels. The accelerated development of green H_2 can be attributed to several factors, including but not limited to:

- **Climate change targets**: To limit the 1.5 ºC increase of global temperature above pre-industrial levels, as set out in the Paris Agreement adopted in 2016 at the United Nations Climate Change Conference, global greenhouse gas emissions will need to peak before 2025 [3]. Moreover, after reaching this peak they should decline by 43 per cent by 2030 and reach net zero by 2050. Therefore, many countries and companies have committed to net-zero emissions by 2050 or earlier, and the industrial sector is considered one of the hard-to-abate sectors:

    - Energy consumption from the industry represents 40% of total final energy consumption and is still dominated by fossil fuels, being the second largest emitting sector after power generation worldwide [4].
    - H_2 is one of the main feedstocks used in the industry sector. However, more than 99% of H_2 is produced from fossil fuels, mainly natural gas and coal. Therefore, green H_2 produced from renewable energy is one of the main pathways to decarbonize the heavy industry processes.
- **Policy support**: Governments around the world are implementing policies and incentives to promote the development and deployment of green H_2, such as tax credits, grants, and subsidies. Some of the main policies driving green H_2 development in the world include:
    - **Targets and incentives**: Governments are setting targets for the deployment of green H_2 and providing incentives to support its development. By 2022, 25 countries released national H_2 strategies as shown in Figure 1 below. For example, in the European Union, the European Commission in its REPowerEU strategy response to reduce Russian fossil-fuel importation dependency has proposed to produce 10 million tonnes of renewable H_2 by 2030 and to import 10 million tonnes by 2030 [5]. In order to accelerate H_2 financing, also the European Commission has proposed establishing the European Hydrogen Bank, with the objective to create investment security and business opportunities for European and global renewable H_2 production. Other renowned incentive is the US Inflation Reduction Act, which expanded tax credits for renewable electricity and created new provisions for clean H_2. Under this framework, renewable electricity and clean H_2 plants can receive a production tax credit of 2.6 cents per kWh and up to $3 per kg of H_2, respectively, for the first 10 years of operation and until 2032 [6].

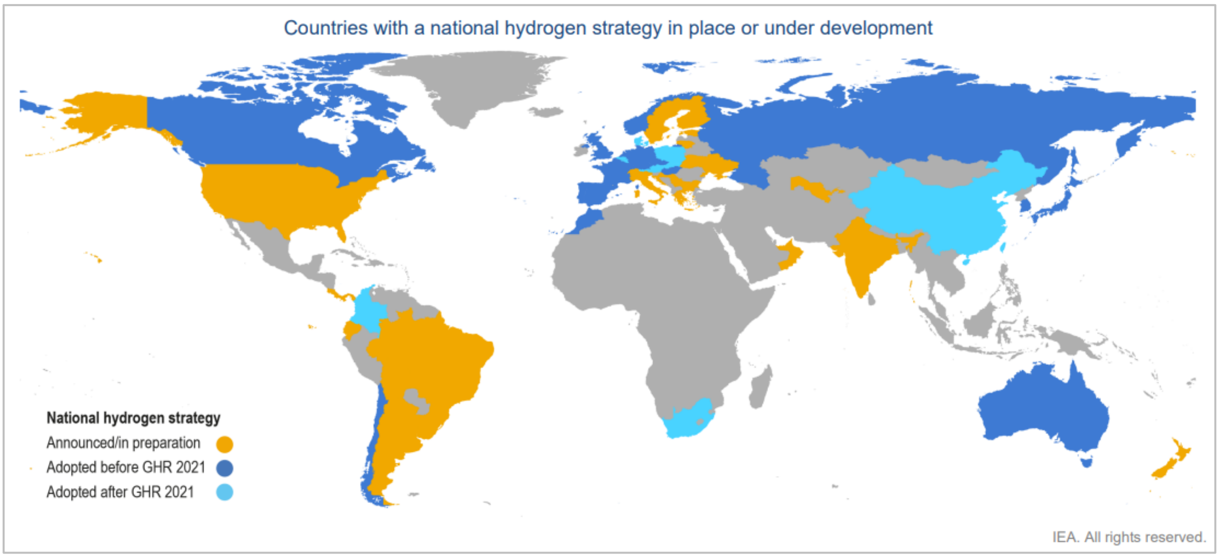


Figure 1: Countries with a national H_2 strategy in place or development. GHR = IEA Global Hydrogen Review. Source: [7]

    - **Carbon pricing and regulation**: Some countries have implemented carbon taxes, cap-and-trade systems, and emissions standards for the transportation and industrial sectors to reduce emissions from fossil fuels. The most illustrative example and the largest carbon market worldwide is the EU Emissions Trading System (ETS). The EU ETS sets a cap on emissions and allows trading of allowances between companies. This creates a carbon price, which incentivizes companies to reduce their emissions [8]. The carbon price has fluctuated over time, reaching a low of less than 5 euros per tonne of CO_2 in 2013 to high-record prices of over 100 EUR/ton CO_2 in 2023 [9].

- **Falling renewable energy costs**: The cost of renewable energy sources such as solar and wind power has been falling, making it increasingly cost-competitive with traditional fossil fuels [10]. This is one of the key aspects to make production of green H_2 more economically viable.

1.1.2 Green Ammonia as Green Hydrogen Derived-Fuel

Green NH_3 is gaining attention as a promising green hydrogen-derived fuel due to several aspects:

- **Technological maturity**: NH_3 has been used as feedstock for the fertilizer industry since the beginning of the 20th century when the Haber-Bosch process was developed [11]. Therefore, the conversion from H_2 to NH_3 is a well-established process. Moreover, there is a wide and scalable NH_3 infrastructure in terms of storage, transportation and ports integration due to the fact that approximately 10% of the global NH_3 produced is seaborne traded, 20 Mton/year [2].
- **High volumetric energy density**: while H_2 has excellent energy density on mass basis, its volumetric energy density is quite poor even compressed or liquified [12]. To effectively transport H_2 over long distances, the volumetric energy density is considered one of the key enablers for international H_2 trade. NH_3 has an edge for transporting H_2 not only due to its higher volumetric energy density but also due to the expertise on its transportation and handling.
- **Wide range of applications**: while NH_3 has been widely used in the fertilizer and other chemical industries, it has the potential to be used in emerging sectors such as fuel for transportation or power generation [1] [2] [13]. Therefore, the market outlook looks promising although dependent on technological development in these sectors.
- **Cost competitiveness**: Green NH_3 is expected to become competitive with grey NH_3 in the medium-term in high renewable energy regions due to falling renewable energy costs, natural gas prices volatility and increasing regulation and taxes on CO_2 emissions [1] [2].

In summary, green NH_3 is attractive in the short term due to its high energy density, established infrastructure, wide range of applications, lower greenhouse gas emissions, and cost competitiveness. These factors make it a promising option for the energy transition and for reducing carbon emissions in various industries.

1.1.3 Integrated Energy Companies Strategic Positioning on Green Hydrogen and Green Ammonia

There are several motivations behind integrated energy companies targeting green H_2 as a decarbonization pathway:

- **Meeting climate change targets**: Many of these companies have committed to achieving net-zero emissions by 2050 or earlier. Green H_2 is a way for them to reduce their emissions from their operations and the products they sell.
- **Diversifying their business**: These companies see green H_2 as a new market opportunity that can help them diversify their business and reduce their dependence on fossil fuels. The potential use of green H_2 and its derived fuels in a variety of industries such as transportation or power generation can create new revenue streams for these companies.
- **Maintaining their role in the energy transition**: These companies recognize that the energy transition is happening and want to maintain their position as key players in the industry by investing in green technologies.
- **Meeting customer demand**: Many of these companies have customers who are demanding more sustainable products and services. Green H_2 is a way for them to meet this demand and remain competitive.

This Master Thesis has been developed in collaboration with Galp Energia S.A. (Galp), a Portuguese integrated energy company with international presence offering multiple forms of energy – from electricity produced from renewable sources to natural gas and liquid fuels [14]. Galp, a traditional oil and gas player, is one of the main players of the energy transition with a specific business unit on Renewables and New Business Development, accounting with more than 1.4 GW of renewables in operation and with a projected pipeline of 12 GW by 2030.

Galp has different business units across the energy value chain, with presence in three continents, Europe, South America and Africa as shown in Figure 2:

- **Upstream**: large portfolio of exploration, development and production of oil and natural gas.
- **Industrial & Energy Management**: this division includes in the Industrial segment of refining, logistics, biofuels and cogeneration activities, while Energy Management comprises the supply and trading of oil, gas and electricity.
- **Commercial**: this business provides a complete and integrated offer to its clients, ranging from oil products, gas, electricity to other convenience services, comprising more than 1,500 service stations and more than 2,000 electric mobility charging points.
- **Renewables & New Business**: division developing a sustainable and diversified portfolio of renewable energy generation with more than 1.4 GW of renewables in operation in Iberia and more than 9 GW of capacity in construction and development between Iberia and Brazil.

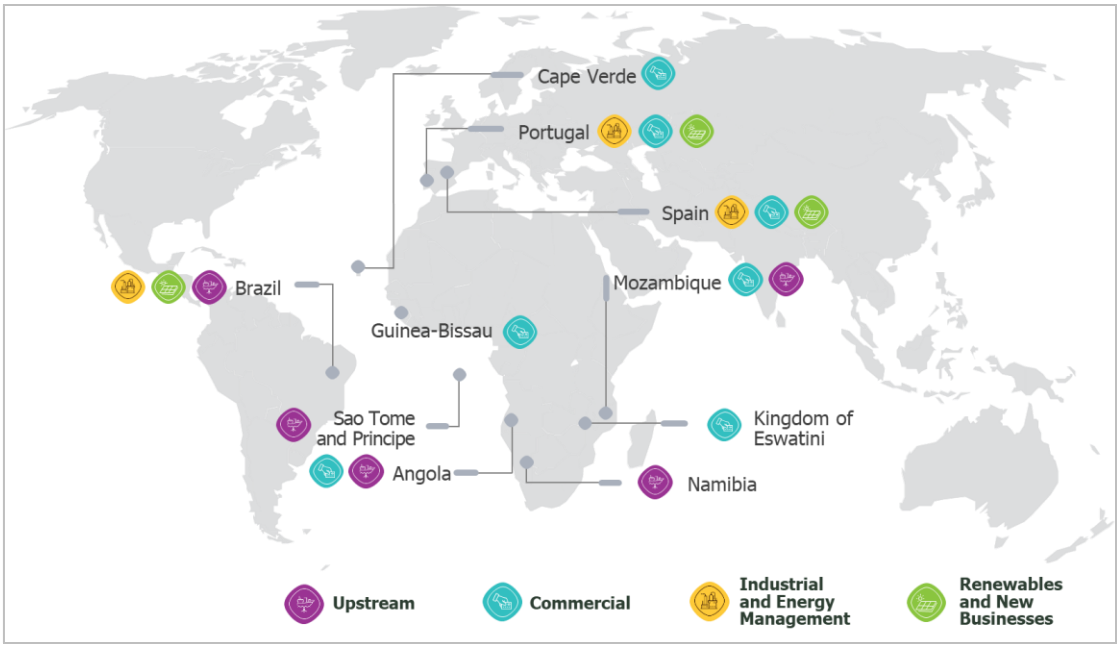


Figure 2: Galp business divisions positioning worldwide. Source: [15]

Galp is the largest oil and gas company in Portugal and has been actively working on its strategy for green H_2. As the largest producer and consumer of grey H_2 in Portugal, the company has recognized the importance of the energy transition and has set a target of reducing the carbon intensity in its refining processes by 50% in 2030 and achieving net-zero emissions in 2050 [15]. Galp's strategy regarding green H_2 includes the following key initiatives:

- **Investing in production facilities**: In 2022, Galp concluded the feasibility study for a 100 MW electrolyser to be implemented in Sines (Portugal), where Galp’s refinery is located. The project has advanced to the basic engineering phase, with additional key systems being created throughout 2022 to support the FID (Final Investment Decision) during 2023 [16]. In addition, alongside EDP and other large energy companies such as Engie or Vestas, Galp is co-leading “GreenH_2Atlantic”, a 100 MW H_2 production hub also located in Sines developed by a consortium composed by 13 European entities [17]. The consortium submitted an R&D project to the EU's "Green Deal Fund" and received a €30m subsidy for the development of the 100 MW electrolyser. The project is under development and the subsidy agreement has already been signed by the EU.
- **Exploring green hydrogen derived fuels**: Green H_2 is also considered a building block of other fuels such as green NH_3, e-methanol or SAF (sustainable aviation fuels) and thus Galp is exploring the potential entrance into these markets relying on its operations expertise and wide presence along these fuels value chain.
- **Developing** H_2 **applications**: Galp is also assessing other opportunities related to green H_2, namely the creation of ecological mobility systems based on H_2, and the development of new concepts for service stations with a low carbon content and an offer of H_2 [16].

Overall, Galp's strategy on green H_2 reflects a commitment to the energy transition and a recognition of the important role that H_2 will play in achieving decarbonization targets.

1.2 Objective

The main objective of the thesis is to develop a techno-economic analysis to assess the potential of replacing grey NH_3 with green produced from renewable energy and green H_2, considering the key metrics to be analysed in order to assess the viability of these projects and its potential as a decarbonisation pathway.

It is therefore essential at first to provide a comprehensive state of the art and background of the opportunity, including but not limited to:

- Green H_2 and NH_3 production pathways and theoretical competitiveness evaluation
- Market trends analysis, including demand projection outlook in established markets (fertilizer and other industrial uses) and in emerging markets (marine fuel, hydrogen carrier and power generation)
- Identification of the key drivers and barriers in the adoption of green NH_3 in the above-mentioned sectors

Then, the techno-economic analysis for a specific case study is developed. The aim of the specific case study is to rely on accurate and realistic data to provide a consistent analysis of the potential grey-to-green NH_3 replacement, comprising:

- Methodology development to define renewable energy in specific high-potential regions and its suitability to establish green H_2 and NH_3 production facilities
- Levelized cost of ammonia (LCOA) assessment previously analysing the levelized cost of energy (LCOE) and levelized cost of hydrogen (LCOH), thus revealing valuable insights into the economic feasibility of the project and its competitiveness versus grey NH_3
- Development of sensitivity analyses to assess the impact of different factors, such as renewable energy or electrolyzer costs on the viability of green NH_3 projects
- Energy intensity and environmental impacts assessment of the green NH_3 production process and its comparison versus fossil-fuels production pathways

1.3 Thesis Outline

Section 2 aims to provide a common background about the state of the art of H_2 and its potential to decarbonise several high-CO_2 intensive sectors. In this section the H_2 value chain is described with an emphasis on its storage and transportation, one of the main challenges that faces the green H_2 development. The role of green H_2 in the future energy system is presented by analysing its main projections.

In section 3, the state of the art of NH_3 is presented, focusing on describing its value chain from its production pathways to end-use in order to establish the necessary background for section 4. Here, green NH_3

competitiveness vs grey is assessed from a theoretical point of view and the market potential in the main offtake markets is provided: fertilizer, other industrial uses, marine fuel, hydrogen carrier and power generation.

Section 5 presents the required methodology to assess green NH_3 projects from a technical and economical perspective. Here, an overview of the methodology used to define the project location is presented alongside the selection of the technical and financial data inputs. Moreover, the specific operational mode adapted to the existing resources and characteristics of the identified location is described.

Section 6 presents an overview of the optimization process developed in the identified location alongside the main technical and financial KPIs obtained. Additionally, the results obtained for the specific green NH_3 case study are compared with industry-based grey NH_3 production in economic, energy and environmental terms.

Finally, section 7 provides the main conclusion and recommendations of the main findings and contributions to the study, as well as a set of future work proposals.

2. Hydrogen state-of-the-art

2.1 Hydrogen Definition

H_2 is the most abundant chemical molecule in the universe. Its combustion does not produce CO_2 or any greenhouse gas emissions and thus, if produced from renewable energy sources, it is one of the most promising energy vectors within the energy transition with enormous potential to decarbonise high-energy consuming sectors [18]. This versatile energy carrier can be transported, stored, combusted, or used as feedstock, similar to hydrocarbons today. Current H_2 uses include energy-intensive industries such as petrochemical refining or fertilizer production, but it could also play a significant role in other sectors in the near future such as heating, steel production, energy storage or mobility applications among others.

2.2 Hydrogen Value Chain

2.2.1 Hydrogen Production Pathways

Even though H_2 is the most abundant chemical molecule in the universe, this element is not found on its pure form on Earth and is integrated in other molecules as water (H_2O) and hydrocarbons such as methane (CH_4). These molecules need to be split to obtain pure H_2 and for this purpose the delivery of energy is necessary. The main routes for H_2 production are presented in Figure 3 below, containing its energy source, the production technology, and its associated emissions and finally the H_2 colour spectrum. This H_2 colour spectrum has been accepted by the industry and the main colours available in the industry are grey, blue and green:

- **Grey hydrogen**: It is the most common form of producing H_2 at mass scale and its technology methods is SMR (Steam Methane Reforming), a process where steam and NG (natural gas) are heated at high temperatures and pressures to react and produce syngas, a mixture of H_2 and carbon monoxide, CO (1). Subsequently, in what is called the "water-gas shift reaction," the carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen (2). The combined output from the steam methane reforming reaction and the water-gas shift reaction (3) involves a final process step called "pressure-swing adsorption" where carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen [19].

  (1) Steam-methane reforming reaction: $CH_4 + H_2O \rightarrow CO + 3H_2$

  (2) Water-gas shift reaction: $CO + H_2O \rightarrow CO_2 + H_2$

  (3) Combined output flow to the pressure-swing adsorption: $CH_4 + 2H_2O \rightarrow 2CO_2 + 4H_2$

- **Blue hydrogen**: For the immediate future the majority of the H_2 to be produced will be used industrially in the form of grey H_2, potentially turning to blue as more CCUS (Carbon Capture, Utilisation and Storage) projects take off [20]. CCUS technologies capture the CO_2 obtained as the by-product of burning the fossil fuels in the different available production technologies.

- **Green hydrogen**: Produced from renewable energy sources that provide electricity to electrolysers, specific equipment for producing free-CO_2 H_2 by splitting water into H_2 and oxygen (4).

  (4) $2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)$

- **Others**: other less common ways to produce H_2 are from nuclear energy (pink), from natural gas pyrolysis (turquoise) or from coal gasification (brown or black).

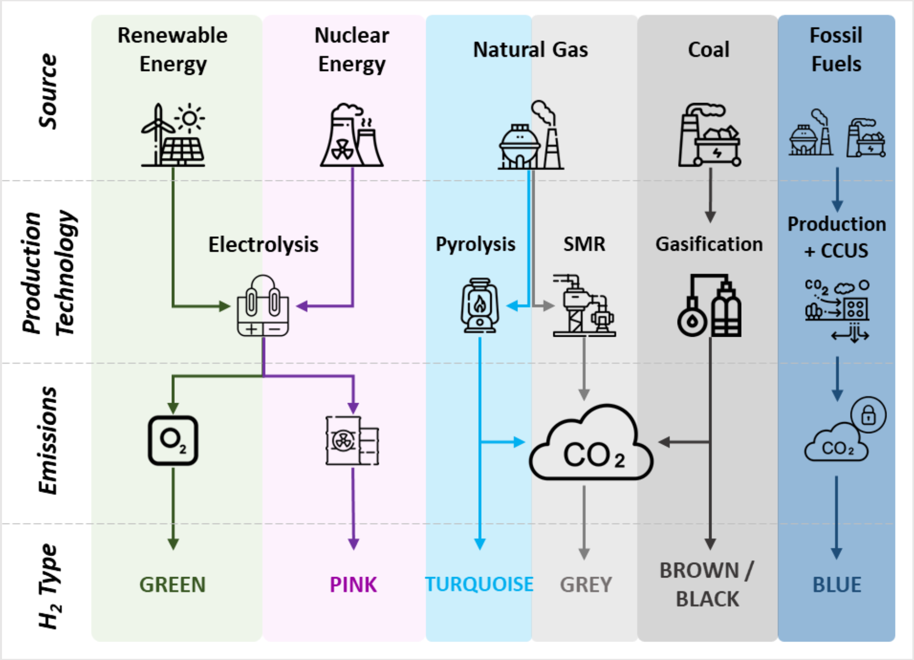


Figure 3: H_2 Production Sources, Technologies, Emissions, and its related colours. Source: own elaboration based on [20], [18]

2.2.2 Hydrogen Global Demand and High-Consuming Sectors

Global H_2 demand reached 94 Mton in 2021, recovering from the 2020 slight decrease in the refining and chemical sectors due to the pandemic and exceeding its previous historical maximum reached in 2019 with 91 Mton [7]. As observed in Figure 4 below, this demand is covered by the following industries:

- **Refining industry** covers an average of 45% of the global demand being the most H_2 consuming sector. Here, H_2 is indispensable as O&G companies use it in a process called hydrodesulphurisation, to remove sulphur impurities from crude oil and upgrade it to lighter products with higher quality.
- **Ammonia (NH_3)**: covering an average of 35% of the global demand it is the second-most H_2 consuming sector. NH_3 is an essential global commodity mainly used to produce synthetic nitrogen-based fertilizers. H_2 and nitrogen are used in the NH_3 production process.
- **Methanol (CH_3OH):** methanol is mainly used as a feedstock to produce chemicals as well as other consumer and industrial products.

- **Iron & Steel:** considered as more recent applications in the steel-making industry, hydrogen-based direct reduced iron (DRI) and H_2 blending in DRI, or blast furnaces are gaining momentum during recent years.
- **Other:** other sectors where H_2 could have a potential impact in the future but remain untapped nowadays are transport, heating and power generation among others.

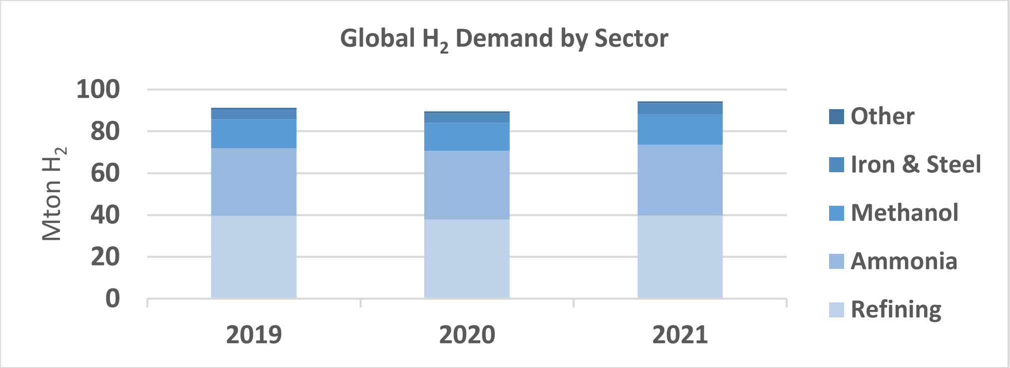


Figure 4: Global H_2 Demand by Sector 2019-2021. Source: Own elaboration based on data from IEA [7] [18]

The 94 Mton H_2 global demand represents a significant 2.5% of the global final energy consumption on an energy content basis [7] and generates 2.3% of global CO_2 emissions [21]. Although the projections and expectations of green H_2 for the medium-term are high, currently more than 99% of it is produced from fossil fuels [7], being therefore a high-priority sector to be decarbonized.

2.2.3 Hydrogen Storage & Transportation

2.2.3.1 Hydrogen Properties

H_2 is a versatile energy carrier with different option of storage and transport, thus enabling various combinations depending on key factors such as distance between production and end-use, demand required, storage time or end-use sector among others.

As of today, H_2 is produced close to the end-use due to two key factors:

- More than 99% of it is produced from fossil fuels, with a worldwide developed transportation and storage infrastructure. Therefore, it is easier to transport the fossil fuels until the end-user facility, which then use them for producing the required H_2.
- H_2 volumetric energy density (energy per unit of volume) in its natural form (gas) is characterized by having one third of the value of natural gas energy density at the same pressure and temperature. Therefore, much more space is needed for its transportation. Moreover, its boiling point is -253ºC so the possibility of transporting it in the liquified form needs of high-energy requirements [7].

However, as both production volumes and transport distances expand to reach the increasing global H_2 demand, infrastructure would need to be further developed. As a clear example of this need is the EU market, which through the implementation of REPowerEU plan in May 2022 in response to Russia’s invasion to Ukraine, the

European Commission amplifies the targets and completes the implementation of the European H_2 strategy. In this plan, the European Commission identifies renewable H_2 as an important energy vector to move away from Russia fossil fuel imports and targets not only the production of 10 million tonnes inside the EU but also the import of 10 million tonnes of renewable H_2 and its derivatives by 2030 [5].

2.2.3.2 Hydrogen Storage

There are different storage options mainly depending on the timescale and amount of H_2 to be stored:

- **Compressed Hydrogen**: most mature form of storing H_2 and is usually employed for short-term and small-scale storage. The H_2 is usually compressed at pressures ranging 700-800 bar although it could be compressed at lower pressures (200-300 bar) [12]. The main disadvantages of this storage option are the difficulty of handling these high-pressures alongside the safety risks associated. Moreover, due to its low energy density, compressed H_2 still occupies much more space than its fossil-fuel competitors such as gasoline or natural gas (refer to Figure 6) and is very expensive in energy terms (see Figure 5).

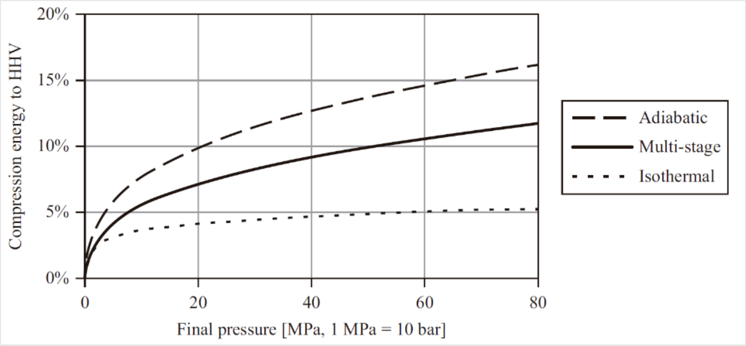


Figure 5: Energy cost of compressing H_2 relative to its High Heating Value [12]

- **Liquid Hydrogen**: converting H_2 gas to liquid implies reaching its boiling point temperatures (-253ºC) thus being an energy consuming process. This energy cost is currently about 10-12 kWh/kg H_2, so around a third of the energy contained in H_2 is consumed during this process [12]. Although this is the form of storing H_2 which requires the least volume (70 kg/m^3), it still needs more space than storing natural gas (see Figure 6). Moreover, its insulation has both technical and volume requirements to avoid heat intrusion traduced in expensive and multilayer vessels.
- **Chemical Storage**: this last option implies the conversion of H_2 into different chemical substances that contain a significant H_2 weight such as NH_3 (17.65% H_2 content), methanol (12.5% H_2 content) metal hydrides (up to 7.6%), chemical hydrides (6-8%), or Liquid Organic Hydrogen Carriers – LOHC (5-8%) [22]. The main disadvantage of this storage method is the conversion and re-conversion costs.

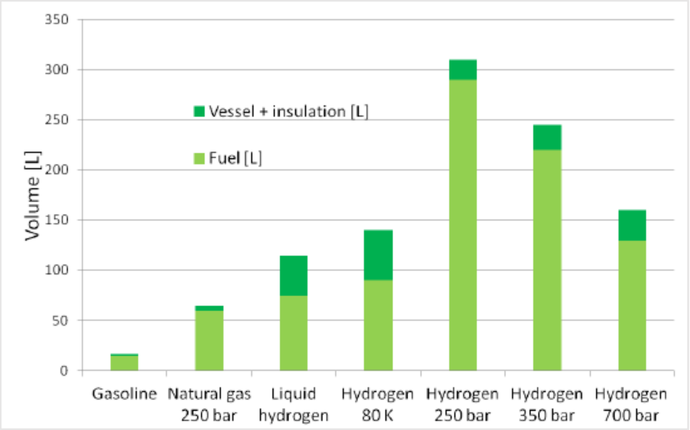


Figure 6: Comparison of storage volume needs for various H_2 storage options, gasoline, and natural gas [22]

These different storage options are also compared in terms of energy density (kWh/kg) and volumetric energy density (kWh/L) in Figure 7, which clearly shows NH_3 and methanol as the most interesting options to store and transport H_2.

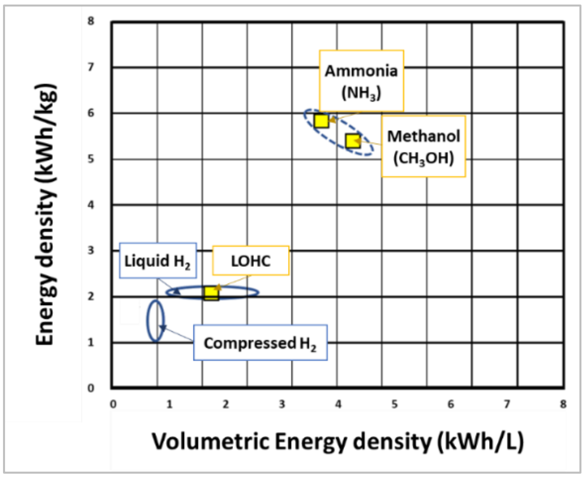


Figure 7: Main H_2 storage and transportation options. Source: own elaboration based on [12]

2.2.3.3 Hydrogen Transportation

The main transportation pathways are by pipeline or by ship for medium to long distances while road transport stays as a possibility for short distances:

- **Road transport**: carried out by trucks, where H_2 can be transported compressed or liquefied. Common for local areas and short distances.
- **Pipeline**: specific H_2 pipelines allow it to be transported in its compressed form. However, as of today only 5,000 km of pipelines are solely dedicated to H_2 [23]. New networks are being planned and existing natural gas networks can be retrofitted to allow H_2 transportation. Moreover, existing natural gas networks allow a certain percentage of H_2 blending in low concentrations (currently between 5-10% is allowed but looking to expand this number soon, it is country and pipeline-dependant).

- **Shipping**: within the maritime options, H_2 transport in the form of NH_3 is currently the most viable option: transport costs for liquefied H_2 are high and LOHC is an embryonic technology, while NH_3 has lower costs and the experience and infrastructure for its transport is already in place. Moreover, NH_3 is an extremely energy-dense molecule that can hold more H_2 per unit volume than liquid hydrogen itself, and which can be kept in a liquid state without significant effort, either by cooling to -33°C or by raising its pressure to 10 bar [12].

2.3 Green Hydrogen Role in the Energy Transition

2.3.1 Green Hydrogen Projections

Current green H_2 production accounts for less than 1% of global capacity due to its high costs compared to its high-related costs in comparison with fossil fuels. However, the development potential is huge, and both a decrease in costs and a great deployment are expected due to technology performance improvement, continuous decrease in renewable energy costs or the achievement of economies of scale in the mass production and roll-out of electrolysers.

It is certainly difficult and, at this point, abstract to precisely quantify the projections for year 2030 as these vary day by day with increasing projects announced alongside the establishment of new policies to propel the development of the technology. However, some numbers from the main industry references are given to measure the scale of the opportunity at worldwide and European levels, and represented in Figure 8 below:

- **Worldwide:** IEA (International Energy Agency) Global Hydrogen Review is an annual publication that tracks H_2 production and demand worldwide, as well as progress in critical areas such as infrastructure development, trade, policy, regulation, investments, and innovation [24]. According to this report and compared with the Hydrogen Project Database 2022 [25], the capacity of announced green H_2 projects has increased 30% from 2022 within one year. By 2030, green H_2 projects in FID (Final Investment Decision) and feasibility stages sum up around 14 Mton production, while including the early-stage projects add up to 28 Mton. It should be highlighted that the pace should advance to reach the NZE (Net Zero Energy by 2050) scenario, which would require over 50 Mton production.

- **Europe:** The European Commission's REPowerEU plan in response to Russia's invasion to Ukraine proposed the revision of the EU H_2 strategy, doubling the previous objective of green H_2 generation to 10 Mton annual domestic production, plus an additional 10 Mton of annual H_2 imports. Based on a Joint Declaration from the European Electrolyser Summit [26], this would need to accelerate the deployment from an almost non-existent business to having an installed capacity of 90-100 GW only for the domestic production.

The above-mentioned numbers are shown in Figure 8 below. It is essential to clarify here that this illustration only aims to give a snapshot of the size of opportunity behind green H_2 development.

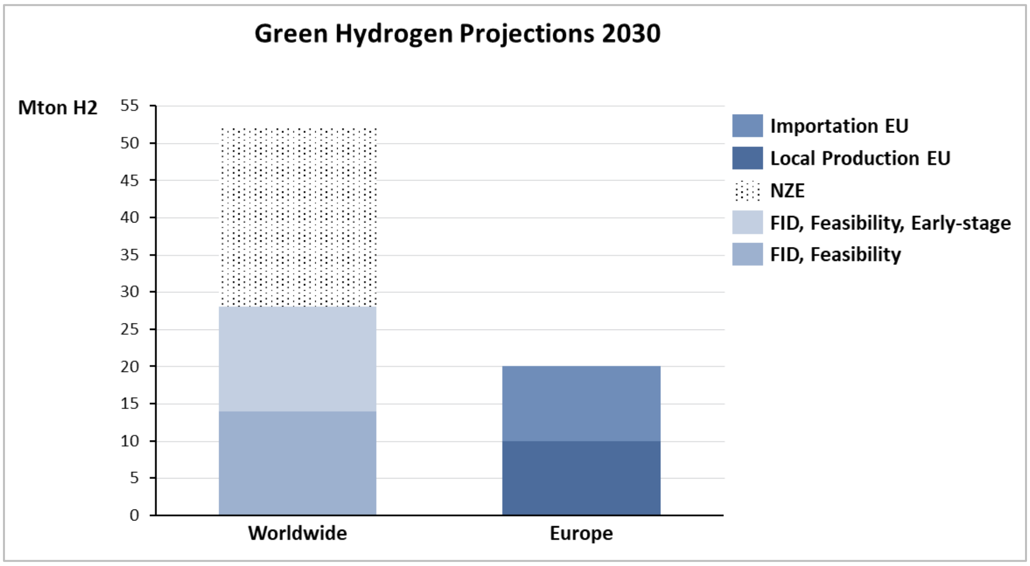


Figure 8: Green H_2 projections for year 2030. Source: own elaboration based on [24] [5]

2.3.2 Green Hydrogen Derived-Fuels

One of the major drivers of green H_2 demand is the growing project pipeline for hydrogen-derived fuels, such as NH_3, methanol, and synthetic hydrocarbons, which offer advantages in terms of storage and transportation compared to pure H_2. These fuels can use existing infrastructure like natural gas pipelines and existing applications. However, the production of hydrogen-based fuels requires additional resources, energy, and feedstock for the conversion of H_2 into these forms.

As of 2022, most of hydrogen-derived fuels projects were on pilot stages consuming a negligible amount of green H_2. However, the increasing appetite due to attractiveness and maturity of the sector has grown exponentially. More than 17 Mton of H_2 equivalent, involving over 300 projects are projected to be operational by 2030 as identified by the IEA in the Global Hydrogen Review 2023, doubling the capacity from the previous year analysis [24].

This trend is set to continue through 2030, with NH_3 accounting for roughly 90% of the announced production, as observed in Figure 9. This substantial share of NH_3 may signal the readiness of the fertilizer industry to adopt low-emission alternatives as feedstock. NH_3, being carbon-free, simplifies supply chains and presents an attractive early mover among hydrogen-based fuels. Moreover, its ability to serve as a long-distance carrier for H_2 capitalizes on the established expertise in NH_3 transportation developed by the fertilizer industry over the years. Green NH_3 will be further analyzed in next chapters to fully understand the size of the opportunity and assess its potential impact in the future energy system.

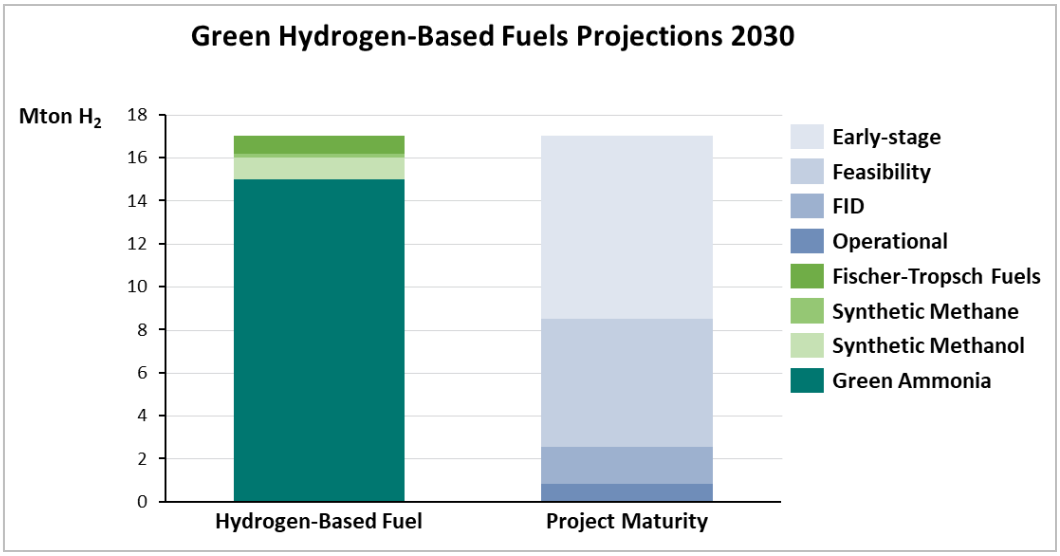


Figure 9: Green hydrogen-based fuels projections for year 2030. Source: own elaboration based on [24]

3. Ammonia state-of-the-art

3.1 Ammonia Value Chain

3.1.1 Ammonia Production Pathways

NH_3 is an essential global commodity mainly used to produce synthetic nitrogen-based fertilizers. It is the second-most H_2 consuming sector covering an average of 35% of its global demand [7].

As well as for H_2 production, almost all NH_3 production relies on the use of fossil fuels, specifically from natural gas (72%), coal (22%) and by-products such as naphtha and heavy fuel oil [2]. NH_3 needs both pure H_2 and nitrogen as inputs for the Haber-Bosch process. This industrial process developed in the early 20th century by Fritz Haber and Carl Bosch involves the catalytic reaction of these gases at high temperature to form NH_3 as shown in Figure 10 below. This exothermic reaction involves high pressures (150-300 atmospheres) and high temperatures in the reactor (400ºC – 500ºC) to obtain NH_3 with 96% to 98% purity.

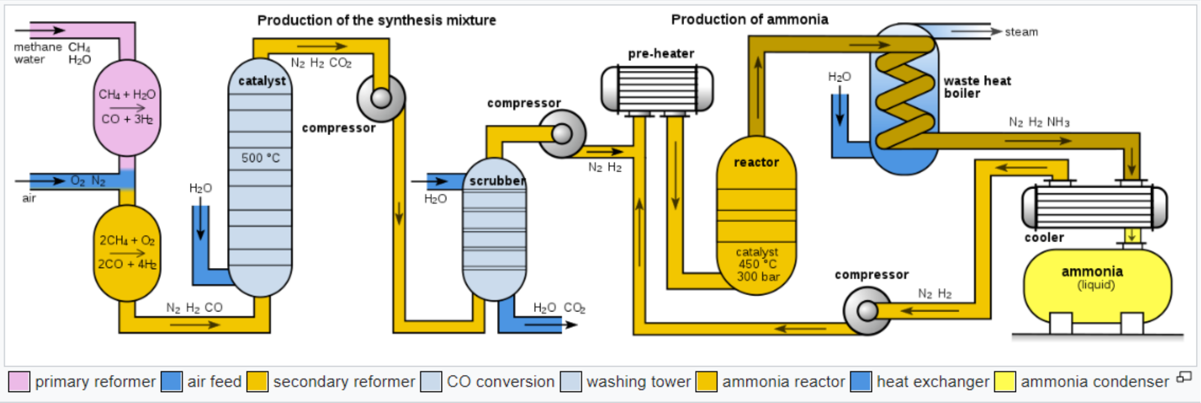


Figure 10: Haber-Bosch process for grey NH_3 production from SMR [11]

The Haber-Bosch process can also be powered by green H_2, thus producing the so-called green NH_3. However, this transition requires the need of additional equipment. Not only the electrolysers are needed to produce the pure H_2 from water and electricity, but also a new supply of nitrogen is needed. The latter is provided with the installation of Air Separation Units, which also need an electricity input in order to capture and separate the air into pure nitrogen. Green NH_3 production process is depicted in Figure 11.

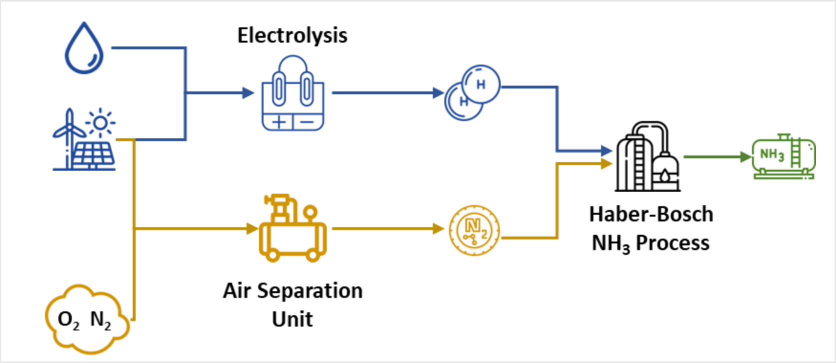


Figure 11: Green NH_3 production schematic. Source: own elaboration

3.1.2 Ammonia Global Demand & High-Consuming Sectors

Global NH_3 demand in 2022 is estimated at 185 million tonnes per year [13] [2] and around 85% is used to make fertilisers for agricultural purposes. Anhydrous NH_3 has been the basis for synthetic nitrogen fertilisers since the invention of the Haber-Bosch process which made it possible to produce NH_3 on an industrial scale. The remaining 15% of the demand comprises its use in a wide variety of sectors and industry applications: mining explosives, refrigerants, fabrics and fibres, products for the chemical and pharmaceutical industry, cleaning products, plastics and paints, or abatement of nitrogen oxides (NO_x) among others [2].

NH_3 demand has been steadily increasing historically as it is related to growing fertiliser and food demand. Therefore, it is expected that the fertiliser industry will remain as the highest-consuming sector in the short to medium term. However, new applications being explored include green NH_3 as a zero-carbon fuel in the maritime sector and for power generation as well as the potential of being a hydrogen carrier for long-range transport due to its enhanced storage properties.

3.1.3 Ammonia Storage & Transportation

As NH_3 is a well-established and mature sector, it has a high technological readiness in terms of storage, transport, and distribution methods. To support the seaborne NH_3 trade, around 20 Mton/year, a significant network of ports, vessels, pipelines, and dedicated storage facilities in NH_3 -producing and consuming countries are needed [13].

Although NH_3 can normally be stored in a liquid or gaseous state, having various options commercially available, it is typically stored in its liquid form, which has a much higher energy density than its gaseous form. Therefore, when large NH_3 quantities are involved (e.g. production facilities, long-distance transportation), NH_3 needs to be cooled at -33ºC, as can be observed in previous Figure 10. The largest NH_3 storage facilities are found at ports close to NH_3 production centers and can individually accumulate up to 50 kt [2]. Figure 12 below provides the mapping of NH_3 loading and unloading storage infrastructure in ports worldwide, a well-established and developed network that allows international trade.

Figure 12: NH_3 ports infrastructure worldwide: loading and unloading storage facilities location. Source: retrieved from [2]

In terms of NH_3 transportation, there are several options available which depend largely on the quantity to be transported. Pipelines provide a reliable and efficient mode of transportation particularly for shorter distances, continuous flow and larger quantities. Rail transportation is also a common possibility for NH_3 distribution within shorter distances while road transport through trucks is also available when delivery locations cannot be reached by other means. Finally, for international trade, NH_3 is transported through specialized tankers, with a dedicated fleet of 40 vessels running continuously [1].

NH_3 transportation and storage options should be considered individually for each project, taking as well into account the safety risks that NH_3 operations entail. NH_3 is a hazardous chemical which, in ambient conditions, is a toxic gas. NH_3 is a toxic, highly reactive, corrosive gas with a strong odor and hardly flammable, so it is necessary to keep in mind the main characteristics of this gas in order to take the necessary measures when handling it, select protective equipment for the personnel and materials for its storage, and define design characteristics to minimize risks of exposure. For this reason, it is often preferable to store NH_3 as a liquid under refrigeration (-33 °C) and not under pressure [2] [13].

3.2 Green Ammonia Role in the Energy Transition

The production and utilization of green NH_3 support the shift away from fossil fuel dependency, reducing greenhouse gas emissions and supporting the decarbonization of industries across various sectors. NH_3 is considered one of the most CO_2 emitting industries due to the utilization of fossil fuels for its production. While grey NH_3 production has reached efficiency technical limits with a carbon footprint of less than 2 tonnes CO_2 / tonne NH_3, in certain regions such as China coal-based NH_3 is the main production pathway with emissions above 3.5 tonnes CO_2 / tonne NH_3, as shown in Figure 13.

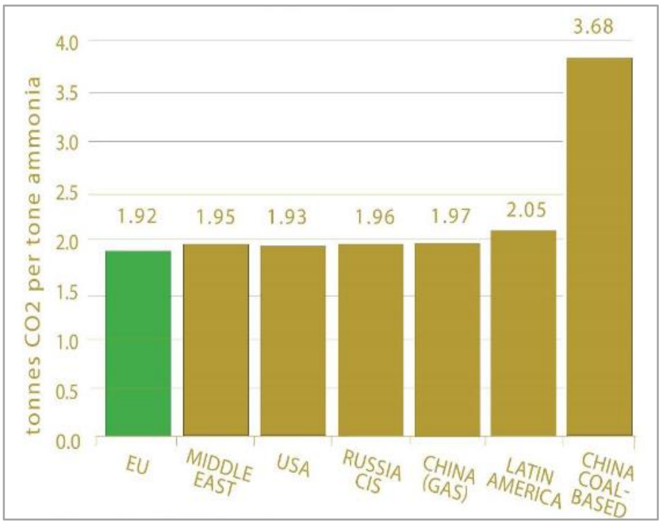


Figure 13: Tonnes CO_2 emitted per ton of NH_3 produced by region and production pathway. Source: [27]

The development of green NH_3 from renewable energy sources would contribute to the deep decarbonization of the industry as this production pathway would be zero-carbon emissions. Moreover, the establishment of carbon markets will incentivise companies to reduce their emissions by targeting carbon-free production pathways.

4. Ammonia global market assessment and demand projections

4.1 Green Ammonia Competitiveness

When looking to green NH_3 projections it is first essential to understand what the competitiveness level of green NH_3 versus the mature and reliable grey NH_3 production is. Grey NH_3 cost is fully dependent on natural gas price:

- Historically, gas prices have been in the range of 2-10 USD/MMBtu (Million British Thermal Units) and thus NH_3 cost has been in the range of 200-400$/ton, as observed in Figure 14 for year 2020.
- Years 2021 and 2022 have been characterised by several worldwide events that created uncertainty and great volatility around the natural gas prices (mainly higher demand post-pandemic, and loss of Russian natural gas supply due to Ukraine's war). During these years, it can be seen that grey NH_3 prices ranged the 600-1,200$/ton with peaks of over 1,600$/ton.
- Future projections target that natural gas prices will recover historical ones [2] [1]. However, the natural gas market is quite volatile and the potential carbon pricing schemes to be included in the policy and regulatory framework could increase the cost of grey NH_3 production.

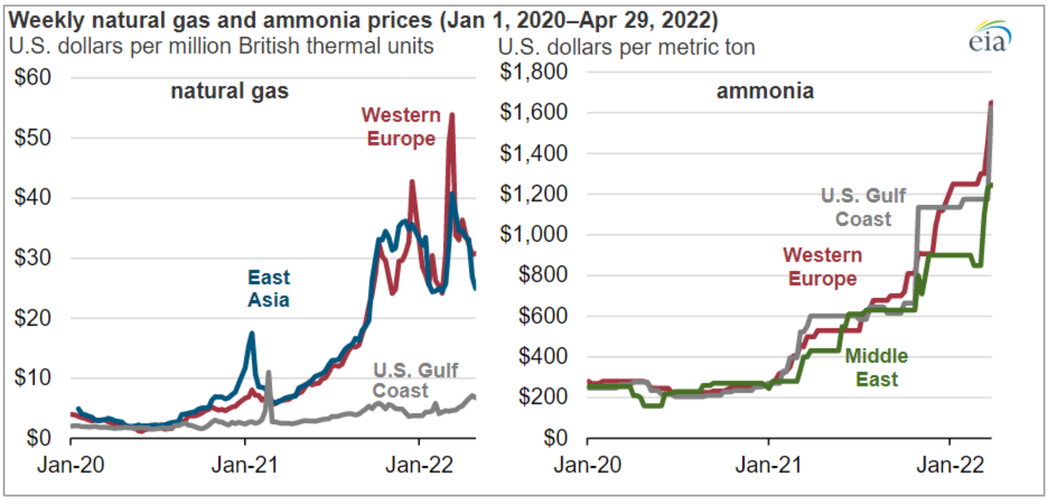


Figure 14: Grey NH_3 economics historical outlook. Source: retrieved from [28]

The volatility of the natural gas prices alongside the increasing sustainability demand through stricter regulatory and policy frameworks is propelling the need of green NH_3. While grey NH_3 pricing relies on natural gas, green NH_3 pricing mainly relies on electricity and electrolyzers costs:

- In Figure 15 it can be observed that green NH_3 production is dependent on where it is produced due to renewable energy costs, therefore each business case should be carefully designed and calculated in order to be competitive with grey NH_3 cost. As of now, the industry is incipient and both the cost of the electrolysers as well as renewables cost remains high. Therefore, it can be observed that green NH_3 cost is higher than grey NH_3 for all the locations shown in the figure.

- Green NH_3 is expected to become competitive with grey NH_3 from 2030 onwards. However, the process could be accelerated by the application of CO_2 taxes as well as with the support of financial mechanisms with CfD (Contracts for Difference) such as the first-in-a-kind schema developed by H2Global [29].

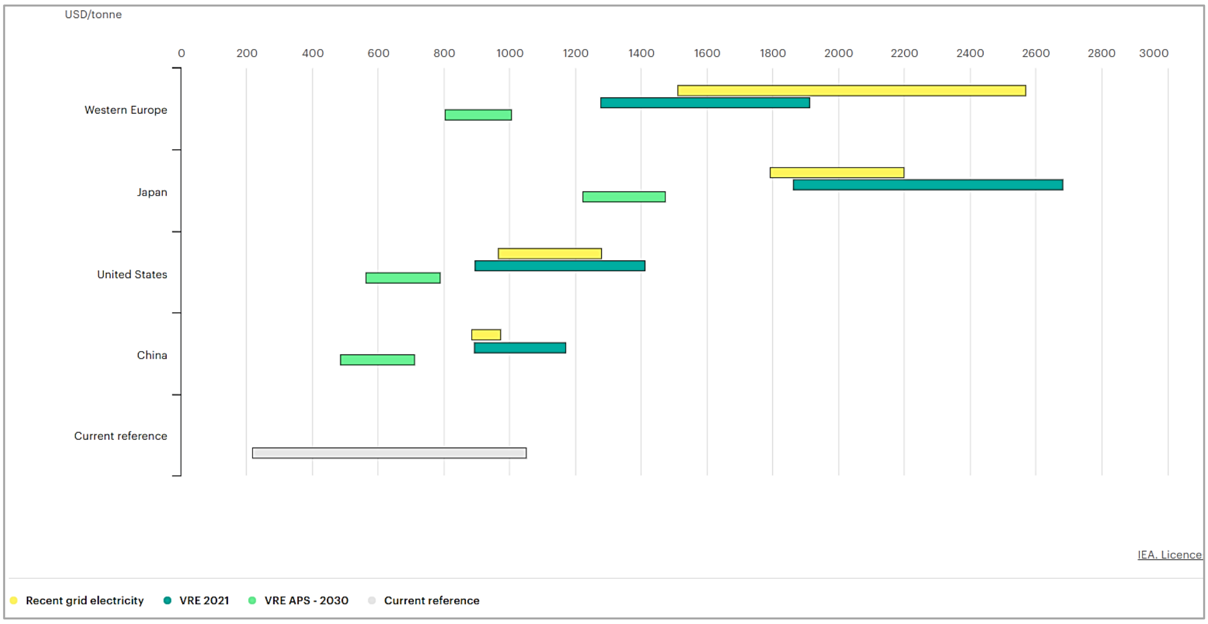


Figure 15: Indicative production costs for green NH_3 in selected regions compared to grey NH_3. Source: retrieved from [30]

As a conclusion, green NH_3 is expected to become competitive with grey NH_3 in the medium term. Nonetheless, in high renewable energy potential areas with competitive energy prices, the parity with grey NH_3 can have a shorter-term outlook. In section 5, the techno-economic analysis would analyze high-renewable energy areas to give a realistic view on the short-term market opportunities and project viability.

4.2 Green Ammonia Demand Outlook

The production of green NH_3 has the capacity to significantly influence the transition towards carbon neutrality through the decarbonisation of its main current use, which is in the production of fertilisers. However, in addition to conventional uses, green NH_3 as a product allows the incorporation of a zero carbon dioxide emissions alternative capable of opening doors to new uses and decarbonising sectors that to date have not had a less polluting alternative.

The demand outlook has been calculated in the short-medium term (2030) and long-term (2050) with the average of the most representative reports and estimations on green NH_3 demand from several trusted sources [2] [31]. These outlooks have been classified by the final use of green NH_3 in conventional markets (Figure 16) and emerging markets (Figure 17). In both it can be observed that green NH_3 demand by 2030 is quite moderate, representing approximately a 10% of all the NH_3 demand, also aligned with the grey vs green competitiveness assessed in the previous section. However, green NH_3 is expected to cover most of the NH_3 demand by 2050, propelled by the huge increase of the emerging markets, being its use as marine fuel the largest demand sector.

- **Existing Markets (Fertilizer, Industry)**: expected to be largest short-term market for green NH_3, with 8 Mton/year consumption by 2030, increasing to 87 Mton/year by 2050.

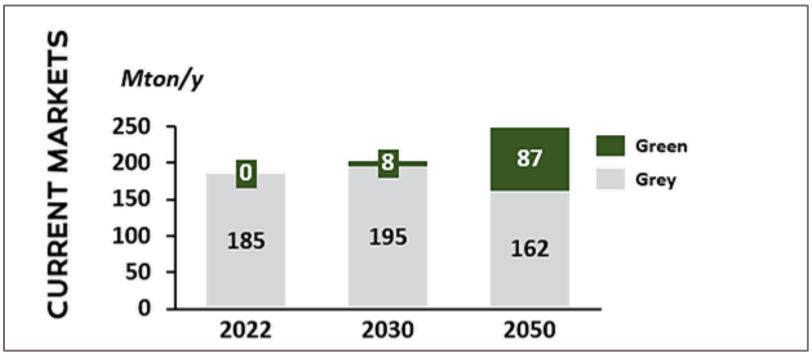


Figure 16: Grey & green NH_3 demand in conventional markets.

Source: own elaboration based on [2] [31]

- **Emerging Markets (Marine Fuel, Power Generation, Hydrogen Carrier)**: expected to be largest long-term market for green NH_3, with almost 300 Mton/year consumption by 2050.

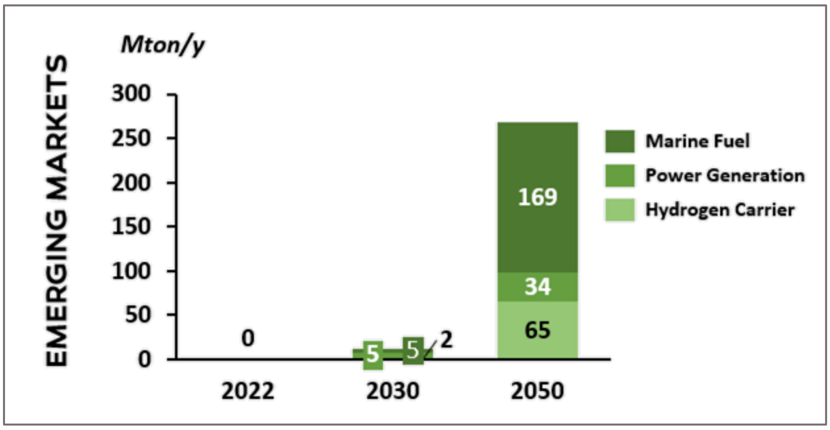


Figure 17: Grey & green NH_3 demand in emerging markets.

Source: own elaboration based on [2] [31]

4.2.1 Existing Markets

Existing markets, namely the fertilizer industry and other industrial uses, covered all the NH_3 demand in year 2022. From these markets, as observed in Figure 18 the fertilizer industry represented the 85% of the demand while the other 15% belongs to other industrial uses [2].

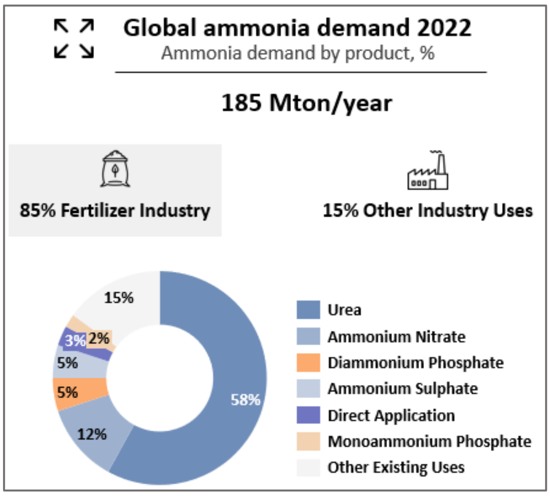


Figure 18: Global NH_3 demand by product, year 2022. Source: own elaboration based on [2]

4.2.1.1 Fertilizer Industry

It is expected to be the main driver for green NH_3 demand in the short to medium term, especially after years 2021 and 2022, when increasing natural gas prices worldwide forced fertilizer companies to close their production facilities due to non-accessible grey NH_3 prices. The fertilizer industry transforms air, natural gas and mined ores into plant nutrition products based on the three essential nutrients: nitrogen (N), phosphorus (P), and potassium (K) [27]. The fertilizers production value chain is represented in Figure 19 below, highlighting the importance of NH_3 as a byproduct and differentiating between the different final mineral fertilizers.

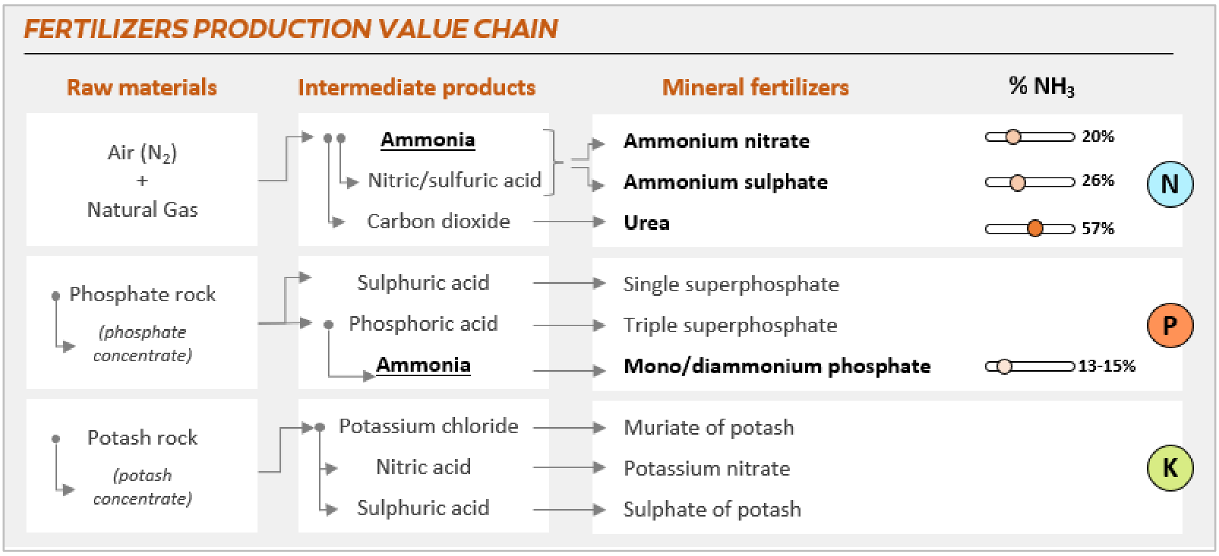


Figure 19: Fertilizers production value chain. Source: own elaboration based on [26]

- **<u>Nitrogen Fertilizers (N)</u>**: represent 78% of global NH_3 demand, as here NH_3 is used as an intermediary to produce all N-Based fertilizers such as urea (57% NH_3 content) or ammonium nitrate (20% NH_3)
- **<u>Phosphate Fertilizers (P)</u>**: Produced from mining phosphate rocks. NH_3 is a byproduct in some P-Based fertilizers as ammonium phosphate (15% NH_3)

- **Potassium Fertilizers (K)**: Produced from mining potash rocks. NH_3 is not used as an intermediary / byproduct in K-Based fertilizers

Within the fertilizer industry it is essential to highlight that urea covers more than half of the global NH_3 demand as seen in Figure 18. Urea, as illustrated in Figure 19, contains carbon dioxide in its synthesis ($CO(NH_2)_2$) and therefore, integrated natural gas-based NH_3 -urea plants are a common practice worldwide as urea uses the CO_2 from the Steam Methane Reforming process to obtain grey H_2 prior to obtain grey NH_3 [2]. Although urea could be fully decarbonized by using biogenic CO_2, natural-gas based NH_3 -urea production will still drive the majority part of the demand in the long-term following industry projections (see Figure 16).

4.2.1.2 Other Industrial Uses

Other industrial uses cover 15% of current global demand and comprise several sectors: fibers and plastics, explosives, NO_x abatement, refrigeration or pharmaceutical among others [1] [2]. This market is really fragmented and therefore the green NH_3 projections and demand are not clearly proven.

4.2.2 Emerging Markets

NH_3 demand for other offtake markets is currently negligible due to incipient technology maturity and high costs although it is expected to grow substantially until 2050, as observed in Figure 17.

4.2.2.1 Marine Fuel

Green NH_3 surges as an excellent zero-emission fuel alternative to be used particularly in the maritime transport in the long-term, expected to gain market share after 2030 when technology matures and being the largest market by 2050 with 169 Mton/year demand. International shipping accounts for 2% of global CO_2 emissions due to the massive use of fossil fuels (over 99% share in the mix) [32], and increasing policies are driving the demand for more sustainable fuels.

The International Maritime Organization set up the first framework in 2018 for reducing GHG emissions vs 2008 levels by at least 40% in 2030 and 70% in 2050 [33], although it should be revised upwards during 2023. A more compelling framework has been recently established in the EU, with the target of reducing GHG emissions vs 2020 levels by at least 80% in 2050 and reach at least 2% of specific renewable fuels as of 2034 [34].

There are several technical scale-up challenges that the sector needs to overcome so that green NH_3 becomes a practical and competitive marine fuel:

- **Engine technology**: NH_3 as marine fuel would propel either internal combustion engines (ICEs) or fuel cells (FCs) with several common technical issues to achieve commercialization: toxicity control, NO_x emissions avoidance and low flammability [13] [35].
    - **ICEs**: NH_3 is used as a fuel in modified 2-stroke and 4-stroke ICEs, requiring temperatures over 600 ºC for the NH_3 to be combusted with an efficiency of 50%. Current models are in a Technology Readiness Level (TRL) 5-6 and use a dual-fuel mix, meaning that NH_3 is mixed with air and in the combustion chamber another fuel is inserted to facilitate the combustion

(see Figure 20 below). It is expected that by year 2026-2028 the ICEs would be able to run fully on NH_3 when acquiring higher TRLs [13].

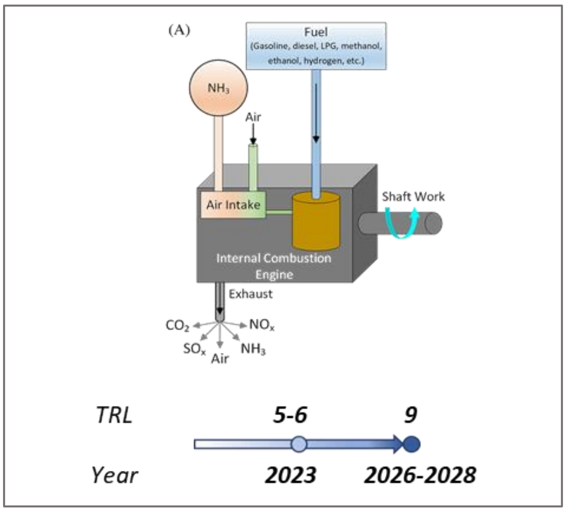


Figure 20: NH_3 as marine fuel in internal combustion engines. Source: own elaboration based on [13] [35]

  - **FCs**: fuel cells are an alternative to ICEs but currently remain with lower TRL (3-4). There are three different type of fuel cells with their particularities, as seen in Figure 21. If using Alkaline FCs (AFC) and Proton Exchange Membrane FCs (PEM), NH_3 needs to be cracked back into H_2 at temperatures between 600 ºC and 900 ºC. This leads to high equipment costs and energy losses. Moreover, in the case of PEM the H_2 needs to be further purified. Finally, Solid Oxide FCs (SOFC) can run on pure NH_3 but need higher temperatures up to 1,000 ºC, occupy more space and have less operating flexibility than AFC and PEM.

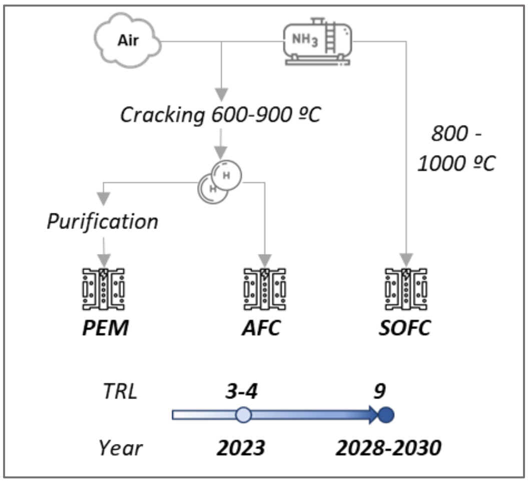


Figure 21: NH_3 as marine fuel in fuel cells. Source: own elaboration based on [13] [35]

- **Infrastructure requirements**: although the NH_3 trading industry is mature, with volumes of 18-20 Mton of grey NH_3 traded yearly (10% of global demand) [2], ports handling and bunkering of NH_3 to power the vessels entails a higher complexity degree [36]. Moreover, as current vessels cannot run on

NH_3, their engines would either need to be retrofitted or completely replaced by electrical-powered propulsion systems to allow the use of FCs.

- **Safety and regulation**: NH_3 is highly toxic, flammable, and corrosive chemical. It is a risk for humans and aquatic life in case of accident and leakage, requiring strict safety standards, measures, and training. Therefore, safety practices leveraging on NH_3 storage & transportation expertise need to be adapted for the use of NH_3 as fuel [36].
- **Alternatives competitiveness**: NH_3 is not expected to compete with marine fossil fuels in the short-term, but surges as a competitive zero-carbon option expected to gain market share when commercially viable. The main properties for assessing its competitiveness can be seen in Figure 22 and the main conclusions are:
    - **Marine fossil fuels**: compared to current marine fuels, NH_3 needs x2.75 & x1.75 storage than HFO (Heavy Fuel Oil) / MGO (Marine Gas Oil) and LNG (Liquefied Natural Gas) respectively to produce the same amount of energy. Although green NH_3 avoids all CO_2 related emissions, the adoption time will depend both on the GHG reduction targets ambition and its technology and infrastructure readiness.
    - **Low-carbon fuels**: liquified H_2 surges as the least interesting possibility due to lower volumetric energy density and energy-intensive storage conditions (-253 ºC). While green NH_3 has the potential for lower energy costs in the long term and is a zero-carbon fuel, e-methanol advantages rely on its immediate availability and ease of handling [35]. Additionally, it meets current safety and engine compatibility standards. E-methanol momentum in the shipping industry is expected to propel its demand by 2030 as there are already 56 methanol vessels in operation or on order [7] and international companies such as Maersk commit to e-methanol. Maersk, one of the global leaders in shipping services, has a 6 Mton/year green methanol demand by 2030 inside its strategy to reach net zero emissions by 2040 [37].

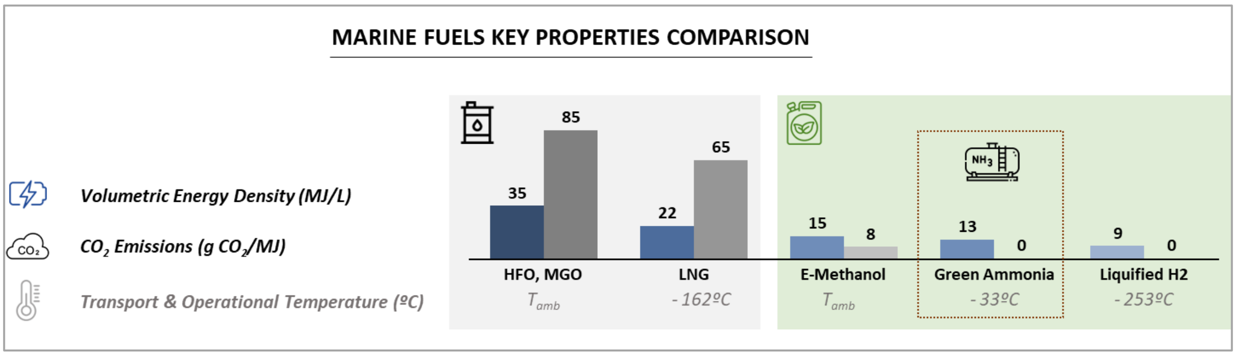


Figure 22: Marine fuels key properties comparison. Source: own elaboration based on: [2]

4.2.2.2 Hydrogen Carrier

The use of NH_3 as hydrogen carrier surges as a cost-effective option for long distances and medium to large-scale H_2 transportation, releasing again it at delivery point through cracking facilities. It is expected to have a role in the medium term propelled by H_2 importation targets from policymakers such as the European

Commission strategy REPowerEU, which establishes that half of the 20 Mton/year of green H_2 to be consumed in EU by 2030 should be imported [5]. It can be seen in Figure 23 that NH_3 as hydrogen carrier will have already a significant impact by 2030.

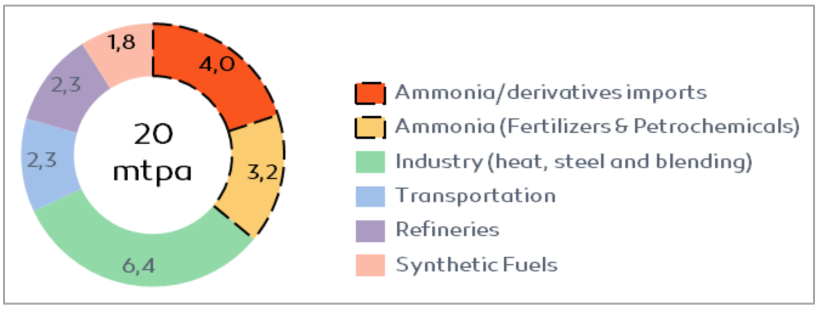


Figure 23: EU H_2 use by sector in 2030 (REPowerEU), mtpa (million tonne per annum). Source: own elaboration based on [5]

The target set up by the EU is increasing the appetite and several large-scale projects for importing green NH_3 have been announced. However, the adoption of NH_3 as hydrogen carrier will depend on the technology scale-up of cracking facilities and the competitiveness of NH_3 versus other H_2 transportation alternatives:

- **NH_3 cracking facilities**: NH_3 cracking is the technology needed for dissociating NH_3 into H_2 and nitrogen, and it is still a technology in R&D for industrial quantities. The main challenges associated with cracking are the high-temperature processes needed (500 ºC - 550 ºC) requiring heat supply with losses ranging 15%-30% as well as the low technological development of large-scale facilities, now with a TRL 5-6 [38].
- **Alternatives competitiveness**: the most established pathway for transporting NH_3 is as well the most cost-efficient way of large-scale H_2 transportation, pipelines [39]. However, pipelines are only available at regional scale or until a certain distance at international scale. Therefore, for long-distance transportation, NH_3 competes with liquified H_2 and with LOHC.

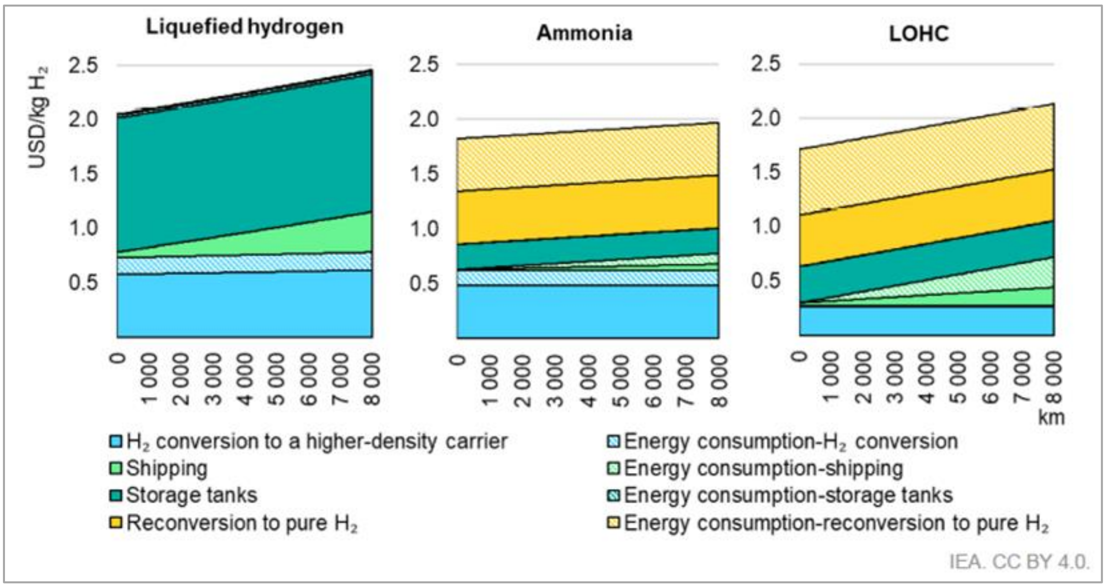


Figure 24: Indicative levelized cost of delivering H_2 by shipping-option step and distance in 2030. Source: retrieved from [39]

It can be seen from Figure 24 that NH_3 provides the most economic pathway for transporting H_2 at long-distances. Liquefied H_2 transportation costs increase significantly with higher volumes and longer distances due to the complexity of its transportation, facing similar problems than the above-mentioned explained for its use as a fuel (expensive storage tanks and boil-off losses due to the -253 ºC requirement). Regarding LOHC, these carriers have the disadvantage of containing only 4-7% H_2 in weight while NH_3 has 17.65% [22], therefore increasing the shipping costs and being a more feasible option at medium distances.

4.2.2.3 Power Generation

Green NH_3 is expected to have a role in power generation in the short to medium term due to Japan and South Korea government plans. Both countries are considering green NH_3 as part of their strategy to reduce CO_2 emissions and power generators are retrofitting coal-fired power plants without major modifications to enable co-firing with green NH_3:

- **Japan**: the Japanese fleet of coal power plants comprises 49GW of installed capacity, which accounted for 30% of electricity supplied in 2021 [40]. Co-firing coal with NH_3 offers a pathway to reduce CO_2 emissions, without phasing out the plants while also being a cost-effective decarbonization option in the short-term due to high renewable energy prices, as seen in Figure 25.

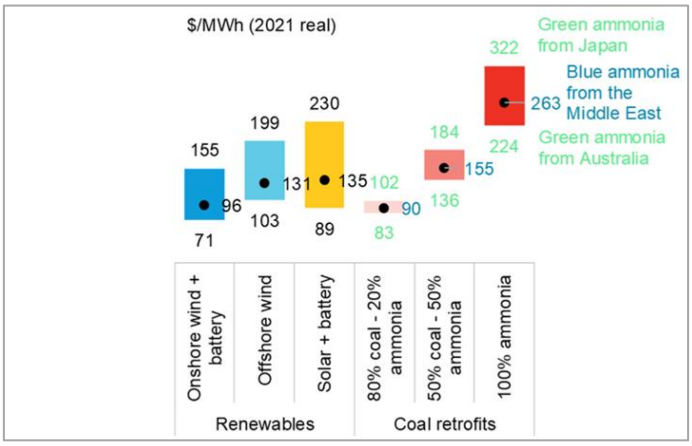


Figure 25: Comparison of levelized costs of electricity in Japan by 2030. Source: retrieved from [40]

Japanese power utility JERA launched in February 2022 an international bidding process to procure 0.5 Mton/year of clean NH_3, starting in 2027 and running into the 2040s. The fuel NH_3 is destined for the Hekinan coal power plant (1GW capacity). JERA and IHI aim to have a 20% co-firing demonstration operational by 2024 and a 50% by 2030 [41].

- **South Korea**: similarly than Japan, South Korea aims to co-fire 20% NH_3 at half of its coal power stations by 2035. The country currently has 60 coal-fired power plants with a capacity of 35.4GW, requiring an estimated 3.8 Mton/year of NH_3 [42].

However, it should be noted that several technical challenges arise, such as the ones mentioned for the use of NH_3 as marine fuel (control toxicity, NO_x emissions abatement and low flammability) alongside the necessity of an additional regulatory framework needed for storing and handling NH_3 at large scale for power production operations.

5. Green Ammonia Techno-Economic Assessment

Section 5 presents the required methodology to assess green NH_3 projects from a technical and economical perspective. It is comprised of 3 differentiated subsections considered to be essential in the analysis. First, the project location is defined, as regions with high-renewable potential should be targeted to potentially make the business case as attractive as possible. Then, a specific operational mode adapted to the existing resources and characteristics of the identified location is described alongside the main equipment and technologies required. Finally, the key financial metrics to be analysed are presented, which would lead to a detailed assessment of the viability of these projects and its potential as a decarbonisation pathway vs fossil fuels-based NH_3.

5.1 Green Ammonia Production in Brazil

5.1.1 Green Hydrogen and Ammonia Location Definition

Site-specific studies of regions with high-renewable potential are essential for providing reliable economic benchmarking of the attractiveness of developing a green NH_3 project. The levelized cost of ammonia (LCOA) is a metric widely used by the industry, as well as its homonymous LCOE (energy) and LCOH (hydrogen) for several reasons [43]:

- Measures lifetime costs divided by NH_3, energy or H_2 production
- Calculates present value of the total CAPEX and OPEX of an asset (NH_3 plant, power plant, electrolyzer…) over an assumed lifetime
- Allows the comparison of different technologies (e.g., wind, solar, natural gas) of unequal life spans, project size, different capital cost, risk, return, and capacities

Several reports have recently assessed the levelized cost of ammonia – LCOA in a country-wise overview for different configurations ([44] [45], [46], [47]) all leading to the conclusion that renewable energy and electrolyzer CAPEX represent more than 80% of the green NH_3 production cost.

Therefore, the first green NH_3 projects are expected to be in high yield solar and wind regions to capture low renewable electricity prices. Moreover, a good combination of these sources is expected to propel the electrolyzer utilization factor and reducing the need of either curtailing renewable energy or adding surplus H_2 storage with the extra costs associated [47].

Brazil is one of the countries with higher potential in the green H_2 and NH_3 economy. Accounting for almost 7% of the planet's renewable energy production [48] and with an impressive 84% of energy mix coming from renewables (7% solar PV, 11% onshore wind energy, 65% hydropower) [49], Brazil surges as one of the most attractive countries to develop green NH_3 in certain areas that combine the potential of solar PV and onshore wind, the most mature and deployed renewable energy sources, as illustrated in Figure 26 and Figure 27:

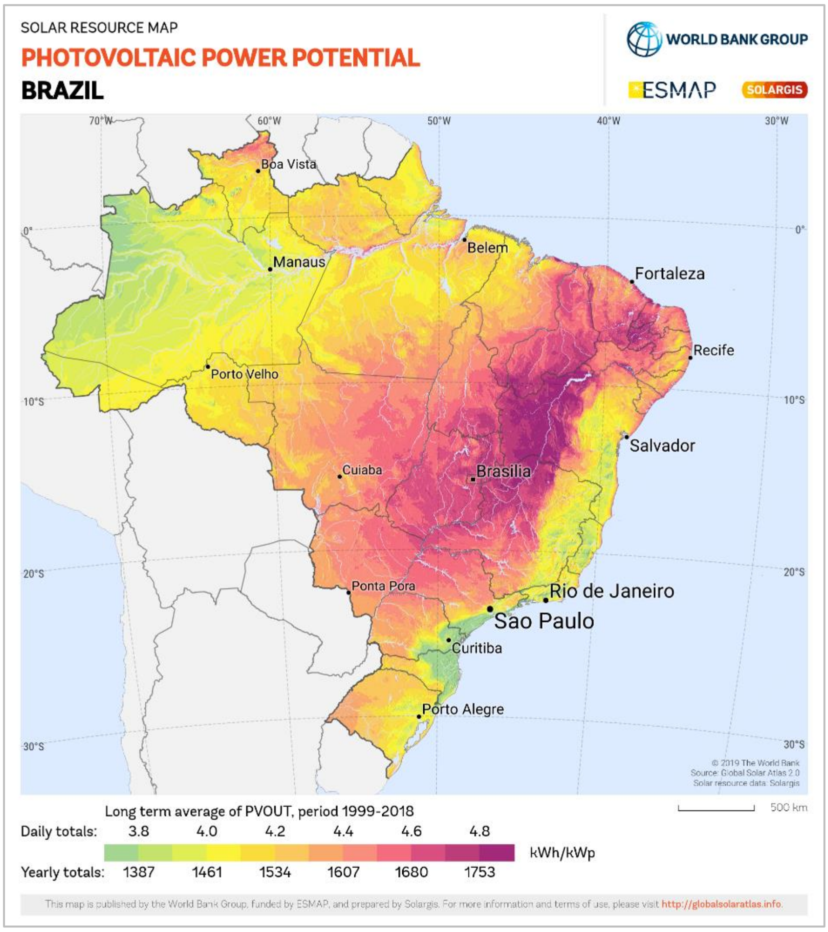


Figure 26: Solar PV power potential in Brazil, long term average period 1999-2018. Source: [50]

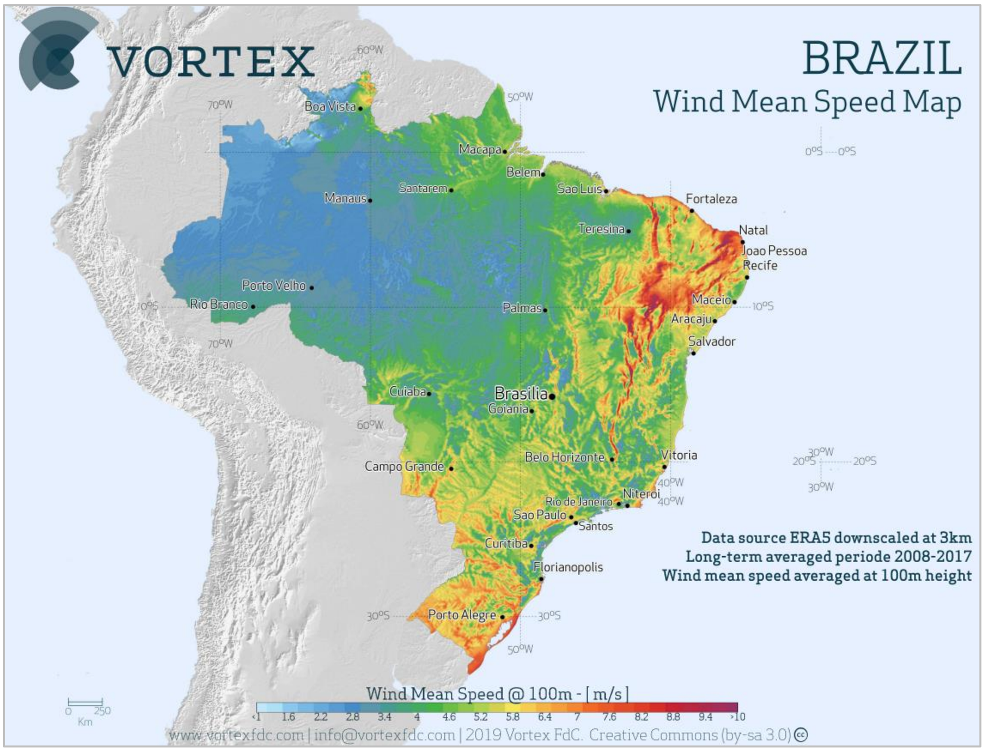


Figure 27: Wind mean speed map in Brazil, long term average period 2008-2017. Source [51]

From Figure 26 and Figure 27 above it can be observed that the best potential location would be in the North-East, specifically in the coastal areas of the states of Ceará (Fortaleza), Rio Grande do Norte (Natal), Paraiba (Joao Pessoa), Pernambuco (Recife) and the inside areas of Bahia (Salvador). Besides renewable energy potential, there are other several key factors to consider such as availability of electricity transmission network and proximity to ports with advanced infrastructure to export the NH_3 to EU.

On the one hand, in terms of electricity transmission network, the North-East region has a well interconnected network due to the presence of numerous wind farms and populated cities as seen in Figure 28.

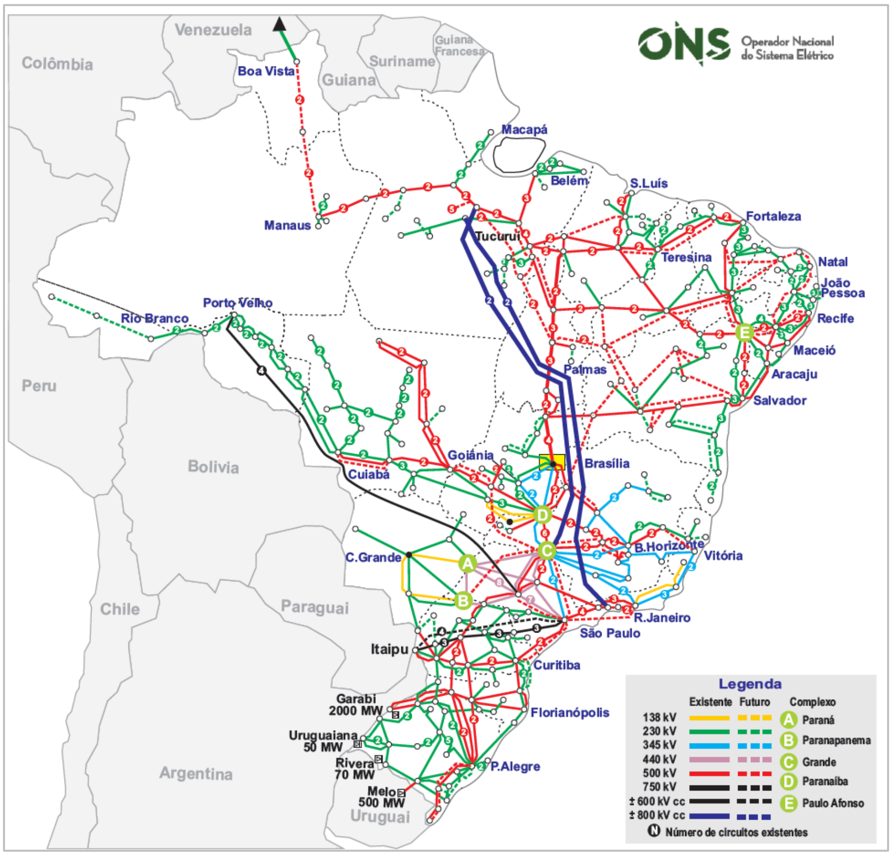
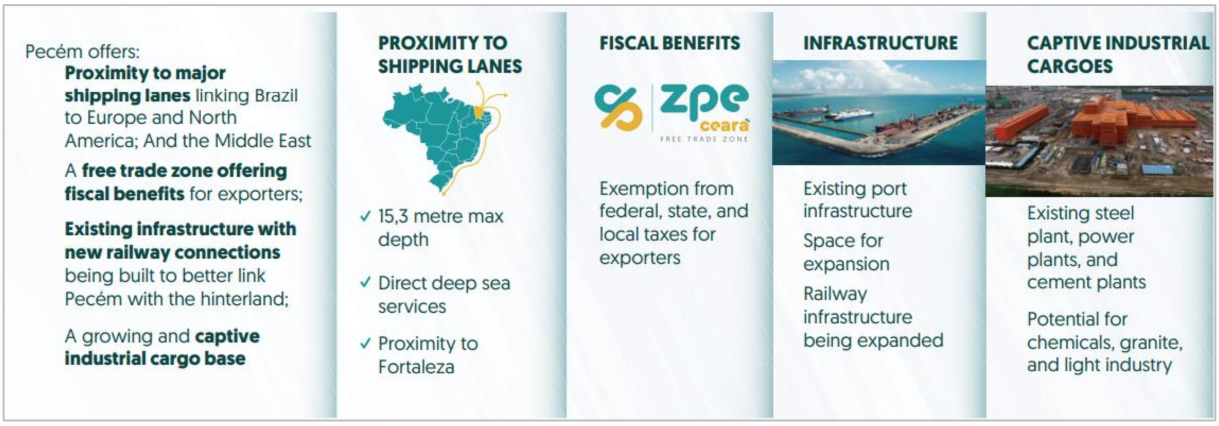


Figure 28: Brazil electricity transmission network. Source: Operador Nacional do Sistema Elétrico [52]

On the other hand, the offtake target market for the green NH_3 produced is the European Union, expected to be the most reachable market in the short-run due to regulation, decarbonization targets, incentives, and market size. Only in terms of market size, the EU-27 currently has 32 NH_3 facilities in operation with a combined capacity of 17.7 Mton/year [53] while Brazil only has 3 NH_3 facilities in operation with a combined capacity of 1.2 Mton/year [54] [55]. Moreover, green H_2 regulation has already been approved in EU and new measures such as CBAM (Carbon Border Adjustment Mechanism) implementation will propel the switch to greener products importation.

As previously observed in Figure 12, there is only one port in the North-East region with the required exporting NH_3 capabilities (loading and unloading), the Port of Aratu-Candeias (Bahia). However, the NH_3 -related infrastructure is privately owned by NH_3, fertilizer and chemical producer Unigel [56]. The start of NH_3 production by Unigel is due to the leasing of two nitrogen fertilizer factories from Petrobras – one in Laranjeiras (SE), the other in Camaçarí (BA) – for a period of ten years, extendable for another ten years, which expanded significantly increase Unigel's presence in agribusiness.

From the other existing industrial ports with export capabilities in the above-mentioned states, the Port of Pecém (Ceará) is acquiring worldwide relevance and attention in the green H_2 and NH_3 field. The growth of the port operations during the last decade have been significant, and with a strategic location about 50km from the capital of the state (Fortaleza) it is also close to major shipping lines connecting Brazil with Europe. Back in 2018, the port signed a partnership with the Port of Rotterdam, retaining a 30% equity in return of joint management and development to foster international investment [57]. The main commercial advantages of the port are seen in Figure 29 below.



Pecém offers:

- **Proximity to major shipping lanes** linking Brazil to Europe and North America; And the Middle East
- A **free trade zone offering fiscal benefits** for exporters;
- **Existing infrastructure with new railway connections** being built to better link Pecém with the hinterland;
- A growing and **captive industrial cargo base**

PROXIMITY TO SHIPPING LANES

✓ 15,3 metre max depth

✓ Direct deep sea services

✓ Proximity to Fortaleza

FISCAL BENEFITS

Exemption from federal, state, and local taxes for exporters

INFRASTRUCTURE

Existing port infrastructure

Space for expansion

Railway infrastructure being expanded

CAPTIVE INDUSTRIAL CARGOES

Existing steel plant, power plants, and cement plants

Potential for chemicals, granite, and light industry

Figure 29: Pecém Port commercial advantages. Source: [57]

This port was a pioneer in the implementation of a green H_2 hub, launched in February 2021 by the Complexo do Pecém, the Federation of Industries of the State of Ceará (FIEC) and the Federal University of Ceará (UFC). The main pillars of the success of the implementation of the green H_2 hub have been:

- **Renewable energy abundancy**: as previously stated, the North-East region of Brazil has emerged as a prime site for the generation of green H_2, due to its favourable wind patterns and abundant sunshine. As of 2021, Brazil had a total wind and solar energy capacity of 21 gigawatts (GW), with nearly 90% of this capacity concentrated in this region, particularly in the state of Ceará.
- **Infrastructure readiness**: robust electrical grid, gas distribution network, future H_2 and NH_3 related infrastructure and new docking berths in a port expansion area. In September 2023, it was announced that the port received 90 M$ from the World Bank to develop infrastructure within the green H_2 hub framework [58].
- **Collaboration agreements and strategic agreements propelling synergies**: The port has signed 32 memorandums of understanding (MoU) to establish an initial commitment to develop green H_2 projects and 3 pre-contracts with leading industrial players (Fortescue, AES Brasil and TransHydrogen Alliance) with land reservation within port facilities [57].
- **Fiscal benefits available**: Brazil has several ZPE (Zonas de Processamento de Exportação) - areas of free trade with the exterior, intended to the installation of companies manufacturing goods to be commercialized abroad. The companies settled in ZPEs have access to tax, exchange, and administrative incentives specific to the regime. Ceará ZPE is the first ZPE of Brazil, founded in 2010 and in operation since 2013, thus giving trust and guidance on promised incentives.

The port of Pecém is the location chosen to further analyze based on the above-mentioned advantages and readiness level.

5.1.2 Green Ammonia Plant Sizing

Plant sizing definition is highly correlated with other factors such as location, market development, technological maturity or investment capacity and is project dependent. For the current analysis, as location is defined and investment capacity is out of the scope of the study, the other 2 parameters will drive the plant sizing decision:

- **Technological maturity**: in terms of technological maturity, the renewables required as well as its infrastructure associated (power transmission, substations…) are considered widely deployed and therefore at the maximum level of maturity. Green H_2 and NH_3 production equipment such as electrolyzers and specific infrastructure, mainly H_2 and NH_3 storage and piping are not considered fully mature. The most advanced electrolyzers, the equipment required to produce green H_2, are Alkaline and Proton Exchange Membrane technologies, ranked in a TRL9 out of 11 maturity levels by the IEA [59].
- **Market development**: as of 2023, the green NH_3 market is considered an emerging market, with projections to have 20 Mton/y production by 2030, or 10% of worldwide NH_3 consumption in 2022, as seen in the market demand outlook developed in section 4. Although the market is expected to grow exponentially by 2050, in the short-term the market potential is reduced. Some of the most relevant green NH_3 projects currently operational and with Commercial Operation Date (COD) before 2030 are exposed in Table 1 below to benchmark sizing references worldwide:

Table 1: Benchmark of relevant green NH_3 projects worldwide

Company	Project Location	Plant Sizing (kton/y)	Electrolyzer Sizing (MW)	COD	Electricity Origin	Source
Fertiberia, Iberdrola	Puertollano (Spain)	**Phase I: 17** Phase II: 200	Phase I: 20 Phase II: 220	**Phase I – 2023, operational** Phase II: not disclosed	100MW Solar PV 20MWh Batteries	[60]
Fertiberia, Lantmännen, Nordion Energi	Lulea-Boden (Sweden)	**500**	600	2026	Wind, hydropower	[61], [62]
Fertiberia, CIP, Enagás Renovables	Sagunto (Spain)	**280**	500 (partly for NH_3 prod.)	2027	1.1 GW solar PV, wind (partly for NH_3 prod.)	[63]
Unigel	Bahia (Brazil)	**Phase I: 60** Phase II: 240 Phase III: 600	Phase I: 60 Phase II: 240 Phase III: 600	**Phase I – 2024 (Construction)** Phase II: 2025 Phase III: 2027	*Undisclosed*	[64], [65], [66]
Cepsa, Yara Clean Ammonia	Cadiz (Spain)	**750**	1,000	2027	Solar PV, wind	[67]
Iberdrola, Trammo	Spain	**100**	*Undisclosed*	2026	500 MW Solar PV, wind	[68]
Madoqua Renewables, Power2X and Copenhagen Infrastructure Partners	Sines (Portugal)	**500**	500	**2024 1st phase** until 2030	*Undisclosed*	[69]

Company	Project Location	Plant Sizing (kton/y)	Electrolyzer Sizing (MW)	COD	Electricity Origin	Source
ACWA Power, Air Products and NEOM	Oxagon (Saudi Arabia)	**1,200**	*Undisclosed*	2026	4 GW Solar PV, wind	[70]
TransHydrogen Alliance	Port of Pecém (Brazil)	**2,200**	2,400	2026 (1st production)	*Undisclosed*	[71]
OCI Global	Texas (United States)	**Phase I: 80** Phase II: 160	Phase I: 100 Phase II: 200	**Phase I – 2025** Phase II - 2026	*Undisclosed*	[72]
Fertiglobe	Ain Sokhna (Egypt)	**90**	100	**FID 2023** COD Not disclosed	260MW Solar PV, wind	[73]

The only integrated green H_2 and green NH_3 plant currently in operation, developed by a strategic agreement between Spanish companies' renewable energy producer Iberdrola and fertilizer production company Fertiberia, contains a 20MW electrolyzer and can produce up to 17kton/y of green NH_3, with potential expansion plans of up to 200 kton/y [60]. The most advanced project in terms of planning, such as Unigel Phase I in Brazil or OCI Global Phase I in the US also target moderate quantities with a potential ramp-up in the medium term [66] [72]. On the other hand, other projects target the large-scale production with quantities over the 1Mton/y. Considering the median value from the selected projects in Table 1, a sizing of 280 kton/y is obtained.

Assuming a more conservative approach, also based on the technological maturity reasoning, the green NH_3 plant sizing has been established at 200 kton/y, aligned as well with the value that Iberdrola and Fertiberia are targeting for the scale-up after validating the technology and integration.

5.1.3 Renewable Energy Location Definition

The methodology for determining the potential best location for renewable power plants in the state of Ceará involves the following steps:

I. **Renewables Resource Assessment**: The study considers both solar PV and wind energy resources. It aims to combine them to maximize the utilization factor of electrolyzers for renewable H_2 production [47].

II. **Transmission Grid Assessment**: The viability of potential locations is heavily influenced by the existing electricity transmission grid. The analysis considers the costs associated with energy transmission and distribution infrastructure.

III. **High-Potential Area Identification**: The combination of the resource and transmission grid assessment leads to several preliminary areas suited for locating the project. The analysis considers areas where existing renewable energy power plants are operational / planned.

IV. **Renewable Energy Location Decision**: In this last step, final coordinates for obtaining the renewable energy profiles are defined. These are based on existing wind farms within the high-potential areas identified. This confirms wind potential (much more variable than sun resource alongside the year) but also project externalities such as land availability and suitability for project development.

5.1.3.1 Renewables Resource Assessment

Solar PV output is more uniform alongside Ceará, as seen in Figure 30, with several areas mapped with higher potential. However, it is expected that wind, with much more variability than solar, and transmission grid availability, will drive the final location decision.

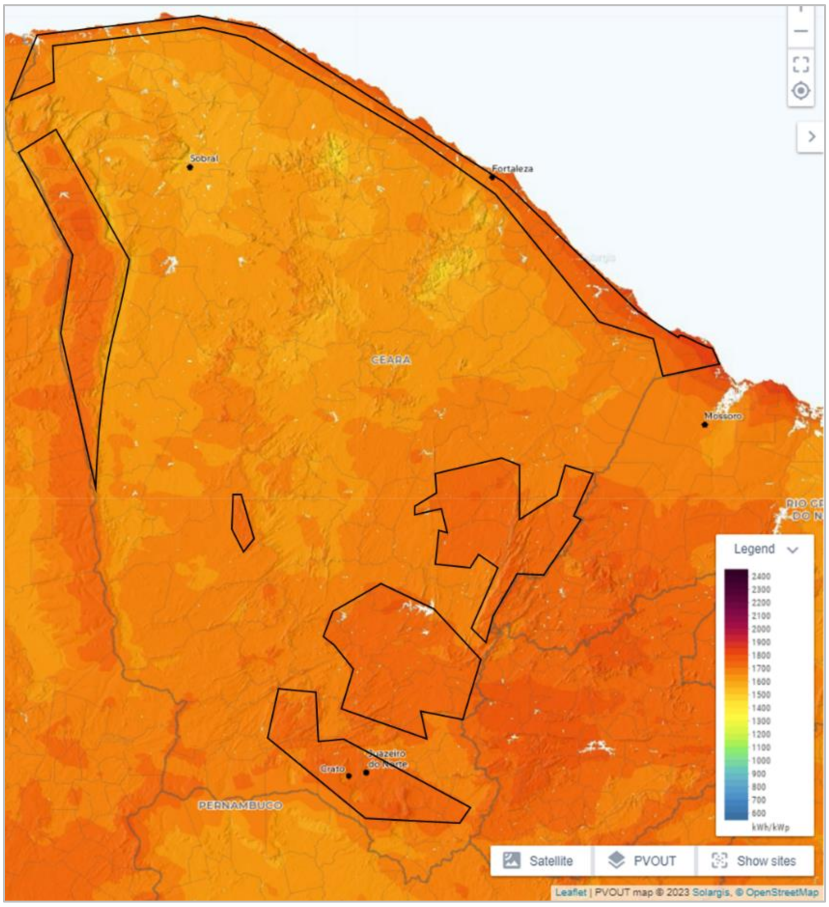


Figure 30: Solar PV power potential in Ceará, measured in specific PV power output.

Source: Own elaboration based on Global Solar Atlas 2.0 [74]

Wind power is analyzed following the same procedure as for solar PV, with the high-potential areas mapped in Figure 31. Onshore wind potential is more restricted alongside the state, with these areas mostly placed along the seaside as well as on the north-west and southern parts of the state.

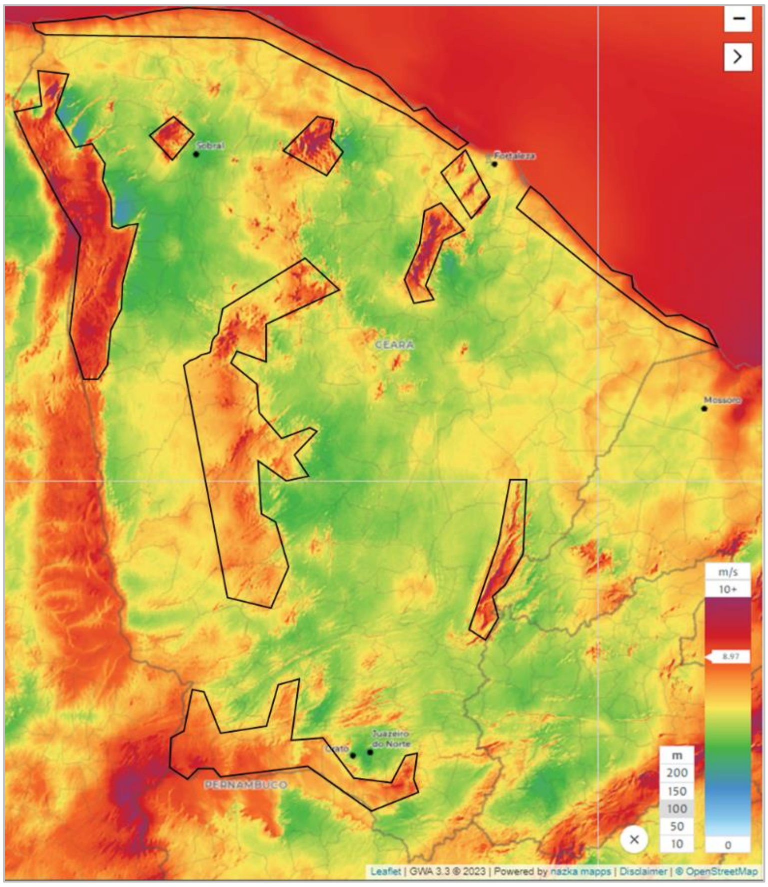


Figure 31: Wind power potential in Ceará, measured in wind mean speed at 100m hub.
Source: Own elaboration based on Global Wind Atlas 3.0 [75]

5.1.3.2 Transmission Grid Assessment

As for the transmission grid availability, Figure 32 precisely maps the high-voltage transmission grid availability. It also represents the protected land areas and both existing and planned power plants. It can be noted that the state is widely covered by a 500/525 kV high-voltage transmission line (red) that connects the north-west and south-east to Fortaleza area, most populated and energy-consuming center in the state. Moreover, a wide range of 230 kV high-voltage networks also support the development of the transmission system, especially in the north due to the large number of wind farms in the area. The specific area where the Port of Pecém is located can also be seen in Figure 33, well-developed in terms of energy infrastructure.

Figure 32: Ceará electricity transmission network, mapping of current and planned power plants and land use differentiation. Source: [76]

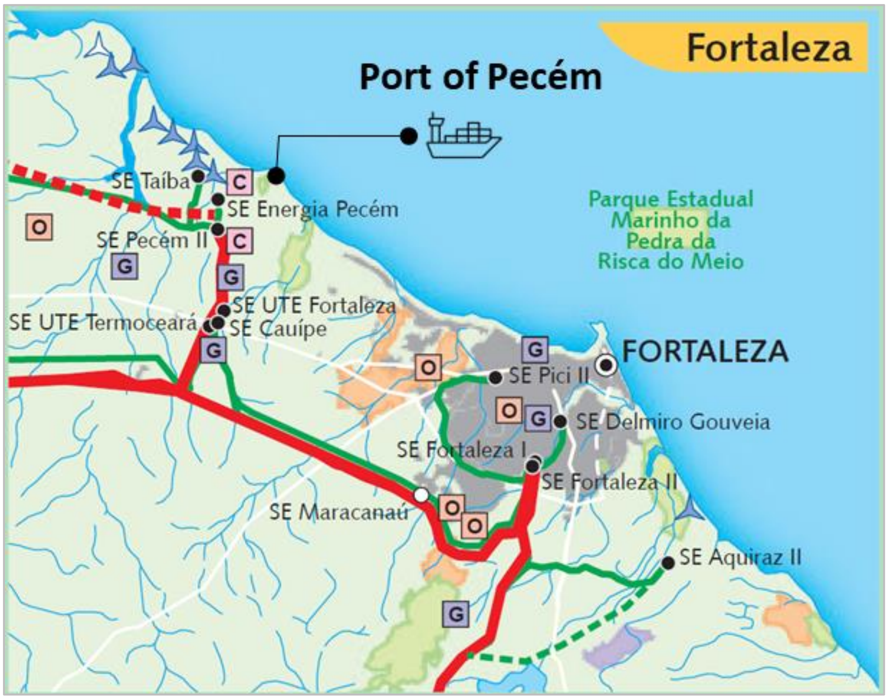


Figure 33: Port of Pecém electricity transmission network, mapping of current and planned power plants and land use differentiation. Source: [76]

5.1.3.3 High-Potential Area Identification

Solar PV and onshore wind high-potential areas mapped above in Figure 30 and Figure 31 respectively have been combined and plotted on top of Figure 32, as can be seen on Figure 34. There are many areas where a good combination of solar PV and wind can be found, however few of these locations are placed where the electricity transmission system is. There have been identified two areas (pinned with orange in the map), the north-west of the state and the north coastal area, which combine the previous aspects as well as the presence of existing / planned wind farms, verifying not only the wind potential of these areas but also the potential for project development.

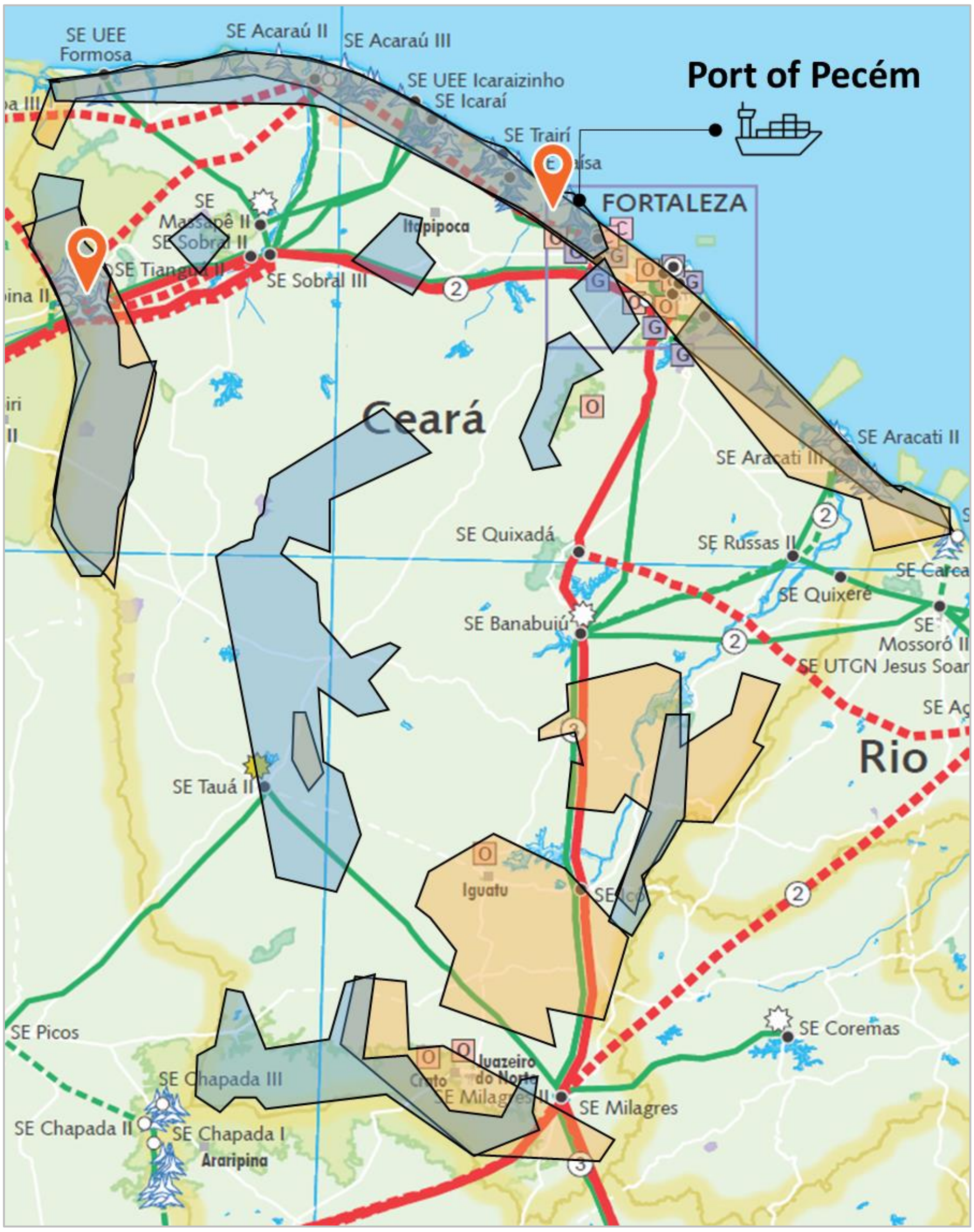


Figure 34: Identification of best potential locations for hybrid solar PV and wind energy production in Ceará state, Brazil. Source: own elaboration based on [74] [75] [76]. High-potential wind areas – blue; high-potential solar PV areas – orange

5.1.3.4 Renewable Energy Location Decision

It is essential to highlight that these high-potential areas within the state will be studied and compared in terms of annual capacity factors as well as representative profiles and variability alongside the year. However, the specific limits of the renewable power plants are considered out of the scope of the study.

As seen in Figure 34, these areas combine good wind and solar resources, access to high-voltage transmission grid and proximity to existing wind farms. The definitive coordinates for assessing the power generation are based on large existing wind farms within the designated areas and can be seen in Table 2.

In the case of the north-coast location, the municipality of Trairí is chosen, as it hosts a hybrid renewable energy project inaugurated in 2023 by Qair Brasil, consisting of the wind complexes Serra do Mato (121.8 MW), Serrote (205.8 MW) and the solar complex Serra do Mato (101.5 MW/124.5 MWp) [77].

For the north-west location, the municipality of Tianguá is chosen, hosting Ventos de Tianguá, composed of five wind farms, 77 wind turbines and a total installed capacity of 141 MW in operation since 2016 and part of Echoenergia portfolio [78].

Table 2: Selected locations for analysis

Location	Latitude	Longitude	Wind Farm Reference	Height (meters above sea level)	Source
Trairí, **north-coast** (Close to Pecém Port)	-3° 16' 14.1" -3.268	-39° 23' 46.6" -39.395	Serrote / Serra do Mato, +300 MW (Qair Brasil)	50 m	[77], [79], [80]
Tianguá, **north-west**	-3° 52' 44.1" -3.890	-41° 11' 33.7" -41.182	Ventos de Tianguá, 141MW (Echoenergia)	600 m	[78], [81]

5.1.4 Renewable Generation and Power Profile in Selected Sites

Assessing renewable energy production and the power profiles in the most precise manner has a great impact on green H_2 and NH_3 operation mode and production costs. The methodology proposed involves several key steps:

I. Renewable Energy Production Variability
II. Open Data Source Eligibility
III. Load Profile Generation Assumptions
IV. Representative Year Selection – P50 approach
V. Power Profile in Selected Sites

5.1.4.1 Renewable Energy Production Variability

Renewable energy production varies from year to year, affecting the energy yield and production costs. Therefore, a significant dataset is needed in terms of timescale, rather than a specific year. Moreover, in general, the variability of wind is much greater than that of solar in most countries both at yearly, weekly and daily scale [82]. Therefore, attention should be paid to determine the power profiles in the most accurate way.

5.1.4.2 Open Data Source Eligibility

Renewables Ninja has been used, an open-source web tool that provides users with a platform to estimate and analyze solar PV and wind hourly energy production for any location. It aims to facilitate the assessment of renewable energy potential and aid in the planning and decision-making processes for renewable energy projects. The tool works by taking weather data from global reanalysis models and satellite observations such as NASA's MERRA-2 [83] [84].

5.1.4.3 Load Profile Generation Assumptions

To obtain the hourly energy production profiles for the specified locations, several inputs and assumptions should be inserted within Renewables Ninja web-tool both for wind energy and solar PV:

- **Wind Energy**: the turbine model is the main input to be included. Vestas V150/4200 has been chosen, as it is the most representative turbine installed recently in Brazil (Figure 36) and it was installed in the Serrote wind farm as recent as 2021 in the north-coast chosen location for further analysis [80]. The KPIs of this turbine can be seen in Table 3 and its power curve is illustrated in Figure 35 below.

Table 3: Selected turbine data

Manufacturer	Model, Commissioning	Rated Power (kW)	Rated wind speed (m/s)	Rotor diameter (m)	Power control	Hub Height (m)
Vestas	V150/4200 2017 [85], [86]	4,200	9.9	150	Pitch	105m, 123m, 145m, 155m and 166m **Selected: 145m**

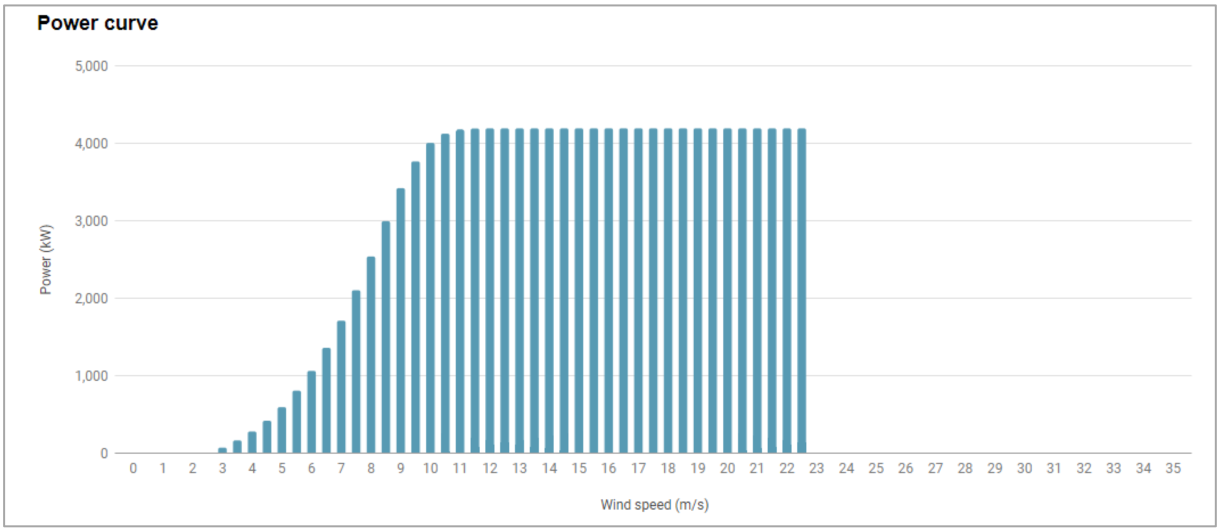


Figure 35: Vestas V150/4000-4200 Power Curve. Retrieved from: [86]

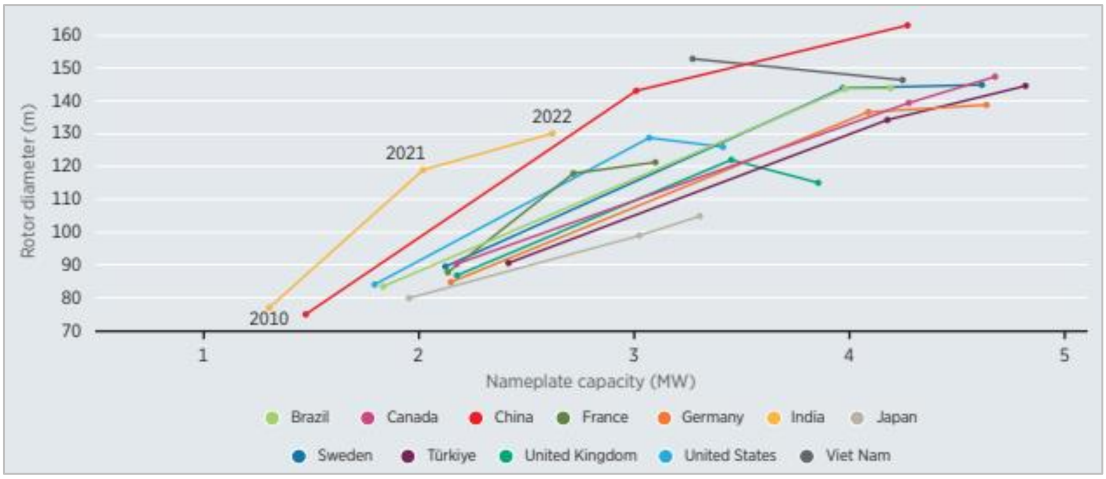


Figure 36: Onshore wind rotor diameter and nominal capacity evolution 2010-2022. Retrieved from: [87]

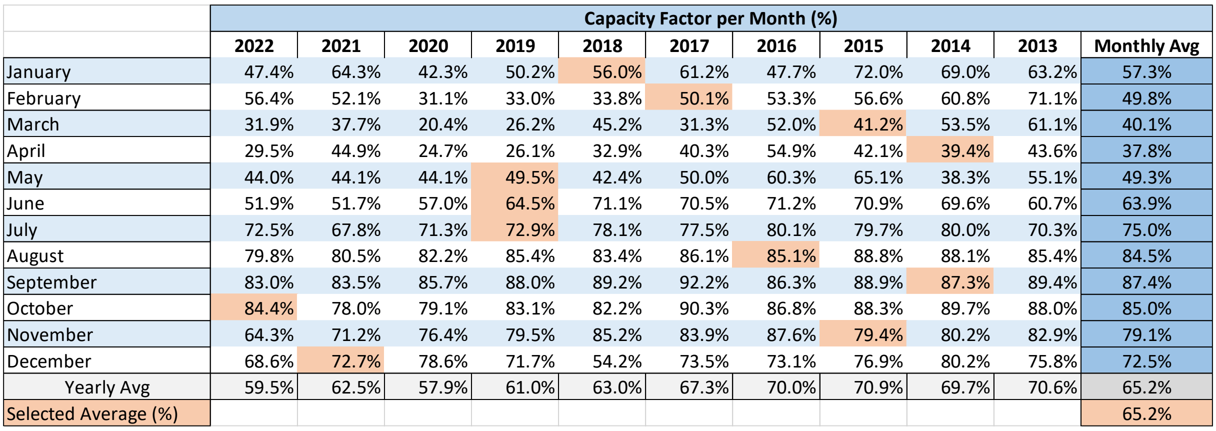
- **Solar PV**: It is assumed that non-tracking standardized modules face north at southern hemisphere sites. The optimal tilt angle has been established with the same value as the sites geographical latitude to achieve optimal energy production [88]

5.1.4.4 Representative Year Selection

As already highlighted, the energy yield differs yearly and therefore a representative year has been selected over a significant 10-year analysis using the P50 approach, a process applied to assess wind energy investments due to its high yearly variability. The P50 figure is the annual average level of generation, where the output is forecasted to exceed 50% over a year. Equity investors are typically more willing to take risks and accept uncertainty, so they tend to focus on the median P50 value as it represents a more optimistic view of the project's potential performance [89].

In the analysis, a representative year is selected is defined for simulating the P50 profile by combining the mean monthly data from individual years (2013–2022). The selection process involves:

- Calculating the total electricity for each month
- Calculating the mean capacity factor for each month
- Identifying the year whose month's capacity factor is closest to the mean monthly value for the established period. This is exemplary represented on Figure 37, which shows the representative year selection in orange for Trairí location and the mean capacity factors selected for each month.
- In this case, the representative year will be composed of: January 2018 – February 2017 – March 2015 – April 2014 – May 2019 – June 2019 – July 2019 – August 2016 – September 2014 – October 2022 – November 2015 – December 2021



	Capacity Factor per Month (%)										
	2022	2021	2020	2019	2018	2017	2016	2015	2014	2013	Monthly Avg
January	47.4%	64.3%	42.3%	50.2%	56.0%	61.2%	47.7%	72.0%	69.0%	63.2%	57.3%
February	56.4%	52.1%	31.1%	33.0%	33.8%	50.1%	53.3%	56.6%	60.8%	71.1%	49.8%
March	31.9%	37.7%	20.4%	26.2%	45.2%	31.3%	52.0%	41.2%	53.5%	61.1%	40.1%
April	29.5%	44.9%	24.7%	26.1%	32.9%	40.3%	54.9%	42.1%	39.4%	43.6%	37.8%
May	44.0%	44.1%	44.1%	49.5%	42.4%	50.0%	60.3%	65.1%	38.3%	55.1%	49.3%
June	51.9%	51.7%	57.0%	64.5%	71.1%	70.5%	71.2%	70.9%	69.6%	60.7%	63.9%
July	72.5%	67.8%	71.3%	72.9%	78.1%	77.5%	80.1%	79.7%	80.0%	70.3%	75.0%
August	79.8%	80.5%	82.2%	85.4%	83.4%	86.1%	85.1%	88.8%	88.1%	85.4%	84.5%
September	83.0%	83.5%	85.7%	88.0%	89.2%	92.2%	86.3%	88.9%	87.3%	89.4%	87.4%
October	84.4%	78.0%	79.1%	83.1%	82.2%	90.3%	86.8%	88.3%	89.7%	88.0%	85.0%
November	64.3%	71.2%	76.4%	79.5%	85.2%	83.9%	87.6%	79.4%	80.2%	82.9%	79.1%
December	68.6%	72.7%	78.6%	71.7%	54.2%	73.5%	73.1%	76.9%	80.2%	75.8%	72.5%
Yearly Avg	59.5%	62.5%	57.9%	61.0%	63.0%	67.3%	70.0%	70.9%	69.7%	70.6%	65.2%
Selected Average (%)											65.2%

Figure 37: Wind gross capacity factor per month for period 2013-2022 for Trairí location, with representative year selection (orange). Source: own elaboration based on Renewables Ninja data

As variations in wind power production are typically higher, the methodology described above is applied for wind power, and the resulting typical months are used to obtain the data relevant for solar power production. This ensures that the monthly wind and solar data sets are based on the same representative years, and thus each comes from the same meteorological conditions.

5.1.4.5 Power Profile in Selected Sites

Table 4 below shows the results of the representative year selection and the P50 approach to calculate the annual average capacity factor both for wind and solar PV in the selected renewable energy locations.

Table 4: P50 wind and solar PV capacity factors in selected locations

Location	Latitude	Longitude	P50 Wind Capacity Factor	P50 Solar PV Capacity Factor
A. Trairí, **north-coast** (Close to Pecém Port)	-3° 16' 14.1" -3.268	-39° 23' 46.6" -39.395	65.2%	19.5%
B. Tianguá, **north-west**	-3° 52' 44.1" -3.890	-41° 11' 33.7" -41.182	52.9%	19.7%

It can be observed that, while solar PV resource is almost equal between the sites, the wind capacity factor is significantly higher for Trairí, which will largely impact the business case. As already stated, is essential to consider not only interannual variability, but also seasonal, and daily variability. While seasonal variability can be observed from the previous step of the methodology, the daily profiles have been obtained for the selected representative year in each location.

A. Trairí (North-Coast)- Seasonal Variability

In Trairí, it can be observed from Figure 38 the large wind seasonal variability. Due to this fact, daily power profiles will be done for the high-wind season (July-December) and for the low-wind season (January-June). Solar PV resource also show some variability as seen in Figure 39, with high-solar and low-solar seasons with same periodicity as for wind.

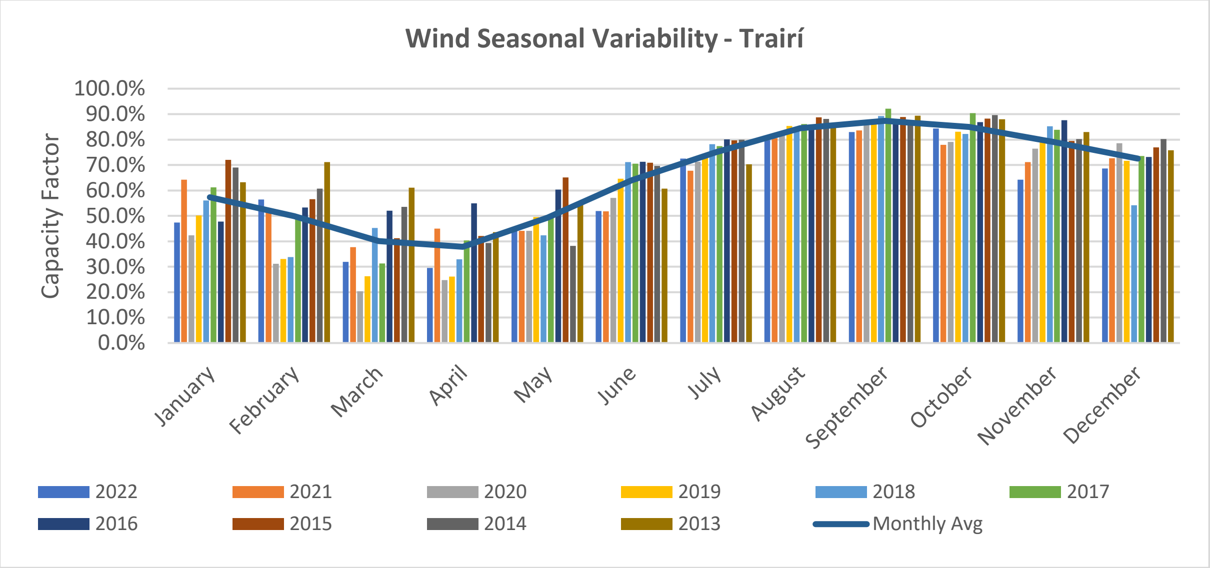


Figure 38: Wind seasonal variability in Trairí for period 2013-2022

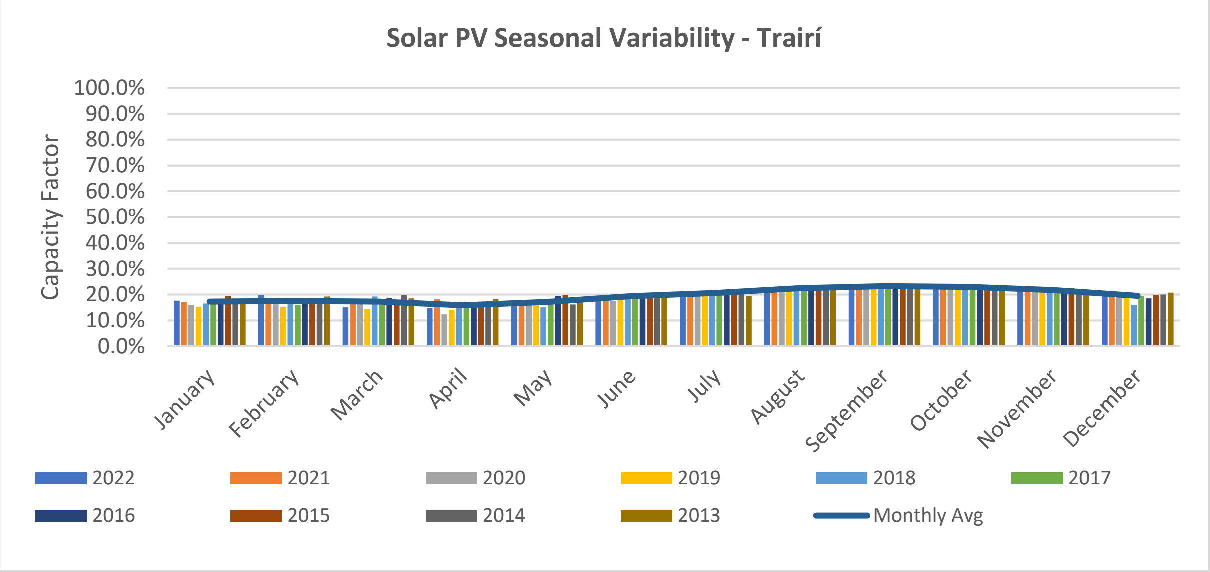


Figure 39: Solar PV seasonal variability in Trairí for period 2013-2022

A. Trairí (North-Coast) - Daily Variability

In terms of daily variability, **Trairí presents an extraordinarily stable wind generation profile**, while solar PV is only available from 09:00-19:00, as can be observed in Figure 40. It can be seen a notable difference as well between the low resource period during January-June (Figure 41) and the high resource period from July-December (Figure 42).

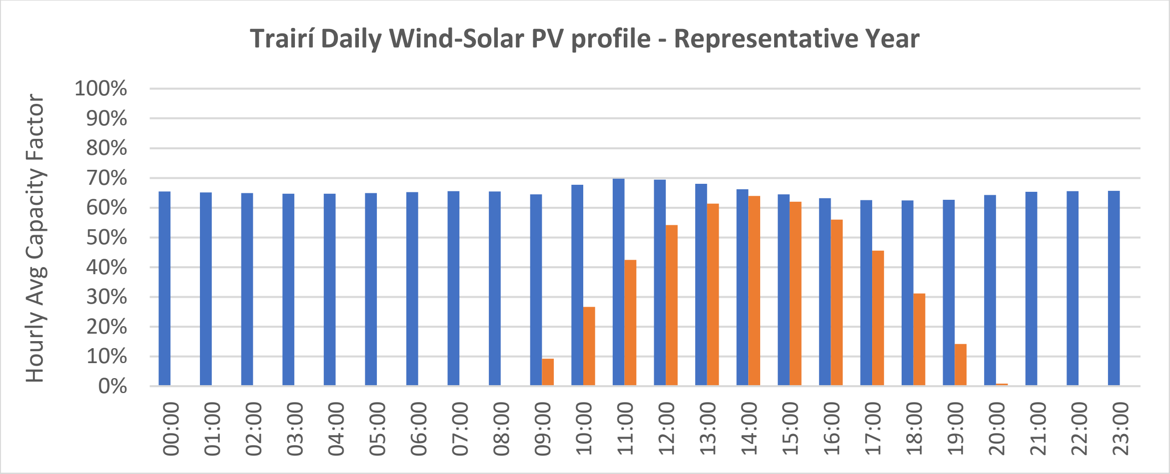


Figure 40: Trairí daily wind and solar PV profile for the representative year

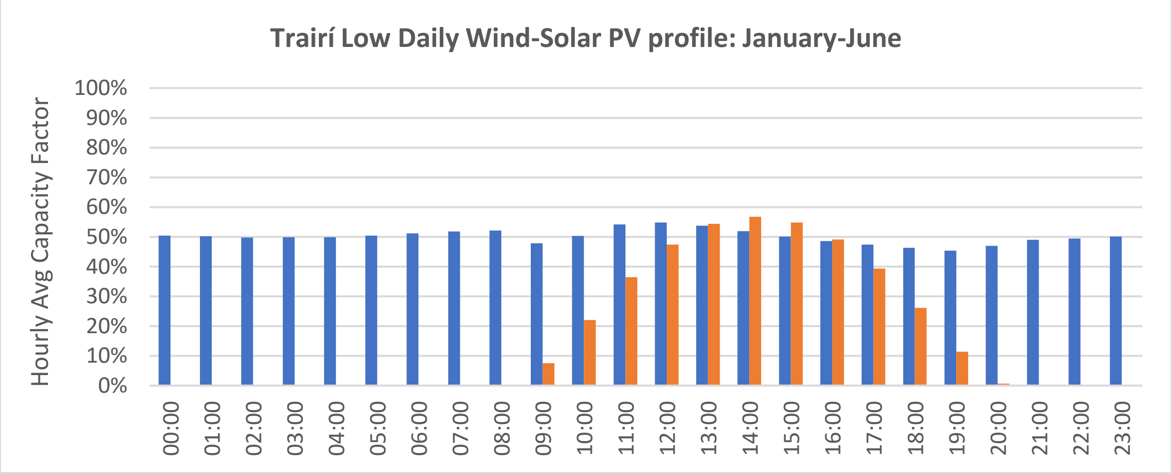


Figure 41: Trairí daily wind and solar PV profile for the low season of the representative year (Jan-Jun)

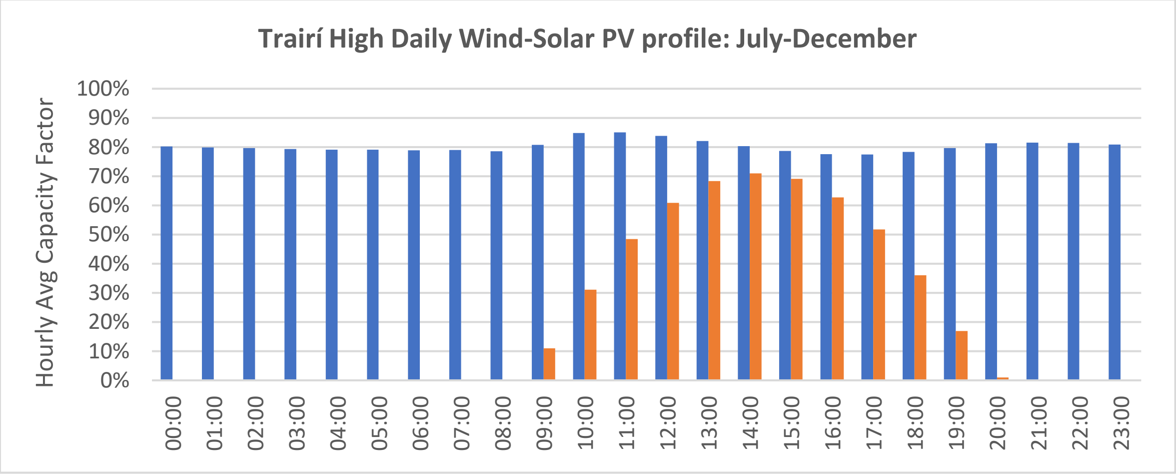


Figure 42: Trairí daily wind and solar PV profile for the high season of the representative year (Jul-Dec)

B. Tianguá (North-West) - Seasonal Variability

In Tianguá, as seen in Figure 43 and Figure 44, the seasonal variability follows the same profile than in Trairí, with higher wind and solar PV resource during July-December and lower in January-June period. Also, it can be noticeable that the wind resource is lower than in Trairí.

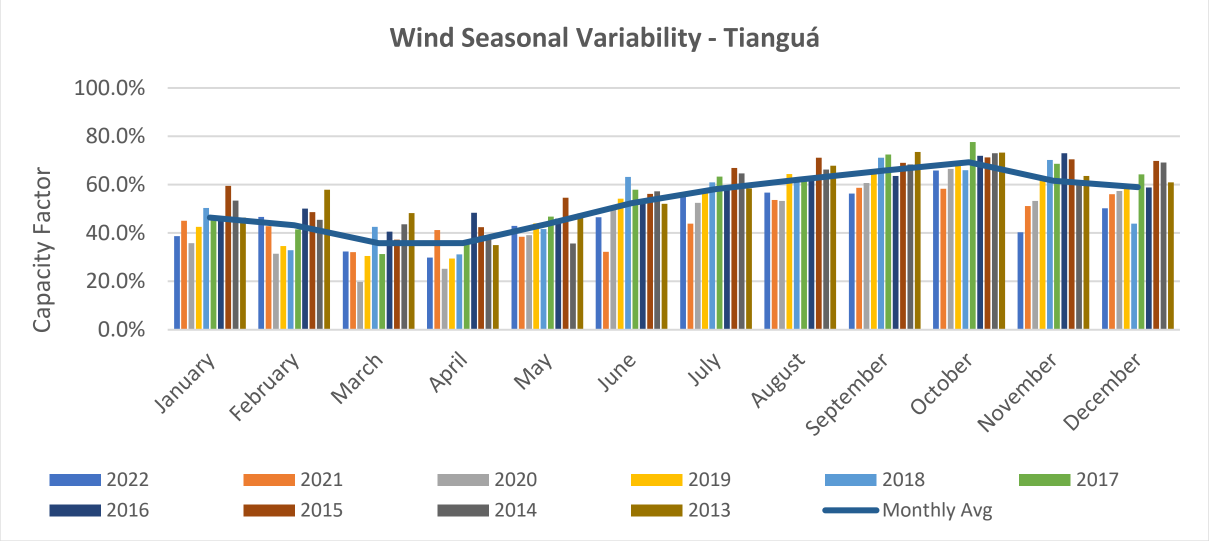


Figure 43: Wind seasonal variability in Tianguá for period 2013-2022

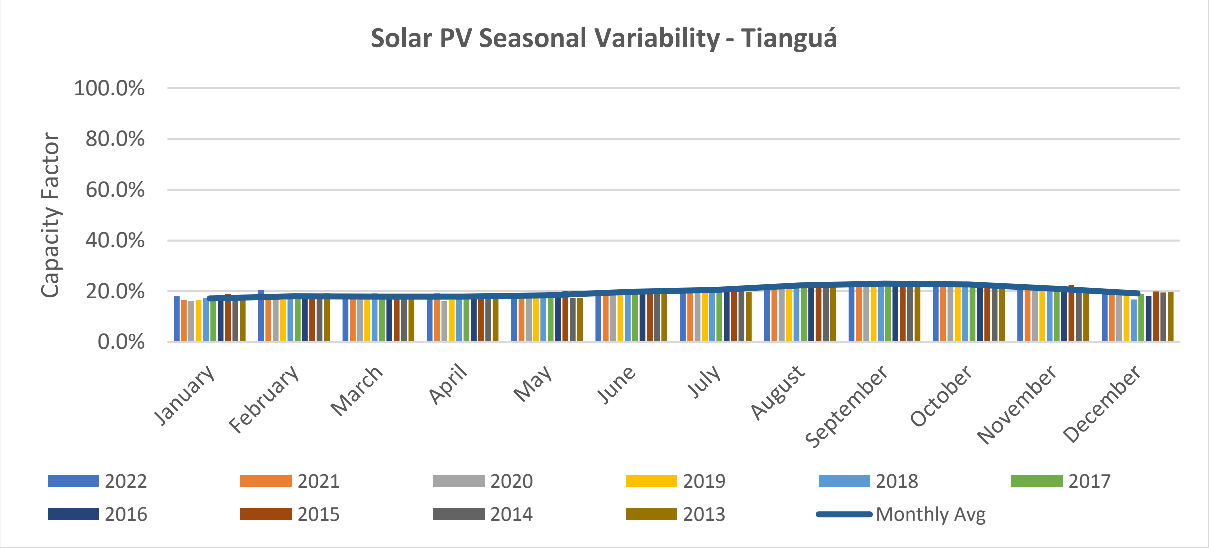


Figure 44: Solar PV seasonal variability in Tianguá for period 2013-2022

B. Tianguá (North-West) - Daily Variability

In terms of daily variability, **Tianguá wind generation profile is much more instable,** with a production valley between 15:00-21:00 that could be partially filed by solar PV generation, with same profile as in Trairí with production between 09:00 and 19:00, as observed in Figure 45. Similar to the Trairí case, it can be seen a notable difference as well between the low resource period during January-June (Figure 46) and the high resource period from July-December (Figure 47).

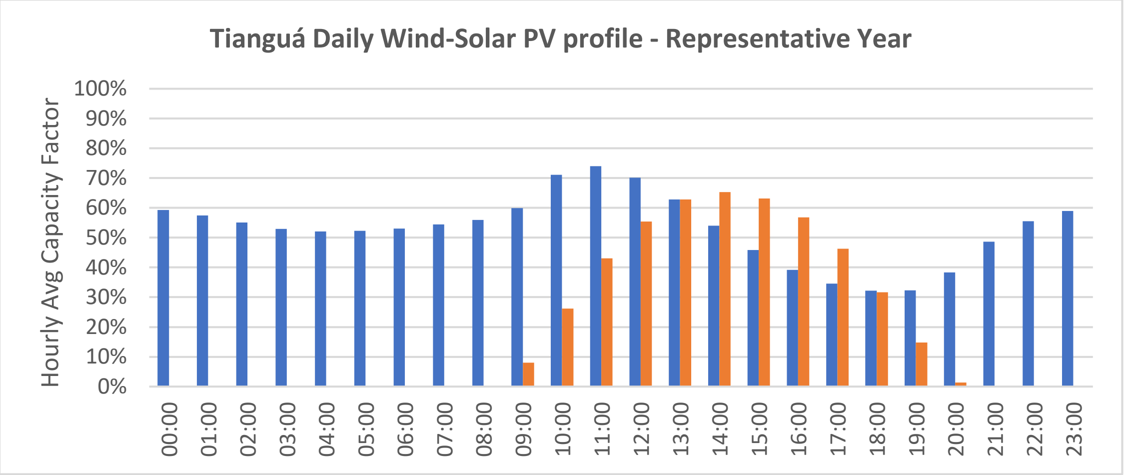


Figure 45: Tianguá daily wind and solar PV profile for the representative year

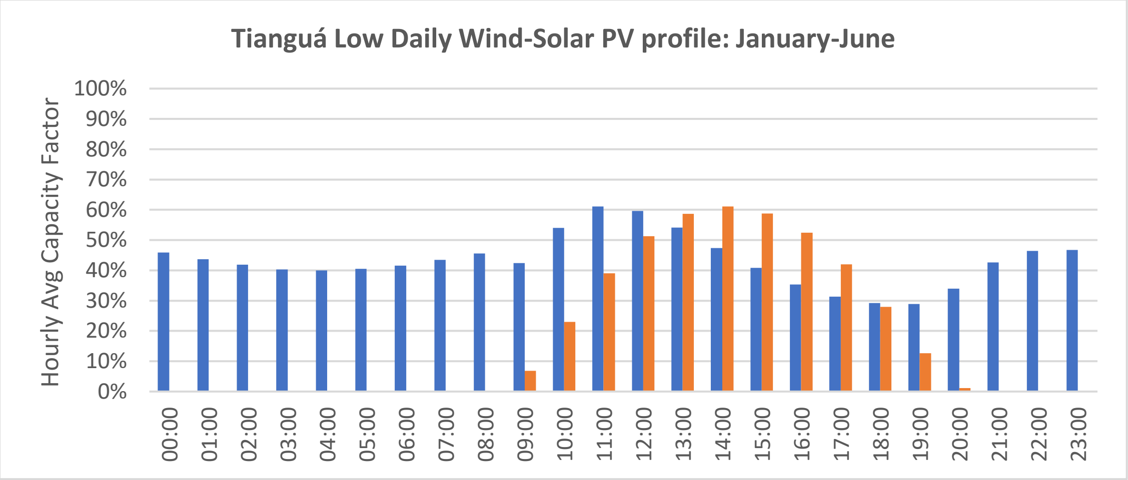


Figure 46: Tianguá daily wind and solar PV profile for the low season of the representative year (Jan-Jun)

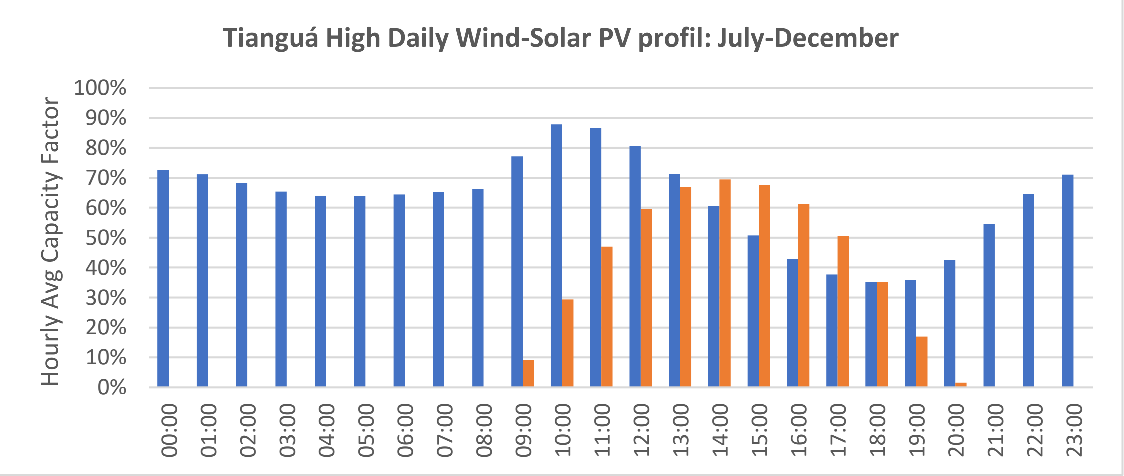


Figure 47: Tianguá daily wind and solar PV profile for the high season of the representative year (Jul-Dec)

5.2 Operational Mode Definition & Techno-Economic Parameters

Integrated green H_2 and green NH_3 plants have several operational modes available depending on several linked factors such as renewable energy generation sources and power profile, grid infrastructure and energy storage availability, green H_2 technology and storage and finally green NH_3 plant configuration.

Proposed Scenario – Trairí, Wind Power, Grid Available, PEM, Flexible Green NH_3

The proposed scenario for defining the operational mode is illustrated with the main system components on Figure 48. The reasoning of the suitability of each of the main system blocks as well as the main techno-economic parameters of this case study are stated within this section.

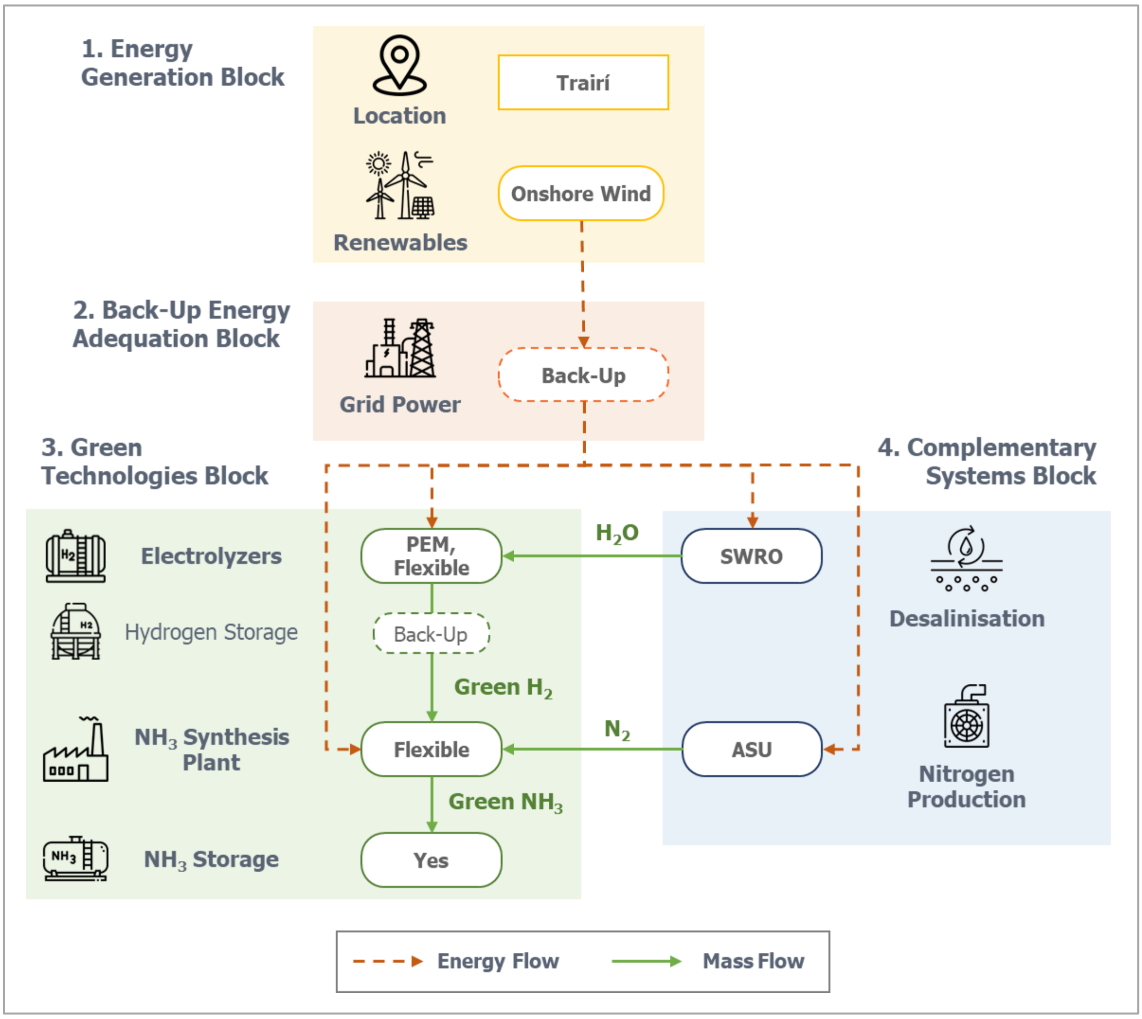


Figure 48: Optimization model key blocks and components, energy, and mass flow representation. Source: own elaboration

5.2.1 Energy Generation Block

The renewable generation calculated in the previous section and the power profiles in Trairí and Tianguá led to several conclusions:

- While solar PV resource is almost equal between the sites, the wind capacity factor is significantly higher for Trairí, which will largely impact the business case.
- Seasonal variability follows the same profile in both locations and for both solar PV and wind. However, it can be as well noticeable that the wind resource is higher in Trairí.
- In terms of daily variability, Trairí presents an extraordinary stable wind generation profile, while Tianguá wind generation profile is much more instable.

Therefore, Trairí has been chosen as the best location and only wind power generation will be considered due to its stable profile throughout the year. It is essential to highlight that the renewable resource has been the main decision-making parameter defining the location and the operational mode. Future work could include preliminary cost-assessments of hybridizing solar PV with wind energy to analyze its potential attractiveness.

The main techno-economic and environmental parameters considered in the analysis are presented in Table 5.

Table 5: Wind Power Techno-Economic and Environmental Parameters

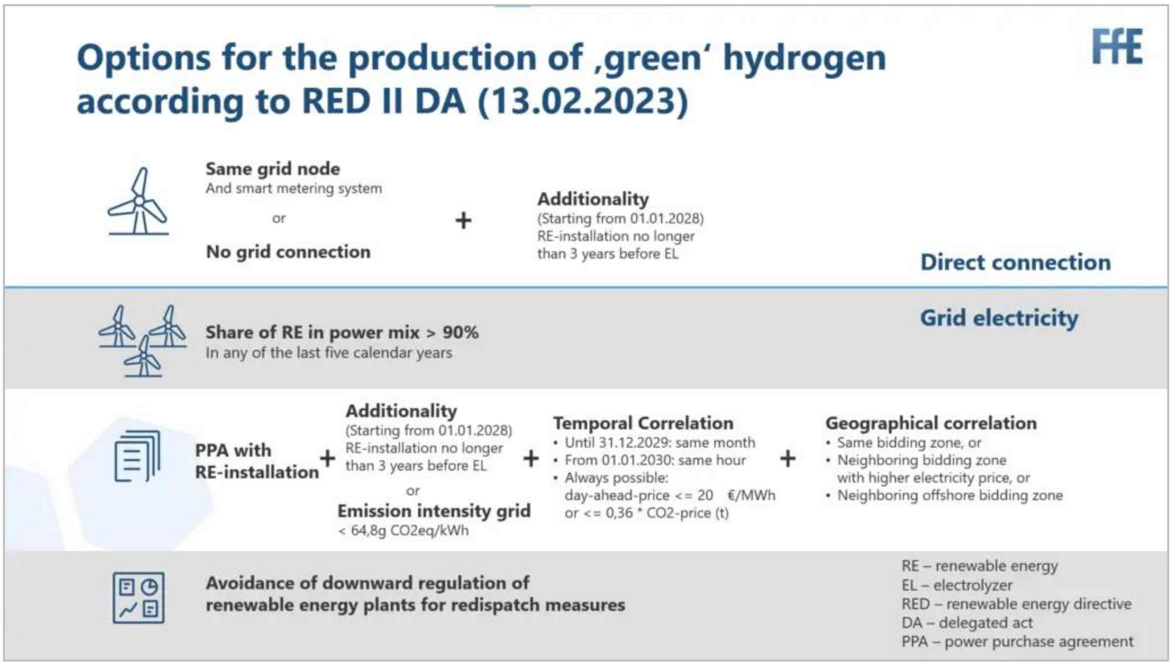
Parameter		Value	Unit	Source
Technical	Turbine Model	V150/4200 2017	-	[85], [86]
	Rated Power	4.2	MW	[85], [86]
	Availability	98%	%	[90]
	Electrical Losses	2.5%	%	[90]
	Plant Wake Losses	6%	%	[90]
	Total Fixed Losses (Sum losses above)	10.5%	%	[90]
Economical	CAPEX – Installed Costs	1,052	$/kW	[91]
	OPEX – Full Service	22	$/kW/year	[91]
Environmental	Equivalent CO_2 emissions	7.3	g CO_2-e / kWh	[90]

5.2.2 Back-Up Energy Adequation Block

As previously analysed, an advanced grid infrastructure is in place. While the addition of energy storage is also considered a viable solution, in this case the system will be able to withdraw electricity from the grid due to the following aspects:

- The preliminary wind energy stability means that low amounts of energy would need to be withdrawn, not making necessary the installation of energy storage systems which would increase the CAPEX substantially.
- In order to comply with EU regulation regarding green H_2, illustrated in Figure 49 below, the produced H_2 will be considered green if it is connected to a power system with >90% renewables share in the mix. In this case study, the Brazilian North-East power system is considered, which in year 2022 had ~ 95% renewable percentage in the mix, as also stated in Table 6 [92].
- However, as the aim of the study is to calculate the potential of installing renewables to produce green H_2 and NH_3 in Brazil, most of the electricity for H_2 production will be coming from the installed wind

energy capacity. The grid will only be used as back-up when wind energy is not available to fulfil the green H_2 and NH_3 system minimum operational requirements.



FfE

Options for the production of ‚green' hydrogen according to RED II DA (13.02.2023)

Same grid node
And smart metering system
or
No grid connection
\+
Additionality
(Starting from 01.01.2028)
RE-installation no longer than 3 years before EL

Direct connection

Grid electricity

Share of RE in power mix > 90%
In any of the last five calendar years

PPA with RE-installation
\+
Additionality
(Starting from 01.01.2028)
RE-installation no longer than 3 years before EL
or
Emission intensity grid
< 64,8g CO2eq/kWh
\+
Temporal Correlation
- Until 31.12.2029: same month
- From 01.01.2030: same hour
- Always possible:
  day-ahead-price <= 20 €/MWh
  or <= 0,36 * CO2-price (t)

\+
Geographical correlation
- Same bidding zone, or
- Neighboring bidding zone
  with higher electricity price, or
- Neighboring offshore bidding zone

Avoidance of downward regulation of renewable energy plants for redispatch measures

RE – renewable energy
EL – electrolyzer
RED – renewable energy directive
DA – delegated act
PPA – power purchase agreement

Figure 49: Overview of power purchase options for green H_2 production. Source: withdrawn from [93]

Table 6: North-East Brazil Grid Techno-Economic Parameters

Parameter		Value	Unit	Source
Technical	Renewable % in NE Grid – Average 2022	95%	%	[92]
Economical	Hourly Average Energy Price in NE Grid (Oct 2021- Oct 2023)	63.67 12.38	R$/MWh $/MWh [1]	[94]
Environmental	Equivalent CO_2 emissions	52.05	g CO_2-e / kWh	[92]

Even though an advanced grid is in place, it is quite uncertain the potential future grid availability. Therefore, a direct connection line between the onshore wind facility and the green H_2 and NH_3 plant is assumed to be installed. Power transmission parameters such as expected losses, costs and the distance among others are reflected in Table 7. Moreover, one substation has also been considered within the onshore wind deployment, assuming that the receiving substation for the green H_2 and NH_3 will be in place and available within the Hydrogen Hub development in the Port of Pecém facilities.

---

[1] Exchange Rate as of 7th October (0.19$ / R$)

Table 7: Power Transmission Techno-Economic Parameters

Parameter		Value	Unit	Source
Technical	Distance between Trairí and Pecém Port (1.2x conservative approach)	70	km	Google Earth
	Transmission Losses	1.1%	% energy transported / 100km	[95]
	Substation Losses	1%	% energy converted	[95]
Economical	Transmission Line CAPEX	190,000	EUR/km/GW	[95]
	Transmission Line Fixed OPEX	0.2%	% CAPEX	[95]
	Renewables substation CAPEX	124,000	EUR/MW	[95]
	Renewables substation Fixed OPEX	2%	% CAPEX	[95]

5.2.3. Green Technologies Block

5.2.3.1 Hydrogen Technology

PEM (Proton Exchange Membrane) electrolysis has been selected due to the following aspects:

- PEM electrolysis is already in TRL9, as well as alkaline, and although it has been traditionally more expensive than Alkaline [24], the projections are that costs will be paired in the near future [96] [97].
- Higher dynamic performance than Alkaline (A/cm^2) [98], allowing a better integration to variable input power from wind effectively capturing production, with load following rates of over 1.5% / second [99].
- High-pressure production of H_2 (30-40 bar), which reduces the demand for downstream compression significantly compared to atmospheric H_2 production [47].

Table 8: Electrolyzer Techno-Economic and Environmental Parameters

Parameter		Value	Unit	Source
Technical	Technology	PEM (Proton Exchange Membranes)	-	-
	Specific Energy Consumption (2025)	51	kWh/kg	[24], [99]
	System Operational Range	10-100%	%	[47], [99]
	Stack Lifetime (until replacement)	80,000	h	[47], [98]
	System Lifetime	20	Years	[47], [24], [98]
Economical	System CAPEX (IEA 2025) (Electrolyzer + BOP + EPC)[2]	1,000	$/kW	[24]
	Fixed OPEX	15	$/kW/year	[47]
	Variable OPEX - Stack Replacement (IEA 2030)	400	$/kW	[24]
Environmental	Equivalent CO_2 emissions	72	g CO_2-e / kg H_2 / stack	[100]

---

[2] BOP – Balance of Plant; EPC – Engineering, Procurement and Construction

It must be noted that, due to simplification purposes for calculating a representative year, wind turbine and electrolyzer annual degradation factors have not been considered. Further scope of the study could include these precise annual degradation factors and strategies to overcome the efficiency losses since the project planning stage.

To mitigate the impact of this phenomenon and to account for it in our model, a practical strategy has been adopted. In practice, electrolyzer stacks are expected to be replaced at approximately 80,000 hours of operation, equating to approximately nine years of service, as stated in Table 8 above. Remarkably, these replacement stacks are anticipated to exhibit not only reduced cost due to industry advances, but also improved efficiency levels compared to the initial installations, effectively counterbalancing the degradation factors that have been omitted in our simplified model.

Furthermore, to reconcile the absence of annual degradation factors and align the simulation with practical operational dynamics, the model has incorporated a conservative replacement interval of seven years for the electrolyzer stacks. This proactive strategy not only safeguards against efficiency losses but also aligns with real-world maintenance practices, emphasizing the pursuit of reliable and efficient green H_2 production.

5.2.3.2 Green Ammonia Plant Configuration

Existing fossil-based Haber-Bosch plants for NH_3 production are inflexible and designed to run uninterrupted at high capacity [101]. However, due to the increasing demand for green NH_3 plants capable of better supporting the variability of solar PV and wind energy, several technology licensors offer flexible NH_3 synthesis technology platforms that can operate down to 5 – 10% of nominal load [101]. This significantly reduces or even eliminates the need for pressurized H_2 storage to address the intermittency of renewables, with high-costs and with several safety and engineering risks due to H_2 high flammability.

In a comparative analysis developed by NH_3 technology licensor Casale, a proprietary optimizer tool compared: 1) Traditional rigid plants, with 70-100% operating range and thus relying on H_2 storage to compile with those loads with 2) Flexible green NH_3 plants, with 10-100% operating range and load ramps of 100%/h. The flexible green NH_3 plants delivered a 35% LCOA reduction mainly due to the reduction of the H_2 storage to 4% of the rigid systems capacity [102]. Moreover, this study reflected on the potential of the cases where the capacity factor acquired values above 50%, where H_2 storage is only used to mitigate the fluctuation for a smoother operation and so the NH_3 nameplate capacity should be designed close to the peak production.

Although nowadays no commercial flexible NH_3 plant is in operation, in the short-term several projects reflected in Table 9 are expected to come online and therefore flexible NH_3 plant configuration has been considered in this case study.

Table 9: Flexible NH_3 operation projects worldwide

Company (Developer)	NH_3 Technology Licensor	Project Location	Plant Sizing (kton/y)	Electrolyzer Sizing (MW)	Flexibility / Operational Range (%)	COD	Source
Topsoe, Vestas and Skovgaard Invest	Topsoe	Lemvig (Denmark)	5	10	5-100% without H_2 storage	2023/ 2024	[103]
Envision Energy	Envision Energy	Chifeng (China)	Phase I: 20 Phase II: 300	Phase I: 35 Phase II: 530	*Undisclosed*	I: 2023 II: 2025	[104]
Mintal Hydrogen	Topsoe	Baotou (China)	390	*Not defined*	10-100% without H_2 storage	2025	[105], [106]

It should be noted that various technical advancements are required for flexible NH_3 synthesis technologies such as electric heaters to conserve temperature profile in the NH_3 synthesis reactor at low operational load, variable load compressors to ramp down compression rates, or the use of surplus nitrogen as an inert to maintain the flows and pressure within the NH_3 loop [101]. The use of surplus nitrogen to maintain the flows and pressure within the NH_3 loop compressor and synthesis has been considered within the ASU load range.

Table 10 lists the main techno-economic parameters considered in the green NH_3 plant configuration:

Table 10: Green NH_3 Plant Techno-Economic parameters

Parameter		Value	Unit	Source
Technical	Green NH_3 Plant Configuration	Flexible	-	-
	Operational Range	10-100%	%	[102], [103]
	Specific Energy Consumption	0.65	kWh / kg NH_3	[44]
Economical	CAPEX	3,450,000	\$ / (ton NH_3/hour)	[44]
	OPEX	2%	% CAPEX	[44]

5.2.3.3 Hydrogen Storage and Ammonia Storage

Regarding H_2 storage, due to the flexibility assumed in the green NH_3 plant, it has been added as back-up to smooth the fluctuation, so the NH_3 nameplate capacity is designed close to the peak production. Therefore, it would only be considered in the economical parameters. In a modelling for a NH_3 flexibility plant up to 20% minimum load range targeted one day of H_2 storage at nominal capacity [107]. Therefore, 12 hours will be considered as assumption in this case study for its sizing and CAPEX associated as the minimum load range in our case is 10%.

Then, green NH_3 storage has also been only considered in the economic parameters, as the energy consumption of its refrigeration until the storage has been included inside the NH_3 synthesis specific energy consumption.

When sizing the storage, it must be highlighted that the green NH_3 targets the EU and thus needs to be exported. Currently, NH_3 shipping is carried out in tankers with an approximate capacity of 40ktons NH_3 [108]. The NH_3 storage has then been sized with this number, being 20% of the nominal yearly capacity, considered enough to have an established and predictable roadmap for exports.

Table 11: Green H_2 and NH_3 Storage Techno-Economic parameters

Parameter		Value	Unit	Source
Technical	Green H_2 Storage days at full load	0.5	days	[107]
	Green NH_3 Storage Required for Export	40	kton NH_3	[108]
Economical	Green H_2 Storage CAPEX	961	\$ / kg H_2	[107]
	Green NH_3 Storage CAPEX	0.81	\$ / kg NH3	[109]

5.2.4 Complementary Systems Block

5.2.4.1 Air Separation Unit

To produce NH_3, nitrogen is supplied via air separation units (ASU), where atmospheric air is split into its primary components by means of a cryogenic distillation process. This nitrogen is then compressed and mixed with H_2 and produces NH_3, and the ASU is one of the units with major capabilities to provide flexibility to the plant. As stated in an article which analyzed deeply the potential flexibility of green NH_3 plants, the H_2:N_2 ratio was found to give the largest flexibility in terms of H_2 intake flux, allowing to reduce it by 67% [110]. This is the reason why the ASU minimum load operational range has been established in the 70%, factor also considered when optimizing the case study. This parameter alongside the other main boundaries of the ASU is reflected in Table 12 below.

Table 12: Air Separation Unit Techno-Economic Parameters

Parameter		Value	Unit	Source
Technical	Technology	ASU (Air Separation Unit)	-	-
	Operational Range	70-100%	%	[110]
	Specific Energy Consumption	0.265	kWh/kg N_2	[44]
Economical	CAPEX	1,500,000	\$ / (ton N_2/hour)	[44]
	OPEX	2%	% CAPEX	[44]

5.2.4.2 Desalinization System

The other necessary input to produce green H_2 and thus green NH_3 is water. As the water availability in the area is unknown and due the green facilities will be located nearby the port nearby, a desalinization plant has been proposed to obtain the water for the electrolyzers, with the main parameters reflected in Table 13. Desalinization has a low footprint in terms of energy consumption and therefore has not been considered in the technical model due to simplification purposes. It has been taken into account in the financial analysis both for CAPEX and OPEX.

Table 13: Desalinization Techno-Economic Parameters

Parameter		Value	Unit	Source
Technical	Technology	Seawater Reverse Osmosis	-	-
	Electrolyzer water requirement	15	m^3 / kg H_2	[44]
	Specific Energy Consumption	3	kWh / m^3	[111]
Economical	CAPEX	5.72	\$/m^3/year	[107]
	OPEX	2%	% CAPEX	Assumption

5.3 Financial Assessment Metrics

Once the techno-economic parameters are defined, the financial analysis extends throughout the full value chain of the project, from electricity generation to green NH_3 delivery. The main goal is to estimate the levelized cost of NH_3 (LCOA) upon delivery previously analysing the levelized cost of energy (LCOE) and levelized cost of hydrogen (LCOH), thus revealing valuable insights into the economic feasibility of the project and its competitiveness versus grey NH_3. However, other key metrics such as total CAPEX required will be obtained as well to assess the magnitude and viability of the project.

In this section, the key metrics of the analysis will be defined together with a discussion of the project finance parameters considered for the study.

5.3.1 Levelized Cost of X (energy, hydrogen, ammonia)

Levelized Cost of Energy (LCOE): The LCOE is a fundamental calculation used in the preliminary assessment of an energy-producing project and can be thought of as the average total cost of building and operating the asset per unit of total electricity generated over an assumed lifetime [112]. The formula to calculate the LCOE is exposed in Equation 1 below.

Equation 1: LCOE Calculation

$$LCOE = \frac{\sum_{i=-n}^{N} \frac{CAPEX_i + OPEX_i}{(1+WACC)^i}}{\sum_{i=-n}^{N} \frac{AEP_{Net,i}}{(1+WACC)^i}}$$

- CAPEX: annualized capital cost, representing the initial cost of investment expenditures
- OPEX: annualized operating cost, representing ongoing maintenance and operation expenditures
- WACC: weighted average cost of capital
- AEP_{Net}: annualized net energy production
- N: project system lifetime

Levelized Cost of Hydrogen (LCOH) and Levelized Cost of Ammonia (LCOA): calculation which follows the same analogy than the LCOE, substituting the annualized net energy production for the amount of H_2 and NH_3 produced yearly respectively.

5.3.2 Levelized Cost of Shipping Ammonia

One of the main objectives of this financial analysis is to estimate the influence of project scale on the levelized cost of ammonia upon delivery, thus revealing valuable insights into the economic feasibility and sustainability of the project. For a chosen vessel, the levelized cost of shipping is a function of annually transported NH_3 which mainly depends on the shipping distance and fuel cost, as represented in Figure 50. In our specific case study, the approximately 7,500 km distance between Port of Pecém and the Port of Rotterdam [113], one of the main NH_3 importers ports in EU which has also 30% stake on the Port of Pecém, has been considered. Fuel cost at 40EUR/MWh_{th}, the average reference given has as well been considered for an estimated cost of 30 EUR/ton NH_3 (35$/ton NH_3 [3]).

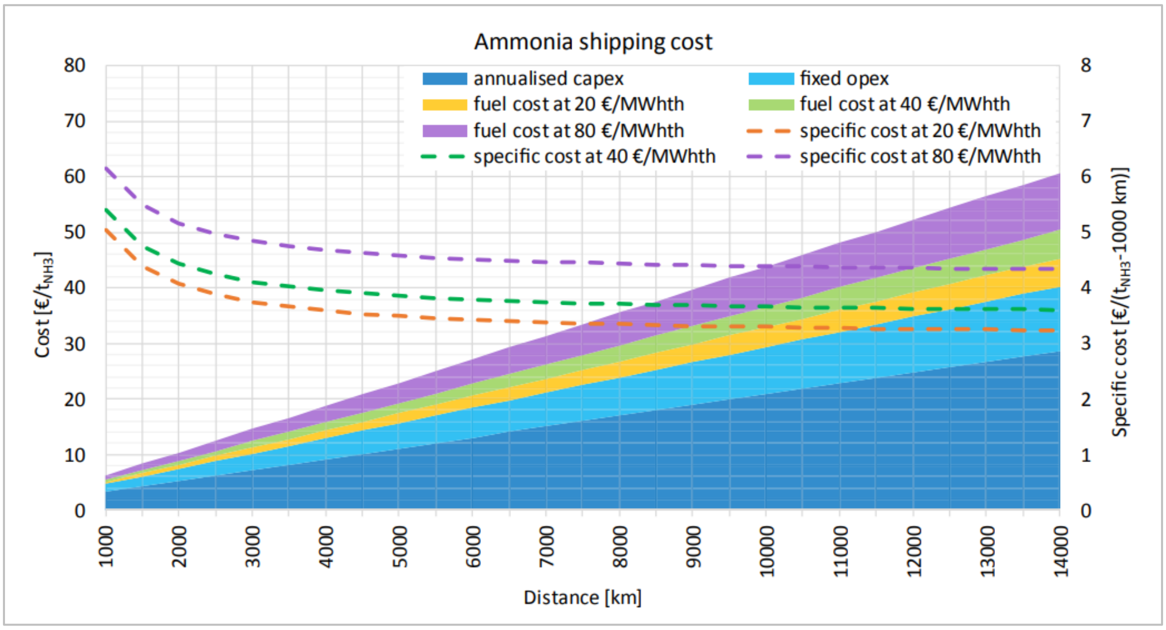


Figure 50: Levelized cost of shipping NH_3 by distance and fuel cost. Source: retrieved from [114]

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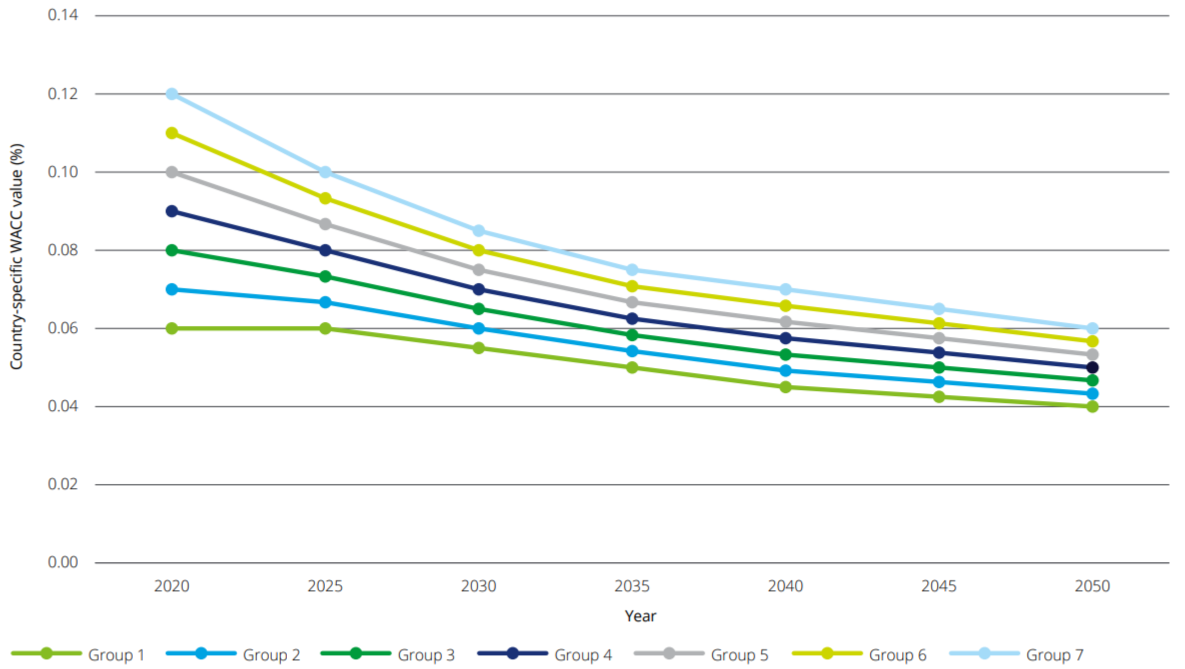
[3] Assuming 1.17 USD/EUR conversion rate

5.3.3 Weighted Average Cost of Capital (WACC)

The cost of capital becomes an important parameter in assessing a firm's potential for net profitability. WACC measures a company's cost of borrowing money. The WACC formula uses both the company's debt and equity in its calculation. In most cases, a lower WACC indicates a healthy business that's able to attract investors at a lower cost. By contrast, a higher WACC usually coincides with businesses that are seen as riskier and need to compensate investors with higher returns [115].

As an example, WACC for onshore wind turbines deployment in Brazil was quoted by IRENA at 6.8% [116]. However, the cost of capital of clean H_2 projects and derivates such as NH_3 should reflect their risk profile, including local regulatory and political risks. Deloitte has analyzed specific country WACC divided by seven different groups according to the Organization for Economic Co-Operation and Development (OECD) country risk classification for officially supported export credits [117]. The study considers a range of WACC going from 6% in 2020, in economically stable regions and countries such as Western Europe, North America, and Australia, to more than 12% in countries such as Iran or Argentina that face long-lasting political or monetary instability, as seen in Figure 51.



Source: Deloitte estimates based on OECD country risk classification.

Note: Groups of countries and regions are defined by the following classification. Group 1: Europe, North America, Australia, Chile. Group 2: China, Saudi Arabia, United Arab Emirates. Group 3: India, Qatar, Mexico, Morocco. Group 4: Colombia, South Africa. Group 5: Brazil, Egypt, Turkey. Group 6: Namibia, Nigeria, Ukraine. Group 7: Argentina, Iran, Tunisia.

Figure 51: Country-specific WACC for LCOH calculations. Source: retrieved from [117]

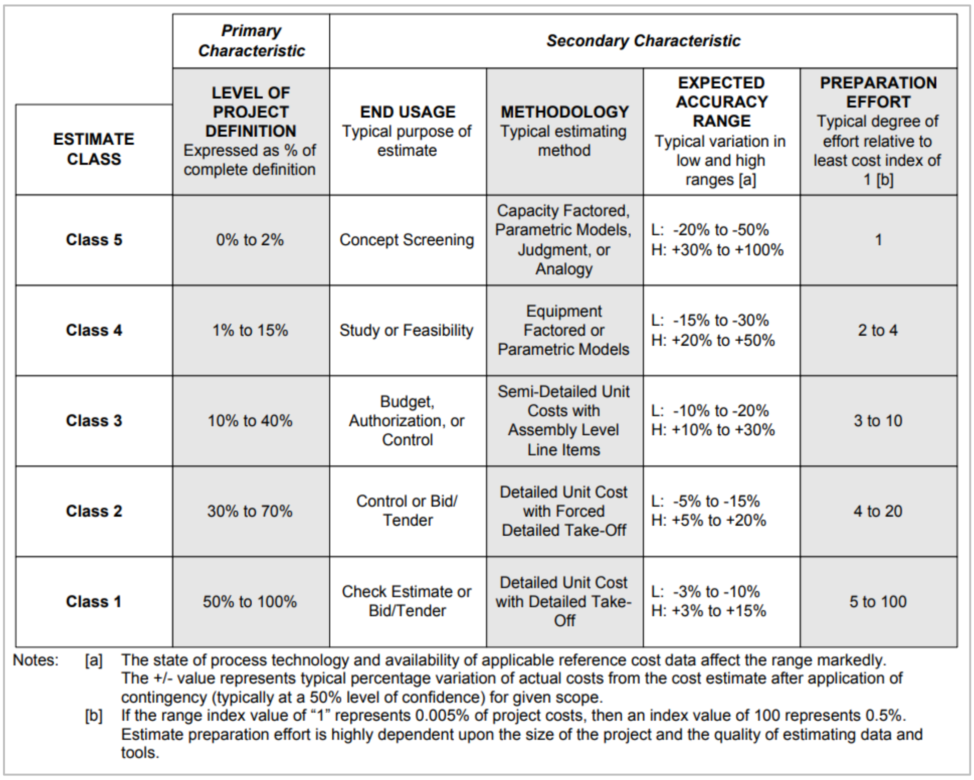
Brazil has been included in group 5, showing a higher risk profile than the first 4 groups with an estimated WACC of 8.5% by 2025, value considered in the analysis although subject to a sensitivity analysis.

5.3.4 Project Lifetime

Fixed assets should be planned with a long-term view. Investment in production assets should consider at least a 20-year lifetime for the electrolyzers, with a 25-year lifetime for renewable assets such as wind and solar power [117]. Project lifetime has then been fixed at 20 years, while further scope of the study could evaluate the potential revenues of the 5 years of remaining lifetime of the wind turbines or even the repowering of these wind turbines to increase their 25 years lifetime, considering the optimal wind conditions of the area.

5.3.5 Cost Estimate Classification System

It is essential to highlight that the project assessment mapped is at an early concept stage, where several assumptions have been considered. At this phase, project details are often limited, and the design needs to be further improved. As a recommended practice of AACE (Association for the Advancement of Cost Engineering) International, the Cost Estimate Classification System provides guidelines for applying the general principles of estimate classification to project cost estimates (i.e., cost estimates that are used to evaluate, approve, and/or fund projects). It maps the phases and stages of project cost estimating together with a generic maturity and quality matrix, which can be applied across a wide variety of industries [118], represented in Figure 52 below:



	Primary Characteristic	***Secondary Characteristic***			
ESTIMATE CLASS	**LEVEL OF PROJECT DEFINITION** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]	**PREPARATION EFFORT** Typical degree of effort relative to least cost index of 1 [b]
Class 5	0% to 2%	Concept Screening	Capacity Factored, Parametric Models, Judgment, or Analogy	L: -20% to -50% H: +30% to +100%	1
Class 4	1% to 15%	Study or Feasibility	Equipment Factored or Parametric Models	L: -15% to -30% H: +20% to +50%	2 to 4
Class 3	10% to 40%	Budget, Authorization, or Control	Semi-Detailed Unit Costs with Assembly Level Line Items	L: -10% to -20% H: +10% to +30%	3 to 10
Class 2	30% to 70%	Control or Bid/ Tender	Detailed Unit Cost with Forced Detailed Take-Off	L: -5% to -15% H: +5% to +20%	4 to 20
Class 1	50% to 100%	Check Estimate or Bid/Tender	Detailed Unit Cost with Detailed Take-Off	L: -3% to -10% H: +3% to +15%	5 to 100

Notes: [a] The state of process technology and availability of applicable reference cost data affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.

[b] If the range index value of "1" represents 0.005% of project costs, then an index value of 100 represents 0.5%. Estimate preparation effort is highly dependent upon the size of the project and the quality of estimating data and tools.

Figure 52: Cost estimate classification matrix for the process industries. Source: withdrawn from [118]

Class 5 estimate would be the most accurate to consider in this assessment, as it is in concept screening and has a low level of engineering and design. It can also be referred as "ANSI Standard Reference Z94.2-1989 Name: Order of magnitude estimate (typically -30% to +50%)" [118]. There has been assumed a cost contingency of

1.2 in the financial model to accommodate the risk of the project development at this stage, being the average of the given values.

6. Results and Discussion

6.1 Technical Analysis

6.1.1 Project Sizing

The optimization process has been modelled using Microsoft Excel, focusing on the key technical parameters exposed in previous section to ensure efficient utilization of wind energy and obtain the green NH_3 yearly production target.

It is essential to highlight that there are two common operational strategies that can be considered to size an integrated green H_2 and NH_3 project. One consists of oversizing the renewables installed capacity to achieve higher electrolyzer and NH_3 synthesis utilization factors, which is an attractive option if the renewables are integrated on its majority by solar PV, with lower LCOE than wind energy. The other strategy consists of sizing the electrolyzers and NH_3 synthesis according to the expected renewables output, considered more attractive when the renewable resource involves in its majority wind energy, with higher LCOE but with higher resource consistency and availability than solar PV. Moreover, expected cost reductions of electrolyzer equipment will propel the adoption of the second operational strategy.

In this specific case study, the second strategy has been considered. The plant's operation has been adjusted based on the representative year for Trairí. The model will be initially sized based on the specific winter power profile to avoid inefficient wind energy curtailment for then be refined with several control loops established to ensure an effective and reliable green NH_3 production.

The Excel model utilizes the onshore wind power profile as an input parameter. The chosen power profile, based on the winter season (July-December) for Trairí location, is characterized by 80.6% average gross capacity factor as referred in Figure 37. However, a net capacity factor of ~70% is considered, accounting with the assumed wind power losses represented before in Table 5. This profile is used to determine the sizing of the different units included in the optimization. To ensure the least wind energy is curtailed and maximizing the output, oversizing is applied to these units at a ratio of 1/0.7 for operating at nominal capacity, as exemplary represented in Table 14.

The equations to obtain the nominal and minimum values represented in Table 14 are defined in the Annex.

Table 14: Project Sizing and Energy Consumption Parameters

Parameter	Unit	Green NH_3 Synthesis	Green H_2 Production	ASU	SWRO	Total
Yearly Production Target	(kton product / year)	200	36	164	540	-
Assumed Yearly Availability	%	98%	98%	98%	98%	-
Oversizing based on wind power profile	Ratio	1/0.7	1/0.7	1/0.7	1/0.7	-
Nominal Hourly Production Target	(ton product / hour)	33.28	5.99	27.29	89.86	-
Specific Energy Consumption	kWh/kg product	0.65	51	0.265	0.003	-
Nominal Hourly Operation Consumption	kWh	21,633	305,523	7,232	270	**334,658**
Nominal Plant Sizing	MW	21.63	305.52	7.23	0.27	-
Minimum Operation Range	%	10%	10%	70%	10%	-
Minimum Hourly Operation Consumption	kWh	2,163	30,552	5,062	27	**37,805**

6.1.2 Control Loop Assessment & Results

The Excel-based model employs a control loop to optimize the plant's operation throughout the representative year. The primary objective is to match the energy output from the wind farm with the system requirements in an hourly basis. The equations to obtain the hourly values for the control loop, as exemplary illustrated in Figure 53 and Figure 54 are defined in the Annex. The control loop operates as follows:

I. Net Energy Output Exceeds Nominal System Requirements – Wind Curtailment

When the net energy generated by the wind farm exceeds the nominal system requirements, the system needs to curtail wind energy production. Then, the other processes operate at a nominal 100% production rate. The objective of the initial oversizing is to limit the number of hours per year where this scenario occurs to avoid energy losses.

An exemplary operation for the hourly operation on the 11th of September of the representative year (month with highest wind energy capacity factor), when wind energy curtailment is required, is exposed in Figure 53. When net energy output is higher than the nominal system requirement, wind energy is curtailed (Periods: 06h; 09h-15h; 19h:23h). On those periods, the production is adjusted to the maximum for H_2, N_2 and NH_3 production. In the remaining periods, the plant adopts a variable operation, as can be seen in period 0h-5h, where H_2, N_2 and NH_3 production adapts with the net energy input.

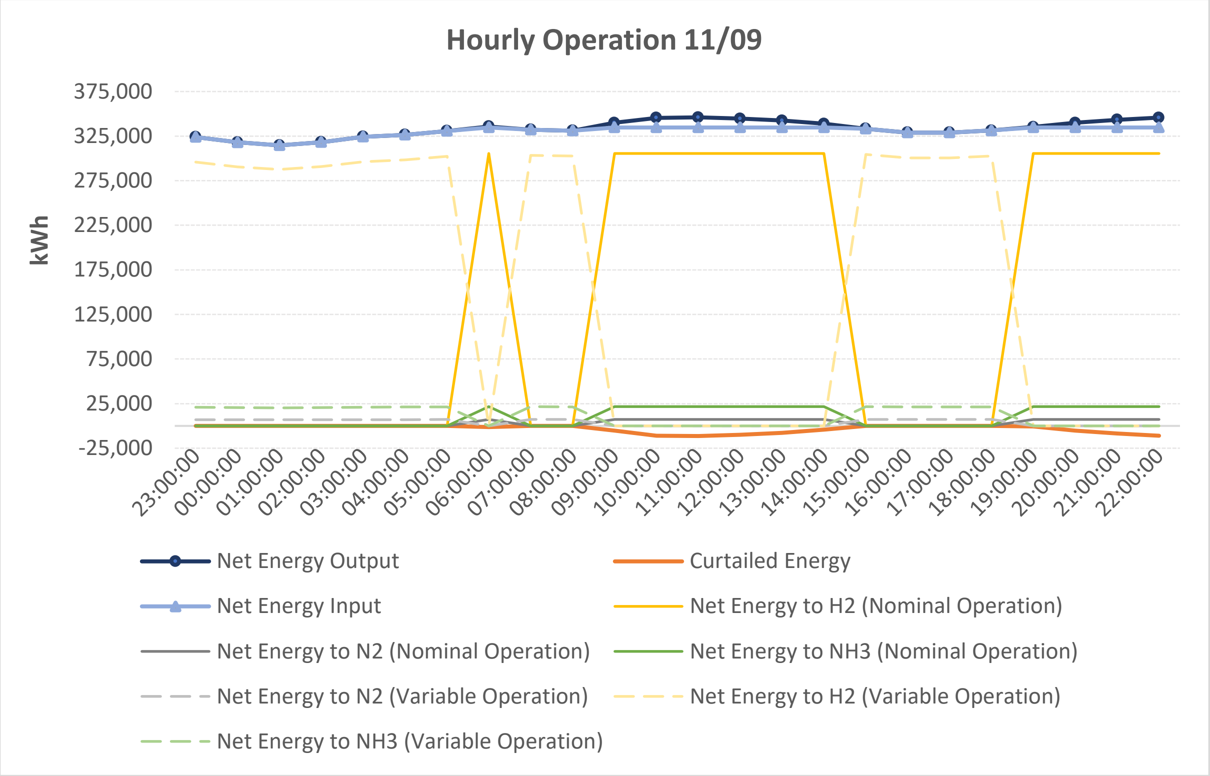


Figure 53: Hourly Operation of the system for 11th September, representing the control loop for wind energy curtailment

II. Net Energy Output Falls Below Minimum System Requirements – Grid Backup

When the net energy falls below the minimum system requirements, the system needs to withdraw energy from the grid. The H_2 and NH_3 synthesis processes continue operating at 10% load while the air separation unit keeps operating at 70% load to provide the flexibility required in the NH_3 synthesis.

An exemplary operation for the hourly operation on the 28th of April of the representative year (month with lowest wind energy capacity factor), when energy from the grid is required, is exposed in Figure 54. When net energy output is lower than the minimal system requirement, energy is withdrawn from the grid (Periods: 03h-11h). On those periods, the production is adjusted to the minimum for H_2, N_2 and NH_3 production. In the remaining periods, the plant adopts a variable operation, where H_2, N_2 and NH_3 production adapts with the net energy input.

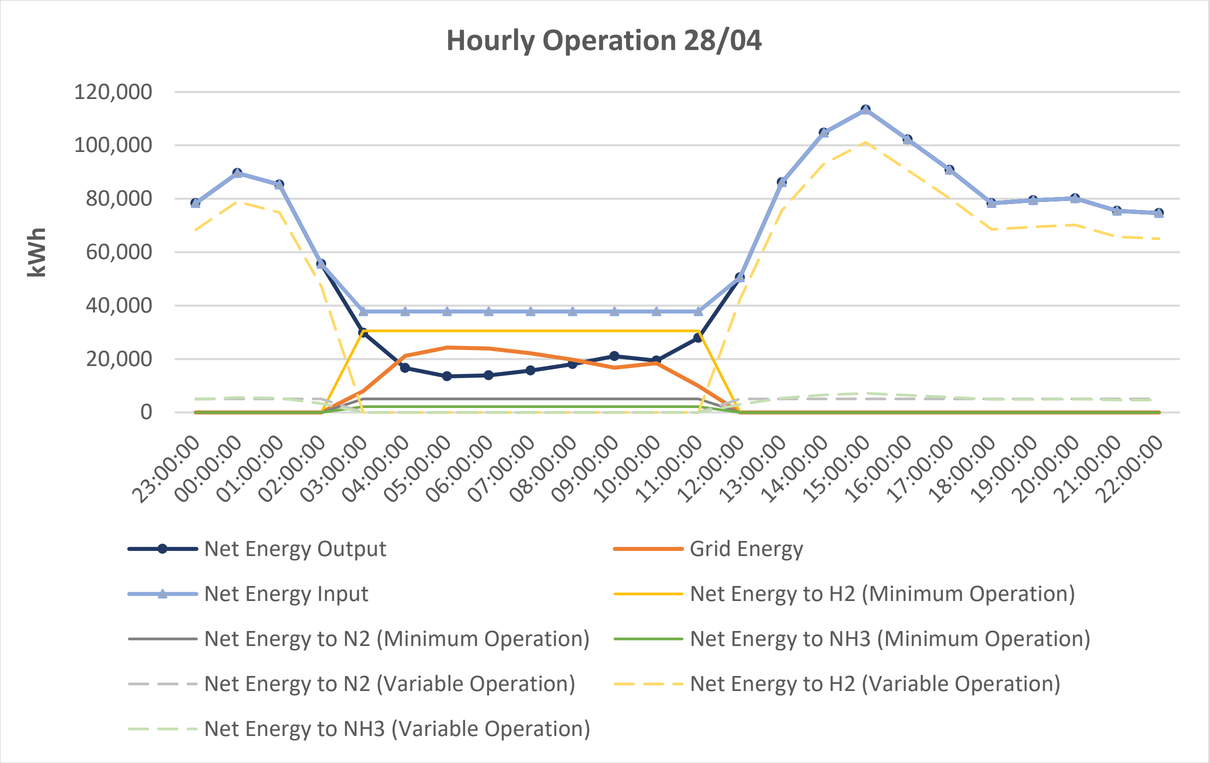


Figure 54: Hourly Operation of the system for 28th April, representing the control loop for grid energy backup support

III. Net Energy Between Nominal & Minimum System Requirements – Variable Operation

In cases where the net energy generated is insufficient to meet the nominal system requirements but still surpasses the minimum system requirements, the plant operates at variable production rates based on available energy. Within this scenario, the air separation unit is always needed to keep at least a 70% load range. This has been as well considered in the model therefore differentiating two sub-scenarios: 10-70% and 70-100% variable operation modes. Variable operation mode can be also noted in previous Figure 53 and Figure 54.

6.1.3 Process Optimization Results

To optimize the process developed in the control loop, the goal seek function played a pivotal role in determining the minimum number of wind turbines necessary to fulfill multiple critical objectives. These objectives encompassed achieving the 200,000 tons per year green NH_3 production target while minimizing wind energy curtailment and the dependence on grid power.

The main results of the optimization are shown in Table 15 below:

Table 15: Key Optimization Results

Section	Parameter	Optimization Result	Unit
ENERGY PRODUCTION			
Wind Turbines	Nº Turbines	97	Nº
	Installed Capacity	407.4	MW
	Annual Net Energy Production	2,086,048	MWh/year
	Annual Net Energy to Green Block (after transportation & substation losses)	2,028,265	MWh/year
Wind Energy Curtailment	Nº hours	257	hours/year
	Energy Curtailed	1,198	MWh/year
	Relative % vs Net Wind Energy Production	0.06 %	%
Energy Withdraw from Grid	Nº hours	139	hours/year
	Energy Withdrawn	2,870	MWh/year
	Relative % vs Net Wind Energy Production	0.14%	%
ENERGY CONSUMPTION – H_2, N_2, NH_3 PRODUCTION			
Project Simulation Output - Energy Consumption	Total Energy Consumption	2,029,936	MWh/year
	Electrolyzers Energy Consumption (%)	91.06	%
	ASU Energy Consumption (%)	2.48	%
	NH3 Synthesis Energy Consumption (%)	6.46	%
Project Simulation Output - H_2, N_2 & NH_3 Production	H_2 Production	36,246	tons/year
	N_2 Production	190,321	tons/year
	NH_3 Production	201,366	tons/year

In terms of energy production, 97 wind turbines (407.4 MW) would be able to deliver the expected energy for producing slightly over 200 kton/year of green NH_3 with the project sizing established. It can be observed from the table and from Figure 55 below that due to the initial sizing based on the winter wind power profile, the energy curtailment is minimum, with a 0.06% curtailed yearly. Moreover, the wind stability is again reflected in the fact that only 0.14% of the energy consumption in the project needs to be withdraw from the grid, allowing a great independency.

Moving to net energy consumption, electrolyzer energy consumption amounts 91.06% of the total project energy consumption, reaffirming the energy intensity associated with green H_2 production, while NH_3 synthesis consumes 6.46% and ASU a residual 2.48%.

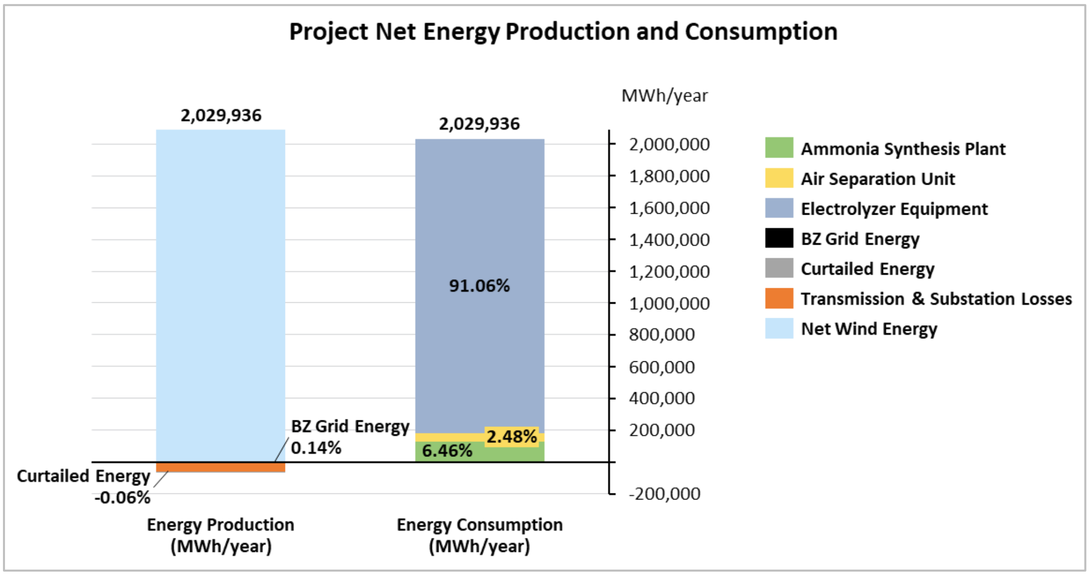


Figure 55: Process optimization output – net energy production & consumption

6.2 Financial Analysis

Within the realm of financial analysis, a comprehensive evaluation of the intricacies involved in the entire value chain of NH_3 production is undertaken. This holistic assessment extends from the initial stage of electricity generation through the various intermediate steps, ultimately culminating in the delivery of green NH_3 to its intended destinations. One of the principal objectives of this financial analysis is to estimate the influence of project scale on the levelized cost of ammonia upon delivery, thus revealing valuable insights into the economic feasibility and sustainability of the project.

6.2.1 Financial KPIs

The main individualized LCOx as well as other financial KPIs such as CAPEX & OPEX for the techno-economic and financial parameters established in section 5 are presented in Table 16 below:

Table 16: Key Financial Results

Parameter		Value	Unit
LCOE	LCOE_Wind	30.0	\$/MWh
	LCOE_Wind_GridInfrastructure	34.0	\$/MWh
	LCOE_Wind_GridInfrastructure_GridEnergy	34.1	\$/MWh
LCOH	LCOH_PEM_SWRO	3.4	\$/ kg H_2
	LCOH_PEM_SWRO_Storage	3.7	\$/ kg H_2
LCOA	LCOA_Synthesis	770.5	\$/ ton NH_3
	LCOA_Synthesis_Storage	789.3	\$/ ton NH_3
	LCOA_Synthesis_Storage_Shipping	831.3	\$/ ton NH_3
CAPEX	Total Project CAPEX	1,263.8	M\$
OPEX	Total Project OPEX	905.3	M\$

- LCOE: it has been subdivided into three sections to account not only for the wind turbines but also for the required grid infrastructure and the back-up energy costs from BZ grid. The most employed reference is the LCOE for the wind energy generation, which based on the model results in 30$/MWh, value aligned with the 95th percentile of the LCOE attributed to Brazil onshore wind from a recent IRENA report regarding renewable generation costs [91].

- LCOH: subdivided into two sections, the first one without H_2 storage and the second one accounting the costs of storing H_2 for smoothing NH_3 plant operation. The obtained value of 3.7 $/kg H_2 is within industry ranges, with a paper from the Energy Ministry of Brazil ranging green H_2 production costs between 3.6 $/kg H_2 and 5 $/kg H_2 [119] or the LCOH range for onshore wind on IEA Global Hydrogen Review 2023 [24].
- CAPEX: as the project's initial investment (CAPEX) exceeds one billion dollars, it is essential for a company's investment commitment to be resolute. Concurrently, the establishment of agreed upon offtake arrangements becomes a critical factor in ensuring the project's economic viability. The overall CAPEX is reflected in Figure 56 with the percentage weight of the different system components. It can be clearly noted that the most CAPEX-intensive components are the wind turbines (40.7%) and the electrolyzer equipment (29.3%), followed by the NH_3 synthesis plant (10.9%). Sensitivity analyses will be carried out to observe LCOA changes with wind turbine and electrolyzer equipment costs.

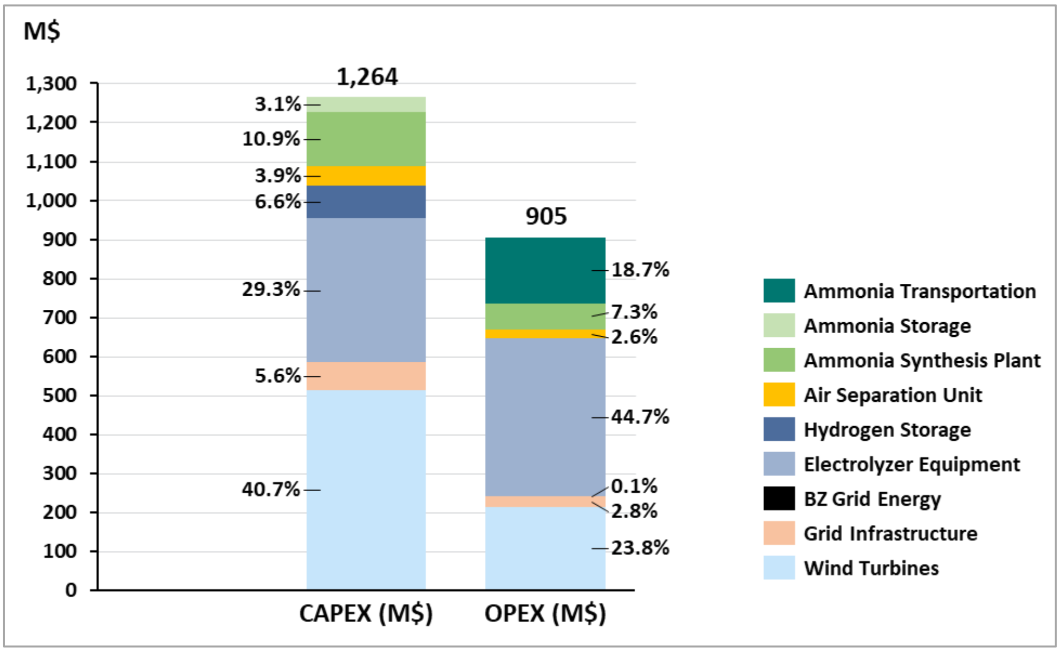


Figure 56: CAPEX & OPEX breakdown by system component

- OPEX: The cumulative OPEX alongside the project lifetime is breakdown by components in Figure 56. It can be seen that the required investment in operation and maintenance is as well quite considerable, reaching almost the billion values. The most OPEX-intensive component is the electrolyzer equipment accounting for almost half of the total OPEX (44.7%) due to the stack replacement needs throughout the project lifetime. Then, wind turbines maintenance (23.8%) and NH_3 shipping upon delivery (18.7%) have also significant importance in the OPEX impact.

6.2.2 LCOA Breakdown

The LCOA breakdown considers both the CAPEX & OPEX of each subcomponent alongside the project value per ton of NH_3. It then gives the weight of each system into the LCOA, key to identify which are the main cost drivers of the project and to propose potential measures to propel better economics.

As already highlighted in the CAPEX & OPEX breakdown analysis, the LCOA breakdown illustrated in Figure 57 below reflects that the most impactful components alongside the project costs are the wind turbines and the electrolyzer equipment, contributing to a 36% and a 33% of the LCOA respectively. NH_3 synthesis with a 10% contribution is the third largest contributor to the LCOA.

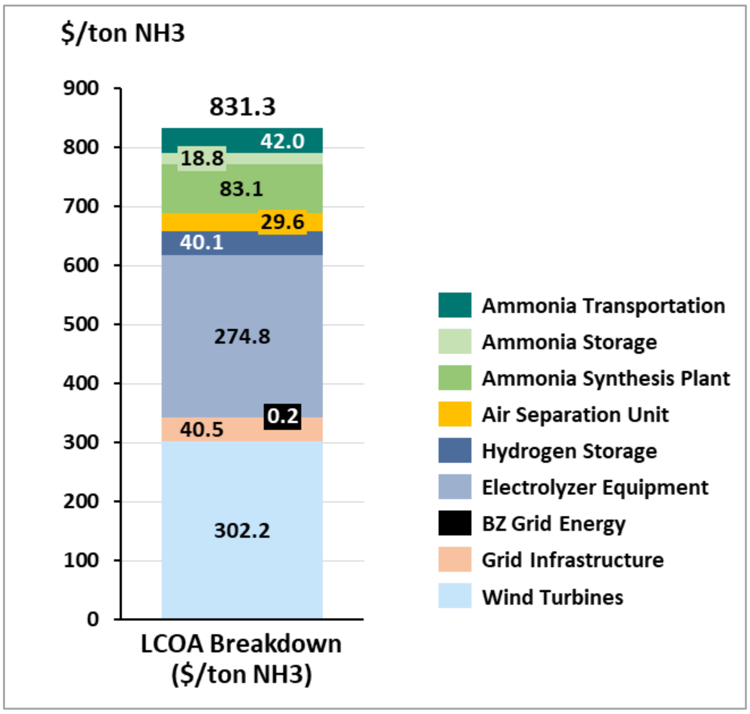


Figure 57: LCOA breakdown by system component

The obtained green NH_3 LCOA, 831 \$/ton NH_3 is aligned with recent studies that analyzed the competitiveness of green NH_3 worldwide. A study developed in 2023 by Fraunhofer Institute, with specific assessment of importing green NH_3 to Germany from 3 Brazil regions (Rio Grande do Norte, Bahia and Rio Grande do Sul) resulted in LCOA ranging 886-961 \$/ton NH_3 [47]. Another study developed to assess green vs grey NH3 competitiveness worldwide and the implications for global natural gas demand resulted in a LCOA ranging 700-800 \$/ton NH_3 [44].

6.2.3 LCOA Sensitivity Analysis

Sensitivity analyses are a valuable practice in decision-making and risk assessment, as they provide a structured and comprehensive way to evaluate the impact of varying key parameters and assumptions on a project or investment. By systematically exploring the potential range of outcomes in response to changing variables, sensitivity analyses offer insights into the robustness and vulnerability of a plan or decision.

As observed in the LCOA breakdown, the most impactful techno-economic parameters are the wind turbine and electrolyzer equipment costs. Moreover, in terms of financial parameters, the WACC has also been subject to sensitivity analysis due to its constant variability. The respective ranges of change during the sensitivity analysis follows the Class 5 order of magnitude estimate (typically -30% to +50%) and are stated in Table 17 below. The 30% CAPEX reduction scenario seems the most reasonable in the short to medium-term due to continuous cost reductions in wind turbines and electrolyzers. Then, although a 50% CAPEX increase is considered an extremely pessimistic scenario, it is essential to consider that current global supply chain disruptions have affected the renewable energy industry, with particular issues within the wind industry substantially increasing its costs. Moreover, the electrolyzer industry is quite nascent and its deployment could be much more costly than expected.

Table 17: LCOA Sensitivity Analysis parameters selection

Parameter	Base Value	Unit	Variation
Wind Turbine CAPEX	1,052	$/kW	736-1,578 $/kW (-30% to +50%)
Electrolyzer System CAPEX	1,000	$/kW	700-1,500 $/kW (-30% to +50%)
Electrolyzer Stack Replacement OPEX	400	$/kW	280-600 $/kW (-30% to +50%)
WACC	8.5	%	5.95-12.75 % (-30% to +50%)

In the sensitivity analysis developed and illustrated in Figure 58, it can be observed that the LCOA range would vary between 740-1,000 $/ton NH_3 for the 3 parameters analyzed. The sensitivity analysis for wind turbines and electrolyzer equipment presents really similar results, aligned with the LCOA breakdown where the weight of them was balanced. As an example, a 20% cost reduction in one of these parameters would entail a 6% reduction of the project LCOA.

The LCOA which presents higher variation within the analysis is the WACC-dependent, with a steeper linear inclination than the others. As an example, if the WACC would be reduced a 20% from the 8.5% established as base value to the onshore wind related WACC in Brazil, 6.8% [116], the project LCOA would be reduced by 7.6%.

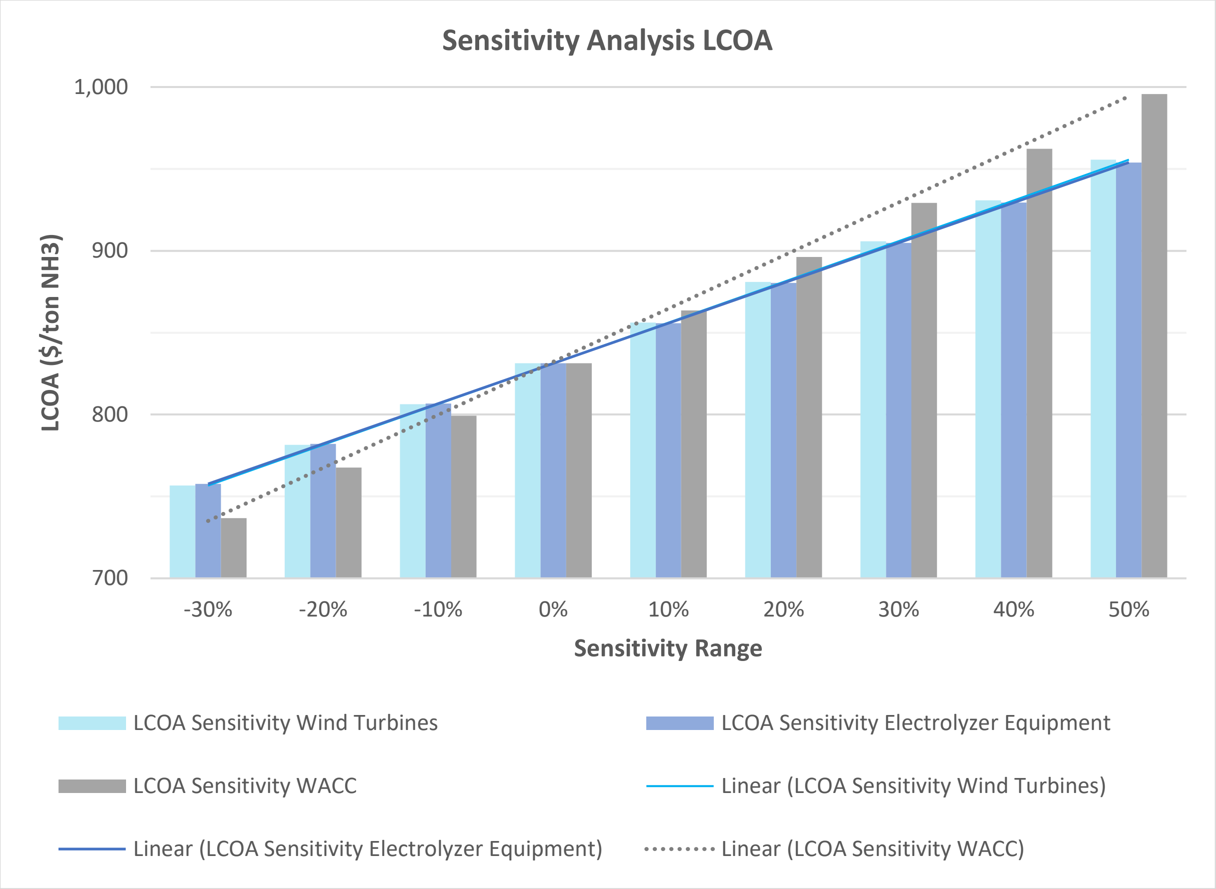


Figure 58: Sensitivity Analysis LCOA - Wind Turbines, Electrolyzer Equipment and WACC Comparison

6.3 Green Ammonia vs Grey Ammonia Competitiveness

One of the main objectives of the techno-economic and financial analysis is to assess the potential of replacing grey NH_3 with green NH_3 in order to assess the viability of these projects and its potential as a decarbonisation pathway. Therefore, the aim of this section is to provide not only a comparison of the grey NH_3 costs with the obtained LCOA in the case study developed, but also to compare other key metrics such as related greenhouse gas emissions and energy intensity of each production process.

Almost all NH_3 production relies on the use of fossil fuels, specifically from natural gas (72%), coal (22%) and by-products such as naphtha and heavy fuel oil [2]. The NH_3 produced from natural gas is known as grey NH_3 and is the most common pathway for industrial NH_3 production.

Natural gas is utilized in the steam methane reforming (SMR) process to produce H_2, subsequently combined with nitrogen to develop the NH_3 synthesis through the Haber-Bosch process. To analyse grey NH_3 production it is then imperative to reflect the main techno-economic and environmental parameters of this production route, stated in Table 18 below and mostly obtained from Yara, one of the largest NH_3 producers and traders worldwide with 7.7 million tons/year NH_3 production [120]:

Table 18: Grey NH_3 production from SMR, Techno-Economic and Environmental Parameters

Parameter		Value	Unit	Source
Technical	SMR Gas Consumption	36	mmbtu/ton NH_3	[121]
		10.55	MWh/ton NH3	[121]
		37.98	GJ/ton NH3	[121]
Economical	Gas Price (OPEX – Fuel)	Variable	\$/MWh	[121]
	Other Production Cost (OPEX)	29	\$/ton NH_3	[121]
Environmental	Equivalent CO_2 emissions	1.92	ton CO_2-e / ton NH_3	[27]

In order to carry out a reliable comparison, the on-site grey NH_3 production and the green NH_3 importation should occur in the same location. Therefore, as the import location was established in the Port of Rotterdam, the facility which would serve as NH_3 is Yara Sluiskil. Yara Sluiskil is located at <100km from the Port of Rotterdam and is the largest NH_3 and fertilizer plant in the Netherlands and one of the largest in Europe, with 1.9 million tonnes/year NH_3 production. Yara Sluiskil mainly uses North Sea gas to produce high-quality nitrogen fertilizers and industrial chemicals [120].

6.3.1 LCOA

As stated in Table 18 above, grey NH_3 production cost is dependent on natural gas prices. As the objective is to compare the green NH_3 produced in Brazil and exported to EU with local grey NH_3 production, TTF natural gas prices have been considered. The TTF (Title Transfer Facility) is the main reference market for natural gas trading in Europe and based in Amsterdam, the Netherlands. TTF most recent yearly prices as well as the short-term forecast (2019-2025) are represented alongside other natural gas indexes in the world in Figure 59 in million British thermal units (mmbtu)[4].

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[4] mmbtu: million British thermal units, 1 mmbtu = 0.293071, e.g., 15 \$/mmbtu = 51.2 \$/MWh

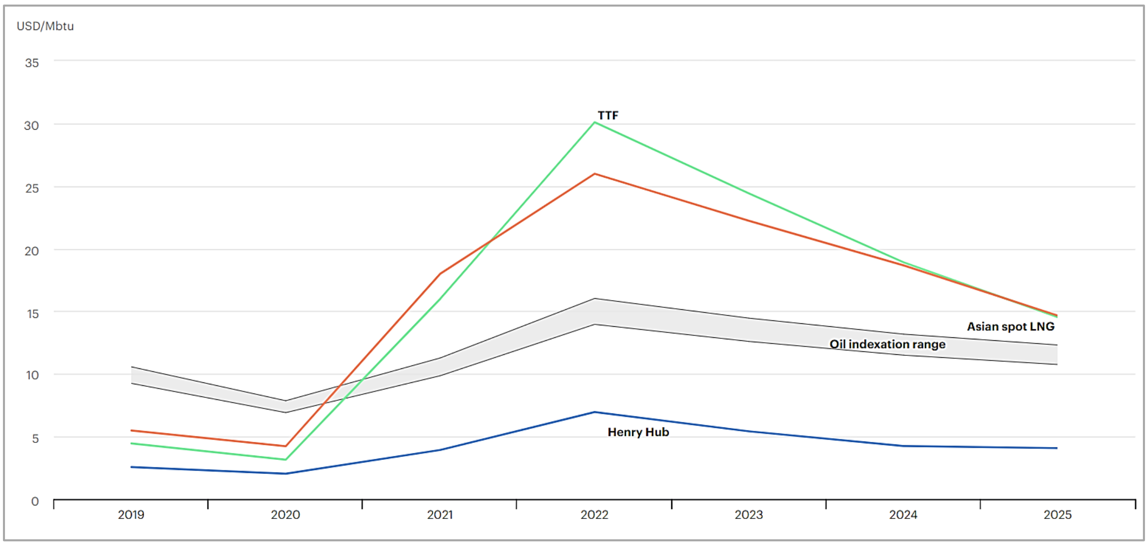

Figure 59: Natural gas yearly price assumptions (\$/mmbtu), 2019-2025. Source: withdrawn from IEA [122]

The natural gas market is quite volatile, therefore several scenarios have been developed to compare the potential grey NH_3 production cost and its comparison with the green NH_3 LCOA. Moreover, potential carbon pricing schemes are to be included in the policy and regulatory framework, thus increasing the cost of grey NH_3 production. EU carbon permits historical prices evolution is represented in terms of EUR/tonCO_2 in Figure 60 below. While carbon permits had historically low prices, its price have surges since 2018 due to increasing policies and restrictions, reaching more than 100 EUR/ton CO_2 in 2022 and expected to keep growing in the medium to long term forecast.

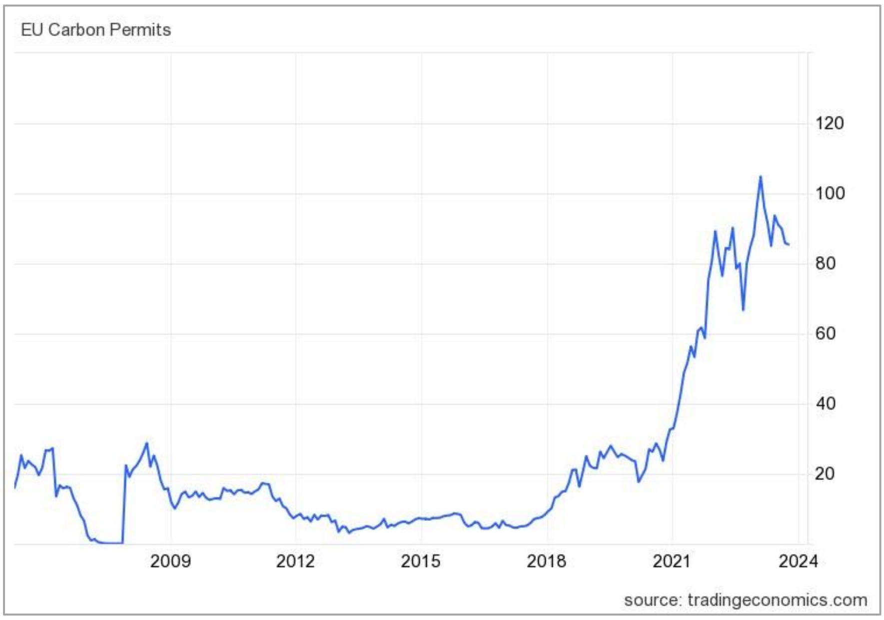

Figure 60: EU carbon permits historical price evolution (2005-2023), EUR/ton CO2. Source: withdrawn from tradingeconomics.com [123]

Figure 61 represents the grey NH_3 production costs for the variable natural gas prices. Moreover, several CO_2 taxes have been proposed to observe the potential impact on top of the grey NH_3 direct cost.

- With TTF natural gas at ~50 \$/MWh, price targeted to be the yearly average in the short-term forecast according to already seen Figure 59, it can be observed that imported green NH_3 would be competitive with grey if carbon taxes reach 150\$/ton CO_2
- Imported green NH_3 would be competitive with grey NH_3 (w/o CO_2 taxes), when natural gas prices surpass ~80 \$/MWh
- With natural gas prices lower than ~35 \$/MWh, imported green NH_3 remains uncompetitive even with carbon taxes of 200\$/tonCO_2
- If considering a green NH_3 LCOA with 30% CAPEX reduction both in wind turbines and electrolyzer equipment technologies, with TTF natural gas at ~50 \$/MWh, green NH_3 would be sooner more cost competitive than grey NH_3 with 50\$/ton CO_2 taxes

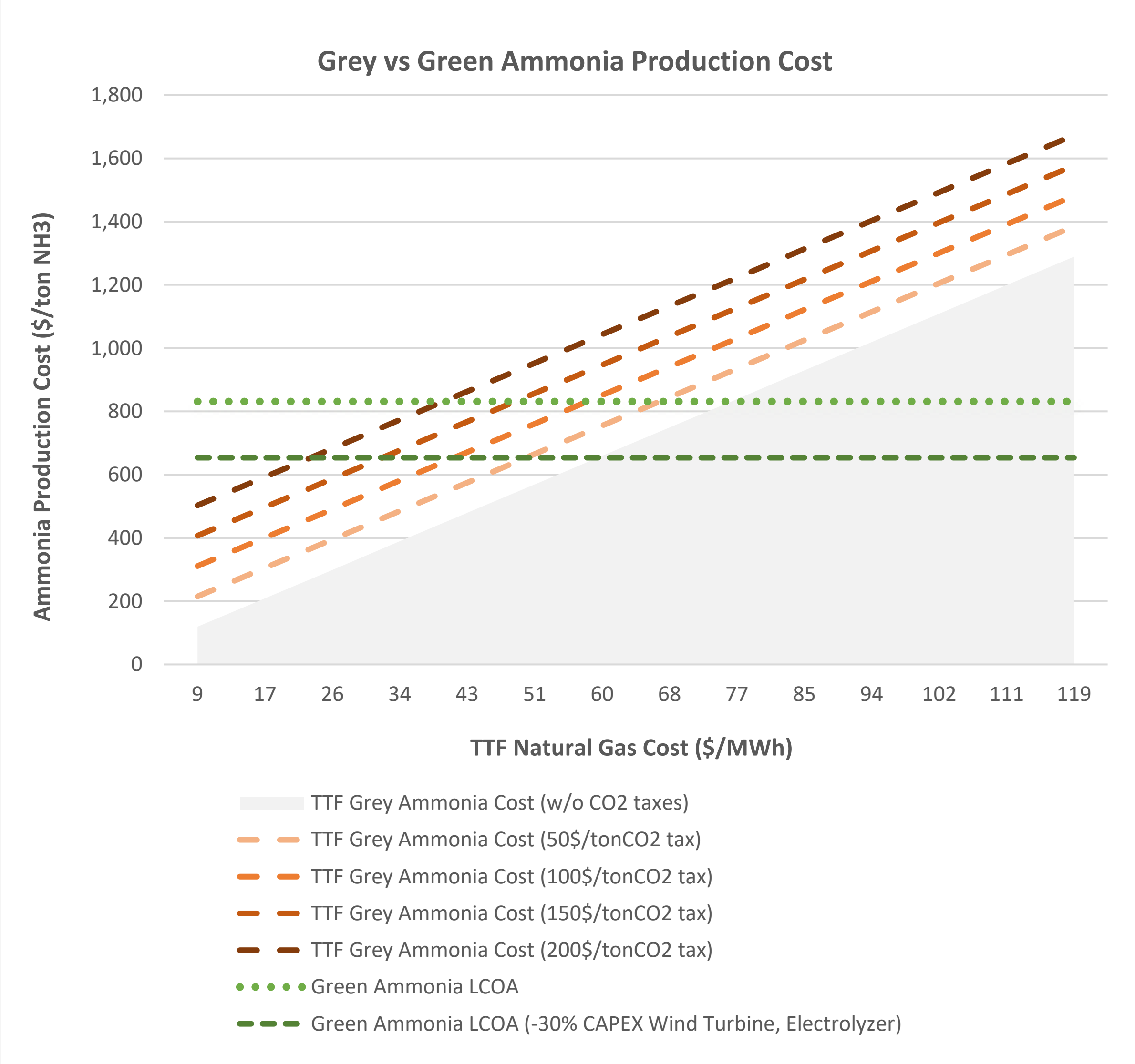

Figure 61: Grey vs green NH_3 production cost, based on TTF natural gas cost

6.3.2 Energy Intensity and CO_2 Footprint

The energy intensity associated to each production process as well as the CO_2 footprint are illustrated respectively in Figure 62 and Figure 63 below.

Moreover, in the green NH_3 specific case study, energy intensity and CO_2 emissions from NH_3 shipping have been considered. Most NH_3 shipping vessels for transportation are nowadays LPG carriers or tankers propelled by heavy fuel oil or marine gasoil with the characteristics stated in Table 19 below. Today, most fully pressurised oceangoing LPG carriers are fitted with two or three horizontal, cylindrical, or spherical cargo tanks and have typical capacities between 20,000 and 90,000 cubic meters and overall length ranging from 140 m to 229 m [124]. For the specific case study, a medium-sized LPG carrier has been considered with net DWT (Dry Weight Tonnage) capable of transporting 40 kton NH_3, according to the NH_3 storage established. Therefore, to calculate the energy intensity 5 trips have been considered. Further scope of the study could include the potential utilization of NH_3 as both transported material and marine fuel powering the vessel.

Table 19: NH_3 Shipping Energy Consumption and Environmental Parameters

Parameter		Value	Unit	Source
Energy Consumption	Deep-sea vessel generic fuel consumption	0.0082	kWh / (DWT-km)	[114], [125]
	Shipping Distance	7,500	km	[113]
	Net DWT (Dry Weight Tonnage)	40,000	ton NH_3	Assumption
Environmental	Equivalent CO_2 emissions	1.2	kg CO_2-eq / kg H_2-eq (15,000 km – NH_3 tanker)	[24]

- In terms of energy intensity, as seen in Figure 62, the GJ/tonNH_3 are quite balanced from the pathways analysed, although being more energy-consuming the grey NH_3 production pathway. The global average energy consumption for NH_3 production is around 36 GJ/tonNH_3 following IRENA Renewable Ammonia report [2], that also states that NH_3 plants in industrialized countries typically have a lower energy consumption (33-36 GJ GJ/tonNH_3) compared to developing countries (36-47 GJ/tonNH_3). It also highlighted that grey NH_3 production energy intensity varies based on the specific plant technology and that energy efficiency measures are not expected, while green NH_3 has a much wider energy efficiency reduction potential due to improvement in electrolysis system efficiency and integration with NH_3 synthesis among others.

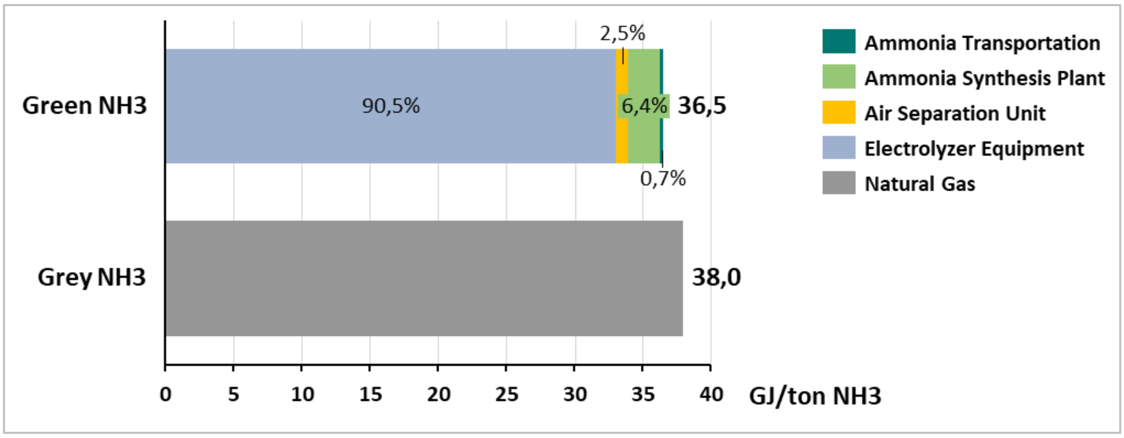

Figure 62: Grey vs green NH_3 energy intensity comparison

- In terms of GHG emissions, as seen in Figure 63, green NH_3 production process considers wind turbine and electrolyzer LCA (Life-Cycle Analysis) as well as shipping emissions parameters for a total of 0.22 $tonCO_2$-eq/$tonNH_3$, acquiring a substantial reduction vs the grey pathway with an established 1.92 $tonCO_2$-eq/$tonNH_3$ in EU facilities [27]. The global NH_3 production technology generates around 0.5 Gt of $CO_{2\text{-eq}}$ annually, accounting for 1% of global greenhouse gas emissions, following IRENA Renewable Ammonia report [2]. In this report, grey NH_3 is aligned with the CO_2-eq obtained in the case study (1.8-2.6 $tonCO_2$-eq/$tonNH_3$) and green NH_3 is expected to be close to reach the lowest range of carbon footprint from electrolysis (0.1-0.9 $tonCO_2$-eq/$tonNH_3$).

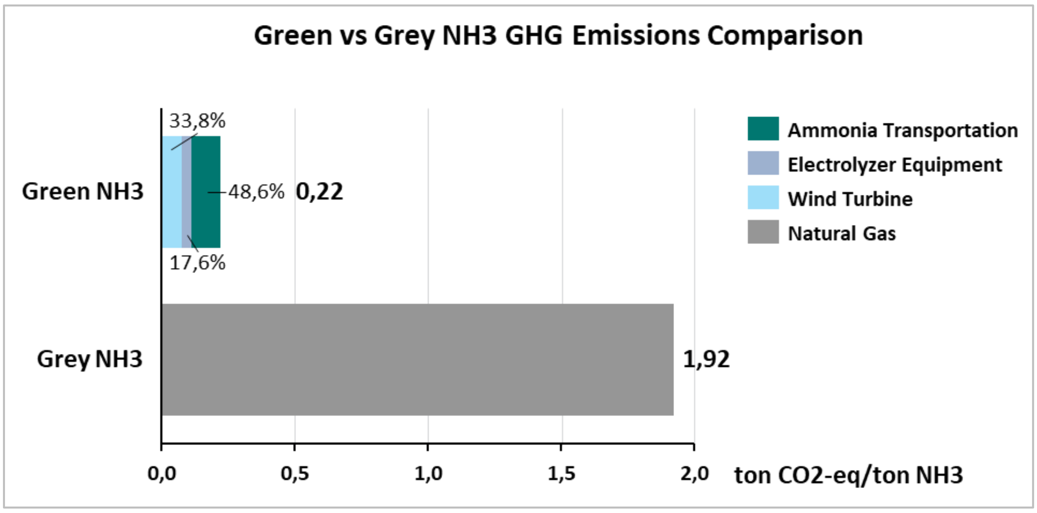

Figure 63: Grey vs green NH_3 GHG emissions comparison

7. Conclusions, Recommendations and Future Work

7.1 Conclusions and Recommendations

H_2 is one of the most promising energy vectors within the energy transition with enormous potential to decarbonise high-energy consuming sectors. Currently, H_2 is mostly produced from fossil-fuels but in the future most of H_2 will be green, produced from renewable energy sources. However, one of the main issues related with H_2 is its complex transportation and storage due to its physical properties, which make this process more complex and expensive than with traditional fossil fuels.

Converting green H_2 into derived fuels such as NH_3 or methanol is in a very mature stage and these latter products present certain advantages such as higher energy density or the opportunity to use existing infrastructure. As of 2022, most of hydrogen-derived fuels projects were in pilot stages consuming a negligible amount of green H_2. However, the increasing appetite due to attractiveness and maturity of the sector has grown exponentially. More than 17 Mton of H_2 equivalent, involving over 300 projects are projected to be operational by 2030, with green NH_3 accounting for roughly 90% of the announced production.

Green NH_3 surges not only as a substitute of grey NH_3 in current uses (fertilizer and industry), but it also emerges as a zero-CO_2 emissions fuel capable of opening doors to new hard-to-decarbonise sectors such as the shipping industry. Green NH_3 demand is expected to surge from almost zero in 2023 (global consumption is 185 Mton/year) to 20 Mton/year by 2030 and over 350 Mton/year by 2050.

Therefore, a techno-economic analysis has been developed to assess the short-term potential of replacing grey NH_3 with green produced from renewable energy and green H_2. Brazil has been the geography targeted to produce green NH_3, as it is one of the countries with higher renewable energy potential worldwide. Based on the technological and market maturity, the green NH_3 plant sizing has been established at 200 kton/y and the Port of Pecém (state of Ceará) has been defined as preferred location for its installation, as it is acquiring worldwide relevance and attention due to the development of a H_2 and NH_3 production hub.

The methodology developed to define renewable energy resource in high-potential geographies inside the state of Ceará has targeted Trairí onshore wind as the most favourable option to produce green NH_3, with capacity factors of over 65%. The optimization process, modelled using Microsoft Excel, focused on the key technical and financial parameters for sizing the project to ensure efficient utilization of wind energy and obtain the green NH_3 yearly production target. This has led to a project size comprising over 407.4 MW wind energy, 305.5 MW electrolyzers and 21.6 MW NH_3 synthesis, with a nominal capacity of 33.3 kton NH_3/hour.

The obtained green NH_3 LCOA of 831 \$/ton NH_3, which includes not only production costs but also shipping from Brazil to EU is aligned with recent studies that analyzed the competitiveness of green NH_3 worldwide. This LCOA has associated a LCOE of 34.1 \$/MWh for wind energy production and a LCOH of 3.7 \$/kg H_2. Moreover, it is essential to highlight the significant economics behind the project: CAPEX exceeds one billion dollars and cumulative OPEX almost reaches the billion dollars, reflecting the high necessary investment behind the green NH_3 opportunity.

The LCOA breakdown reflects that the most impactful components alongside the project costs are the wind turbines and the electrolyzer equipment, contributing to 36% and 33% of the LCOA respectively. NH_3 synthesis with a 10% contribution is the third largest contributor to the LCOA. If achieving a 30% reduction in wind turbines and electrolyzer equipment CAPEX, a LCOA of 654 \$/ton NH_3 is obtained, impacting significantly with a 20% LCOA reduction versus the base case.

When comparing the green NH_3 LCOA with the grey NH_3 production pathway, variable natural gas TTF (\$/MWh) prices as well as several potential carbon taxes (\$/ton CO_2) have been considered. Brazil imported green NH_3 LCOA-base case (831 \$/ton NH_3) would be competitive with expected short-term grey NH_3 (natural gas TTF at 50\$/MWh) if carbon taxes reach 150\$/ton CO_2. In case of low natural gas prices, TTF < 35 \$/MWh, imported green NH_3 remains uncompetitive even with carbon taxes of 200\$/tonCO_2. On the contrary, in case of high natural gas prices, TTF > 80\$/MWh, imported green NH_3 would be competitive with grey NH_3 without carbon taxes.

If considering the green NH_3 LCOA-optimistic (654 \$/ton NH_3) with 30% CAPEX reduction both in wind turbines and electrolyzer equipment technologies, with TTF natural gas at ~50 \$/MWh, green NH_3 would be sooner more cost-competitive than grey NH_3 with 50\$/ton CO_2 taxes.

When comparing the energy intensity both production pathways are quite balanced, although being more energy-consuming the grey NH_3 production pathway with 38 GJ/ton NH_3 than the green one including shipping with 36.5 GJ/ton NH_3. Finally, in terms of carbon intensity, it can be noticed the significant difference between both production pathways, with green NH_3 having an almost insignificant 0.22 tonCO_2-eq/tonNH_3 versus the 1.92 tonCO_2-eq/tonNH_3 from the grey production.

The obtained results demonstrate that green NH_3 produced from high-renewable energy potential geographies is expected to become competitive with grey NH_3 produced in the EU in the short to medium-term, depending on variable natural gas and carbon taxes prices. However, the investment behind the opportunity is impressive and project financing and ensuring offtake acquire an extremely relevant role. The deployment of green NH_3 projects worldwide could be accelerated by the successful application of carbon taxes as well as with the support of financial mechanisms with CfD (Contracts for Difference) such as the first-in-a-kind schema developed by H2Global.

It can be concluded that policy and investment framework will have a leading role in the development of the green H_2 and NH_3 industry until it reaches the competitiveness with grey NH_3 propelled by economies of scale and subsequent cost reductions through experience in this nascent industry.

7.2 Future Work

As this study is considered to be at conceptual stage of development, there are several workstreams that could be further developed, including but not limited to:

- Assessment of other high renewable energy potential geographies following the methodology from this specific case study and develop the associated model development for them, including the hybridization of wind energy with solar PV, and battery storage systems when necessary
- Development of real-time model optimization, moving from the hourly-basis period considered in this assessment to a minute or even second basis. This improved optimization could also include the addition of H_2 storage systems into the model, only considered in this assessment in economic terms. Moreover, electrolyzer efficiency varies with load range operation in real-time. Specific electrolyzer efficiencies could be also considered in this enhancement of the model
- Assessment of current financial mechanisms such as H2Global or European Hydrogen Bank and methodology proposal of financial mechanisms to support the deployment of the green H_2 and NH_3 sectors

Bibliography

[1] IEA, “Ammonia Technology Roadmap,” 2021. [Online]. Available: https://www.iea.org/reports/ammonia-technology-roadmap. [Accessed 31 October 2023].

[2] IRENA, “INNOVATION OUTLOOK: RENEWABLE AMMONIA,” 2022. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf?rev=50e91f792d3442279fca0d4ee24757ea. [Accessed 31 October 2023].

[3] United Nations, “Goal 13: Take urgent action to combat climate change and its impacts,” 2023. [Online]. Available: https://www.un.org/sustainabledevelopment/climate-change/. [Accessed 31 October 2023].

[4] IEA, “IEA-Industry,” 2023. [Online]. Available: https://www.iea.org/topics/industry. [Accessed 31 October 2023].

[5] European Commission, “EU hydrogen strategy,” 2022. [Online]. Available: https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en. [Accessed 31 October 2023].

[6] International Council on Clean Transportation, “CAN THE INFLATION REDUCTION ACT UNLOCK A GREEN HYDROGEN ECONOMY?,” 2023. [Online]. Available: https://theicct.org/ira-unlock-green-hydrogen-jan23/. [Accessed 31 October 2023].

[7] IEA, “Global Hydrogen Review 2022,” 2022. [Online]. Available: https://www.iea.org/reports/global-hydrogen-review-2022. [Accessed 31 October 2023].

[8] European Commission, “EU Emissions Trading System (EU ETS),” 2023. [Online]. Available: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en. [Accessed 31 October 2023].

[9] Trading Economics, “EU Carbon Permits,” 2023. [Online]. Available: https://tradingeconomics.com/commodity/carbon. [Accessed 31 October 2023].

[10] World Economic Forum, “World Economic Forum,” World Economic Forum, 2022. [Online]. Available: https://www.weforum.org/agenda/2022/09/renewable-energy-electricity-emissions-iea/. [Accessed 31 October 2023].

[11] Wikipedia, “Haber Bosch process,” [Online]. Available: https://en.wikipedia.org/wiki/Haber_process. [Accessed 31 October 2023].

[12] B. E. G. T. Ulf Bossel, “The Future of the Hydrogen Economy: Bright or Bleak?,” Version of 15 April 2003 updated for distribution at the 2003 Fuel Cell Seminar. [Online]. Available: https://planetforlife.com/pdffiles/h2report.pdf. [Accessed 31 October 2023].

[13] Y. A. G. R. F. H. Jose Fuster Justiniano, “Industria del Amoníaco: estado actual y oportunidades,” 2022. [Online]. Available: https://4echile.cl/wp-content/uploads/2022/10/Industria-del-amoniaco-estado-actual-y-oportunidades-para-la-descarbonizacion.pdf. [Accessed 31 October 2023].

[14] Galp Energia S.A., “Galp - About Us,” 2023. [Online]. Available: https://www.galp.com/corp/pt/sobre-nos/a-galp. [Accessed 31 October 2023].

[15] Galp, “Galp Strategy,” 2023. [Online]. Available: https://www.galp.com/corp/en/about-us/galp/strategy#:~:text=Galp%20aims%20to%20reshape%20its,towards%20a%20green%20energy%20hub.. [Accessed 31 October 2023].

[16] Galp, “Galp - Green Hydrogen,” Galp, 2023. [Online]. Available: https://www.galp.com/corp/en/about-us/what-we-do/industrial-midstream/green-hydrogen. [Accessed 31 October 2023].

[17] GreenH2Atlantic, “GreenH2Atlantic,” 2023. [Online]. Available: https://www.greenh2atlantic.com/project. [Accessed 31 October 2023].

[18] IEA, “IEA - Hydrogen,” 2023. [Online]. Available: https://www.iea.org/reports/hydrogen. [Accessed 31 October 2023].

[19] US DOE, “Hydrogen Production: Natural Gas Reforming,” US Department of Energy: Office of Energy Efficiency & Renewable Energy, [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming. [Accessed 31 October 2023].

[20] CIC energiGUNE, “HYDROGEN PRODUCTION METHODS AND ITS COLOURS,” CIC energiGUNE, May 2022. [Online]. Available: https://cicenergigune.com/en/blog/hydrogen-production-methods-colours. [Accessed 31 October 2023].

[21] M. Liebreich, BloombergNEF, 12 December 2022. [Online]. Available: https://about.bnef.com/blog/liebreich-the-unbearable-lightness-of-hydrogen/. [Accessed 31 October 2023].

[22] A. F. d. S. Ferreira, “Emerging Energy Technologies - Hydrogen Storage”.

[23] Frontier Economics & Fundacion Naturgy, “El transporte de hidrógeno. La importancia del amoniaco,” 2022. [Online]. Available: https://www.fundacionnaturgy.org/publicacion/el-transporte-de-hidrogeno-la-importancia-del-amoniaco/. [Accessed 31 October 2023].

[24] IEA, “IEA Global Hydrogen Review 2023,” 2023. [Online]. Available: https://www.iea.org/reports/global-hydrogen-review-2023. [Accessed 31 October 2023].

[25] International Energy Agency (IEA), “Hydrogen Projects Database,” 2022. [Online]. Available: https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database#overview. [Accessed 31 October 2023].

[26] European Clean Hydrogen Alliance, “Electrolyser Summit Joint Declaration,” 2022. [Online]. Available: https://ec.europa.eu/docsroom/documents/50014/. [Accessed 31 October 2023].

[27] Fertilizers Europe, “Facts & Figures,” 2023. [Online]. Available: https://www.fertilizerseurope.com/fertilizers-in-europe/facts-figures/. [Accessed 31 October 2023].

[28] U.S. Energy Information Administration, “Weekly natural gas and ammonia prices (2020-2022),” 2023. [Online]. Available: https://www.eia.gov/. [Accessed 31 October 2023].

[29] H2Global, “The H2Global Instrument,” 2023. [Online]. Available: https://www.h2global-stiftung.com/project/h2g-mechanism. [Accessed 31 October 2023].

[30] IEA, “Indicative production costs for ammonia via electrolysis in selected regions compared to current references,” IEA, 2023. [Online]. Available: https://www.iea.org/data-and-statistics/charts/indicative-production-costs-for-ammonia-via-electrolysis-in-selected-regions-compared-to-current-references. [Accessed 31 October 2023].

[31] Wood Mackenzie, “How to kick-start a global,” November 2022. [Online]. Available: https://www.woodmac.com/horizons/avoiding-pand-ammonia-how-to-kick-start-a-global-low-carbon-ammonia-industry/. [Accessed 31 October 2023].

[32] IEA, “IEA International Shipping,” 2023. [Online]. Available: https://www.iea.org/reports/international-shipping. [Accessed 31 October 2023].

[33] International Maritime Organization, “IMO Strategy,” 2023. [Online]. Available: https://www.imo.org/en/OurWork/Environment/Pages/IMO-Strategy-on-reduction-of-GHG-emissions-from-ships.aspx. [Accessed 31 October 2023].

[34] European Parliament, “Fit for 55: deal on new EU rules for cleaner maritime fuels,” 2023. [Online]. Available: https://www.europarl.europa.eu/news/en/press-room/20230320IPR77909/fit-for-55-deal-on-new-eu-rules-for-cleaner-maritime-fuels. [Accessed 31 October 2023].

[35] DNV, “DNV Maritime Forecast 2022-2050,” 2022. [Online]. Available: https://www.dnv.com/maritime/publications/maritime-forecast-2023/index.html. [Accessed 31 October 2023].

[36] Mærsk Mc-Kinney Møller Center, “Maritime Decarbonization Strategy 2022,” 2022. [Online]. Available: https://cms.zerocarbonshipping.com/media/uploads/publications/Maritime-Decarbonization-Strategy-2022.pdf. [Accessed 31 October 2023].

[37] Maersk, “Maersk and the Spanish Government to explore large-scale green fuels production,” 2022. [Online]. Available: https://www.maersk.com/news/articles/2022/11/03/maersk-and-the-spanish-government-to-explore-large-scale-green-fuels-production. [Accessed 31 October 2023].

[38] IRENA, “IRENA GLOBAL HYDROGEN TRADE TO MEET THE 1.5ºC CLIMATE GOAL: PART II – TECHNOLOGY REVIEW OF HYDROGEN CARRIERS,” 2022. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_Global_Trade_Hydrogen_2022.pdf?rev=3d707c37462842ac89246f48add670ba. [Accessed 31 October 2023].

[39] IEA, “IEA Energy Technology Perspectives 2023,” 2023. [Online]. Available: https://iea.blob.core.windows.net/assets/a86b480e-2b03-4e25-bae1-da1395e0b620/EnergyTechnologyPerspectives2023.pdf. [Accessed 31 October 2023].

[40] BloombergNEF, “Japan’s Costly Ammonia Coal Co-Firing Strategy,” BNEF, 2022. [Online]. Available: https://assets.bbhub.io/professional/sites/24/BNEF-Japans-Costly-Ammonia-Coal-Co-Firing-Strategy_FINAL.pdf. [Accessed 31 October 2023].

[41] J. Atchison, “JERA opens tender for long-term ammonia supply contract,” Ammonia Energy Association, February 2022. [Online]. Available: https://www.ammoniaenergy.org/articles/jera-opens-tender-for-long-term-ammonia-supply-contract/. [Accessed 31 October 2023].

[42] L. Collins, “South Korea aims to burn millions of tonnes of clean hydrogen and ammonia for giga-scale power production,” Recharge - NHST Media Group, October 2021. [Online]. Available: https://www.rechargenews.com/energy-transition/south-korea-aims-to-burn-millions-of-tonnes-of-clean-hydrogen-and-ammonia-for-giga-scale-power-production/2-1-1099333. [Accessed 31 October 2023].

[43] DOE Office of Indian energy, “Levelized Cost of Energy (LCOE),” [Online]. Available: https://www.energy.gov/sites/prod/files/2015/08/f25/LCOE.pdf. [Accessed 31 October 2023].

[44] D. Saygin, H. Blanco, F. Boshell, J. Cordonnier, K. Rouwenhorst, P. Lathwal and D. Gielen, “Ammonia Production from Clean Hydrogen and the Implications for Global Natural Gas Demand,” 2023. [Online]. Available: https://www.mdpi.com/2071-1050/15/2/1623. [Accessed 31 October 2023].

[45] N. L. M. L. G. K. M. a. D. S. M. Abhishek Bose, “Spatial Variation in Cost of Electricity-Driven Continuous Ammonia Production in the United States,” 2022. [Online]. Available: https://pubs.acs.org/doi/10.1021/acssuschemeng.1c08032. [Accessed 31 October 2023].

[46] S. C. Carlos Arnaiz del Pozo, “Techno-economic assessment of blue and green ammonia as energy carriers in a low-carbon future,” 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S019689042200108X?via%3Dihub. [Accessed 31 October 2023].

[47] M. H. C. T. C. K. S. L. A. S. T. S. Christoph Hank, “Site-specific, Comparative Analysis for Suitable Power-to-X Pathways and Products in Developing and Emerging Countries,” 2023. [Online]. Available: https://www.ise.fraunhofer.de/en/publications/studies/power-to-x-country-analyses.html. [Accessed 31 October 2023].

[48] IEA, “Brazil aims to make a global impact on clean energy innovation,” 2023. [Online]. Available: https://www.iea.org/commentaries/brazil-aims-to-make-a-global-impact-on-clean-energy-innovation. [Accessed 31 October 2023].

[49] Governo do Brasil, “Renewable energy in the Brazilian energy matrix: the share of solar energy reached 6.9% and wind energy, 10.9%,” [Online]. Available: https://www.gov.br/en/government-of-brazil/latest-news/2022/renewable-energy. [Accessed 31 October 2023].

[50] Solargis, “Solar resource maps of Brazil,” The World Bank, Global Solar Atlas 2.0, Solar resource data: Solargis, 2020. [Online]. Available: https://solargis.com/maps-and-gis-data/download/brazil. [Accessed 31 October 2023].

[51] Vortex, “BRAZIL WIND MAP,” [Online]. Available: https://vortexfdc.com/resources/brazil-wind-map/. [Accessed 31 October 2023].

[52] Operador Nacional do Sistema Elétrico, “Mapa do Sistema de Transmissao,” [Online]. Available: https://www.ons.org.br/paginas/sobre-o-sin/mapas. [Accessed 31 October 2023].

[53] Hydrogen Europe, “Clean Ammonia in the future energy system,” 2023. [Online]. Available: https://hydrogeneurope.eu/wp-content/uploads/2023/03/2023.03_H2Europe_Clean_Ammonia_Report_DIGITAL_FINAL.pdf. [Accessed 31 October 2023].

[54] Unigel, “Unigel inicia produção de fertilizantes nitrogenados em Sergipe e se torna o maior produtor de ureia no país,” 2021. [Online]. Available: https://www.unigel.com.br/unigel-inicia-producao-de-fertilizantes-nitrogenados-em-sergipe-e-se-torna-o-maior-produtor-de-ureia-no-pais/. [Accessed 31 October 2023].

[55] GlobalFert, “Outlook GlobalFert 2023,” 2023. [Online]. Available: https://globalfert.com.br/outlook-globalfert/. [Accessed 31 October 2023].

[56] Unigel, “Unigel bate recorde histórico de exportação de amônia pelo Porto de Aratu-Candeias, na Bahia,” [Online]. Available: https://www.unigel.com.br/unigel-bate-recorde-historico-de-exportacao-de-amonia-pelo-porto-de-aratu-candeias-na-bahia/. [Accessed 31 October 2023].

[57] Complexo do Pecem, “HUB DE HIDROGÊNIO VERDE DO COMPLEXO DO PECÉM,” [Online]. Available: https://www.complexodopecem.com.br/hubh2v/. [Accessed 31 October 2023].

[58] Complexo do Pecem, “Cofiex aprova financiamento do Banco Mundial para obras de infraestrutura do Hub de H2V no Pecém,” [Online]. Available: https://www.complexodopecem.com.br/cofiex-aprova-financiamento-do-banco-mundial-para-obras-de-infraestrutura-do-hub-de-h2v-no-pecem/. [Accessed 31 October 2023].

[59] IEA, “Electrolysers,” 2023. [Online]. Available: https://www.iea.org/energy-system/low-emission-fuels/electrolysers. [Accessed 31 October 2023].

[60] Fertiberia, “Proyecto H2F,” 2023. [Online]. Available: https://www.fertiberia.com/amoniacoverde/puertollano-proyecto-h2f-planta-de-hidrogeno-amoniaco-y-fertilizantes-verdes/. [Accessed 31 October 2023].

[61] Fertiberia, “Proyecto Green Wolverine,” 2023. [Online]. Available: https://www.fertiberia.com/amoniacoverde/proyecto-green-wolverine-suecia/. [Accessed 31 October 2023].

[62] Ammonia Energy Association, “Renewable ammonia in Sweden,” [Online]. Available: https://www.ammoniaenergy.org/articles/renewable-ammonia-in-sweden/. [Accessed 2023 October 2023].

[63] CatalinaPtX, 2023. [Online]. Available: https://catalinaptx.com/es/inicio/. [Accessed 31 October 2023].

[64] Hydrogen Insight, “Ten-fold expansion | Brazilian chemicals giant unveils $1.5bn growth plans for green hydrogen plant,” [Online]. Available: https://www.hydrogeninsight.com/production/ten-fold-expansion-brazilian-chemicals-giant-unveils-1-5bn-growth-plans-for-green-hydrogen-plant/2-1-1390060. [Accessed 31 October 2023].

[65] thyssenkrupp, “Unigel and thyssenkrupp nucera sign Memorandum of Understanding to increase production capacity of green hydrogen plant,” [Online]. Available: https://www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/unigel-and-thyssenkrupp-nucera-sign-memorandum-of-understanding-to-increase-production-capacity-of-green-hydrogen-plant-175720. [Accessed 31 October 2023].

[66] Unigel, “Com investimento total de US$ 1,5 bilhão, Bahia terá primeiro projeto de hidrogênio verde em escala industrial no Brasil,” [Online]. Available: https://www.unigel.com.br/com-investimento-total-de-us-15-bilhao-bahia-tera-primeiro-projeto-de-hidrogenio-verde-em-escala-industrial-no-brasil/. [Accessed 31 October 2023].

[67] Cepsa, “Cepsa and Yara Clean Ammonia seal an alliance to connect southern and northern Europe with green hydrogen, in the presence of the kings of Spain and the Netherlands,” 2023. [Online]. Available: https://www.cepsa.com/en/press/cepsa-and-yara-clean-ammonia-seal-an-alliance-on-green-hydrogen. [Accessed 31 October 2023].

[68] Iberdrola, “Sellamos con Trammo el mayor acuerdo de Europa para la exportación de amoniaco verde,” 2023. [Online]. Available: https://www.iberdrola.com/sala-comunicacion/noticias/detalle/iberdrola-trammo-sellan-mayor-acuerdo-de-europa-para-exportacion-amoniaco-verde. [Accessed 31 October 2023].

[69] MadoquaPower2X, “A WORLD-LEADING GREEN HYDROGEN AND AMMONIA PROJECT IN PORTUGAL,” [Online]. Available: https://madoquapower2x.com/. [Accessed 31 October 2023].

[70] NEOM, “NEOM GREEN HYDROGEN COMPANY COMPLETES FINANCIAL CLOSE AT A TOTAL INVESTMENT VALUE OF USD 8.4 BILLION IN THE WORLD’S LARGEST CARBON-FREE GREEN HYDROGEN PLANT,” [Online]. Available: https://www.neom.com/en-us/newsroom/neom-green-hydrogen-investment. [Accessed 31 October 2023].

[71] TransHydrogen Alliance, “Casa dos Ventos and Comerc sign a memorandum with TransHydrogen Alliance for the production and export of ammonia,” [Online]. Available: https://transhydrogenalliance.com/casa-dos-ventos-and-comerc-sign-a-memorandum-with-transhydrogen-alliance-for-the-production-and-export-of-ammonia/. [Accessed 31 October 2023].

[72] OCI Global, “OCI Global enters into green hydrogen supply agreement with New Fortress Energy’s ZeroParks for green ammonia production in Texas,” 2023. [Online]. Available: https://oci-global.com/news-stories/press-releases/oci-global-enters-into-green-hydrogen-supply-agreement-with-new-fortress-energys-zeroparks-for-green-ammonia-production-in-texas/. [Accessed 31 October 2023].

[73] Ammonia Energy Association, “Renewable ammonia opportunities in Egypt,” 2022. [Online]. Available: https://www.ammoniaenergy.org/articles/renewable-ammonia-opportunities-in-egypt/. [Accessed 31 October 2023].

[74] Solargis s.r.o. on behalf of the World Bank Group, “Global Solar Atlas 2.0,” [Online]. Available: https://globalsolaratlas.info/map. [Accessed 31 October 2023].

[75] Technical University of Denmark (DTU), “Global Wind Atlas 3.0,” The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, [Online]. Available: https://globalwindatlas.info/. [Accessed 31 October 2023].

[76] epe - Empresa de Pesquisa Energética, “Mapa do Sistema Integrado Nacional,” 2023. [Online]. Available: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-168/Mapa%20do%20Sistema%20Integrado%20Nacional.pdf. [Accessed 31 October 2023].

[77] CanalEnergia, “Qair Brasil inaugura cluster hibrido de 429,4 MW no Ceará,” 2023. [Online]. Available: https://www.canalenergia.com.br/noticias/53252840/qair-brasil-inaugura-cluster-hibrido-de-4294-mw-no-ceara. [Accessed 31 October 2023].

[78] Echoenergia, “Ventos de Tianguá,” 2023. [Online]. Available: https://www.echoenergia.com.br/en/nossos-ativos/complexo-eolico-tiangua/. [Accessed 31 October 2023].

[79] The Wind Power, “Serra Do Mato (Brasil),” 2023. [Online]. Available: https://www.thewindpower.net/windfarm_es_37824_serra-do-mato.php. [Accessed 31 October 2023].

[80] The Wind Power, “Serrote (Brazil),” [Online]. Available: https://www.thewindpower.net/windfarm_en_30112_serrote.php. [Accessed 31 October 2023].

[81] The Wind Power, “Ventos de Tiangua (Brasil),” 2023. [Online]. Available: https://www.thewindpower.net/windfarm_es_23817_ventos-de-tiangua.php. [Accessed 31 October 2023].

[82] D. F. D. D. L. e. a. Tong, “Geophysical constraints on the reliability of solar and wind power worldwide,” 2021. [Online]. Available: https://www.nature.com/articles/s41467-021-26355-z. [Accessed 31 October 2023].

[83] S. a. S. I. Pfenninger, “Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data,” 2016. [Online]. Available: www.renewables.ninja. [Accessed 31 October 2023].

[84] I. a. P. S. Staffell, “Using Bias-Corrected Reanalysis to Simulate Current and Future Wind Power Output,” 2016. [Online]. Available: https://www.renewables.ninja/. [Accessed 31 October 2023].

[85] Vestas, “V150-4.2 MW™,” 2023. [Online]. Available: https://www.vestas.com/en/products/4-mw-platform/V150-4-2-MW. [Accessed 31 October 2023].

[86] TheWindPower, “Vestas > V150/4000-4200,” 2023. [Online]. Available: https://www.thewindpower.net/turbine_es_1490_vestas_v150-4000-4200.php. [Accessed 31 October 2023].

[87] International Renewable Energy Agency, “Renewable power generation costs in 2022,” 2023. [Online]. Available: https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf?rev=3b8966ac0f0544e89d7110d90c9656a0. [Accessed 31 October 2023].

[88] RatedPower, “How PV panel tilt affects solar plant performance,” RatedPower, 2022. [Online]. Available: https://ratedpower.com/blog/pv-panel-tilt/#:~:text=For%20latitudes%20between%205%C2%B0,the%20latitude%20multiplied%20by%200.85.. [Accessed 31 October 2023].

[89] Renewables Valuation Institute, “How to model P50, P75, and P90 energy yield?,” 2023. [Online]. Available: https://courses.renewablesvaluationinstitute.com/pages/academy/how-to-model-p50-p75-and-p90-energy-yield. [Accessed 31 October 2023].

[90] Vestas, “Life Cycle Assessment of Electricity Production from an onshore V150-4.2 MW Wind Plant,” 2022. [Online]. Available: https://www.vestas.com/content/dam/vestas-com/global/en/sustainability/reports-and-ratings/lcas/LCA%20of%20Electricity%20Production%20from%20an%20onshore%20V150-4.2,%204.5MW%20Wind%20Plant_Final.Web.pdf.coredownload.inline.pdf. [Accessed 31 October 2023].

[91] IRENA, “Renewable power generation costs in 2022,” 2022. [Online]. Available: https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf?rev=cccb713bf8294cc5bec3f870e1fa15c2. [Accessed 31 October 2023].

[92] Electricity Maps ApS, “Brazil,” 2022. [Online]. Available: https://www.electricitymaps.com/data-portal/brazil. [Accessed 31 October 2023].

[93] FfE Munich, “How is green hydrogen defined according to the EU’s delegated act?,” 2023. [Online]. Available: https://www.ffe.de/en/publications/how-is-green-hydrogen-defined-according-to-the-eus-delegated-act/. [Accessed 31 October 2023].

[94] CÂMARA DE COMERCIALIZAÇÃO DE ENERGIA ELÉTRICA, “painel de preços,” CCEE, 2023. [Online]. Available: https://www.ccee.org.br/precos/painel-precos. [Accessed 31 October 2023].

[95] J. J. D. M. M. M. M. S. K. v. d. L. D. P. M. B. Anthony Wang, “Analysing future demand, supply, and transport of hydrogen,” Guidehouse, June 2021. [Online]. Available: https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021.pdf. [Accessed 31 October 2023].

[96] US Department of Energy, “Technical Targets for PEM Electrolyzer Stacks and Systems,” 2023. [Online]. Available: https://www.energy.gov/eere/fuelcells/technical-targets-proton-exchange-membrane-electrolysis. [Accessed 31 October 2023].

[97] US Department Of Energy, “Technical Targets for Liquid Alkaline Electrolyzer Stacks and Systems,” 2023. [Online]. Available: https://www.energy.gov/eere/fuelcells/technical-targets-liquid-alkaline-electrolysis. [Accessed 31 October 2023].

[98] US Department Of Energy, “Technical Targets for Proton Exchange Membrane Electrolysis,” 2022. [Online]. Available: https://www.energy.gov/eere/fuelcells/technical-targets-proton-exchange-membrane-electrolysis. [Accessed 31 October 2023].

[99] Plug Power, “Plug EX-4250D Electrolyzer,” [Online]. Available: https://resources.plugpower.com/electrolyzers/ex-4250d-f041122. [Accessed 31 October 2023].

[100] M. R. K. H. L. F. A. C. W. S. H. J. M. C. C. R. G. Guangling Zhao, “Life cycle assessment of H2O electrolysis technologies,” 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360319920327087. [Accessed 31 October 2023].

[101] K. Rouwenhorst, “Flexible ammonia synthesis: shifting the narrative around hydrogen storage,” Ammonia Energy Association, 27 April 2023. [Online]. Available: https://www.ammoniaenergy.org/articles/flexible-ammonia-synthesis-shifting-the-narrative-around-hydrogen-storage/. [Accessed 31 October 2023].

[102] S. P. GIOVANNI GENOVA, “Casale flexible green ammonia plant, the economically viable green production,” Casale, 2022. [Online]. Available: https://ureaknowhow.com/wp-content/uploads/2022/05/2022-06-Genova-Casale-flexible-green-ammonia-plant-the-economically-viable-green-production.pdf. [Accessed 31 October 2023].

[103] State of green, “REDDAP: The world’s first dynamic green ammonia plant,” 8 August 2022. [Online]. Available: https://stateofgreen.com/en/solutions/reddap-the-worlds-first-dynamic-green-ammonia-plant/. [Accessed 31 October 2023].

[104] Envision Energy, “Envision Energy-Green Hydrogen and Green Ammonia Business,” 2022. [Online]. Available: https://www.ammoniaenergy.org/wp-content/uploads/2022/10/Envision-Hydrogen-Green-Hydrogen-and-Green-Ammonia-Business-AEA.pdf. [Accessed 31 October 2023].

[105] Topsoe, “TOPSOE SIGNS AGREEMENT ON FIRST COMMERCIAL SIZE DYNAMIC GREEN AMMONIA PLANT IN CHINA,” 19 January 2023. [Online]. Available: https://www.topsoe.com/press-releases/topsoe-signs-agreement. [Accessed 31 October 2023].

[106] A. Sorensen, “Flexible ammonia production,” 2022. [Online]. Available: https://www.ammoniaenergy.org/wp-content/uploads/2023/06/Project-Features-speaker-slides-May-2023.pdf. [Accessed 31 October 2023].

[107] M. I. R. N.-L. M. M. R. B.-A. Zac Cesaro, “Ammonia to power: Forecasting the levelized cost of electricity from green ammonia in large-scale power plants,” 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261920314549. [Accessed 31 October 2023].

[108] Hydrogen Insight, “ANALYSIS | Are there enough ships to carry exports of hydrogen as ammonia?,” 22 August 2023. [Online]. Available: https://www.hydrogeninsight.com/analysis/analysis-are-there-enough-ships-to-carry-exports-of-hydrogen-as-ammonia-/2-1-1503513. [Accessed 31 October 2023].

[109] R. N.-L. •. C. F. •. Z. C. •. R. B.-A. •. K. ROUWENHORST, “Techno-Economic Aspects of Production, Storage and Distribution of Ammonia,” 2021. [Online]. Available: https://ris.utwente.nl/ws/portalfiles/portal/276441421/3_s2.0_B9780128205600000084_main.pdf. [Accessed 31 October 2023].

[110] C. P. Julien Armijo, “Flexible production of green hydrogen and ammonia from variable solar and wind energy: Case study of Chile and Argentina,” 2019. [Online]. Available: https://pdf.sciencedirectassets.com/271472/1-s2.0-S0360319919X00610/1-s2.0-S0360319919342089/main.pdf?X-Amz-Security-Token=IQoJb3JpZ2luX2VjEAUaCXVzLWVhc3QtMSJIMEYCIQCKsBRe6gBE6rSLr4rgdBZ3BeJFlMPCtTIsJpH6rtngTwIhAOLLKW58coLIiF4wLqhi%2Fh0N7NoXegPbOab69jea%2. [Accessed 31 October 2023].

[111] Wikipedia, “Desalination,” [Online]. Available: https://en.wikipedia.org/wiki/Desalination. [Accessed 31 October 2023].

[112] Corporate Finance Institute, “Levelized Cost of Energy (LCOE),” [Online]. Available: https://corporatefinanceinstitute.com/resources/valuation/levelized-cost-of-energy-lcoe/. [Accessed 31 October 2023].

[113] Searoutes, [Online]. Available: https://app.searoutes.com/routing/details/core/BRPEC/NLRTM?routing=%7B%22p%22%3A%5B%7B%22c%22%3A%5B-38.80305423%2C-3.530170622%5D%2C%22l%22%3A%22BRPEC%22%7D%2C%7B%22c%22%3A%5B4.056346273%2C51.960134394%5D%2C%22l%22%3A%22NLRTM%22%7D%5D%2C%22r%22%3A%5B%7B%2. [Accessed 31 October 2023].

[114] R. W. J. S. C. B. Mahdi Fasihi, “Global potential of green ammonia based on hybrid PV-wind power plants,” 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261920315750. [Accessed 31 October 2023].

[115] Investopedia, “Weighted Average Cost of Capital (WACC) Explained with Formula and Example,” 2023. [Online]. Available: https://www.investopedia.com/terms/w/wacc.asp. [Accessed 31 October 2023].

[116] IRENA, “The cost of financing for renewable power,” 2023. [Online]. Available: https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/May/IRENA_The_cost_of_financing_renewable_power_2023.pdf?rev=8ba5ec0a558148f085e285b247523fb5. [Accessed 31 October 2023].

[117] Deloitte, “Green hydrogen: Energizing the path to net zero ; Deloitte’s 2023 global green hydrogen outlook,” 2023. [Online]. Available: https://www2.deloitte.com/content/dam/Deloitte/at/Documents/presse/at-deloitte-wasserstoffstudie-2023.pdf. [Accessed 31 October 2023].

[118] AACE International, “COST ESTIMATE CLASSIFICATION SYSTEM – AS APPLIED IN ENGINEERING, PROCUREMENT, AND CONSTRUCTION FOR THE PROCESS INDUSTRIES,” 2005. [Online]. Available: https://www.costengineering.eu/Downloads/articles/AACE_CLASSIFICATION_SYSTEM.pdf. [Accessed 31 October 2023].

[119] Brazil Ministry of Mining & Energy, “2031 TEN-YEAR ENERGY EXPANSION PLAN,” 2021. [Online]. Available: https://www.gov.br/mme/pt-br/assuntos/secretarias/sntep/publicacoes/plano-decenal-de-expansao-de-energia/pde-2031/english-version/relatorio_pde2031_cap12_eus.pdf. [Accessed 31 October 2023].

[120] Yara, “Yara Integrated Report 2022,” [Online]. Available: https://www.yara.com/siteassets/investors/057-reports-and-presentations/annual-reports/2022/yara-integrated-report-2022.pdf. [Accessed 31 October 2023].

[121] Yara, “Ammonia and urea cash cost,” [Online]. Available: https://www.yara.com/investor-relations/analyst-information/calculators/ammonia-and-urea-cash-cost/. [Accessed 31 October 2023].

[122] IEA, “Natural gas price assumptions, 2019-2025,” 2022. [Online]. Available: https://www.iea.org/data-and-statistics/charts/natural-gas-price-assumptions-2019-2025. [Accessed 31 October 2023].

[123] Trading Economics, “EU Carbon Permits,” [Online]. Available: https://tradingeconomics.com/commodity/carbon. [Accessed 31 October 2023].

[124] Wikipedia, “Gas carrier,” [Online]. Available: https://en.wikipedia.org/wiki/Gas_carrier. [Accessed 31 October 2023].

[125] M. &. J. A. &. V. K. H. &. K. R. Bännstrand, “Study on the optimization of energy consumption as part of implementation of a ship energy efficiency management plan (SEEMP).,” 2016. [Online]. Available: https://www.researchgate.net/publication/296561654_Study_on_the_optimization_of_energy_consumption_as_part_of_implementation_of_a_ship_energy_efficiency_management_plan_SEEMP. [Accessed 31 October 2023].

Annex

Technical Analysis Equations

A) Project Sizing

Parameter	Unit	Formula
Nominal Hourly Production Target	$\frac{ton\ product\ (NH_3, H_2, N_2, H_2O)}{hour}$	$\frac{Yearly\ Production\ Target\ \left(\frac{kton\ product}{year}\right) \times 1{,}000(\frac{ton\ product}{kton\ product})}{365\ \left(\frac{days}{year}\right) \times 24(\frac{hours}{day}) \times Assumed\ Yearly\ Availability\ (\%)} \times Oversizing\ Ratio$
Nominal Hourly Operation Consumption	kWh	$Nominal\ Hourly\ Production\ Target\ \left(\frac{ton\ product}{hour}\right) \times Specific\ Energy\ Consumption\ \left(\frac{kWh}{kg\ product}\right) \times 1{,}000(\frac{kg}{ton}) \times 1 hour$
Nominal Plant Sizing	MW	$\frac{Nominal\ Hourly\ Production\ Target\ \left(\frac{ton\ product}{hour}\right) \times Specific\ Energy\ Consumption\ \left(\frac{kWh}{kg\ product}\right) \times 1{,}000(\frac{kg}{ton})}{1{,}000\ kW/MW}$
Minimum Hourly Operation Consumption	kWh	$Nominal\ Hourly\ Production\ Target\ \left(\frac{ton\ product}{hour}\right) \times Specific\ Energy\ Consumption\ \left(\frac{kWh}{kg\ product}\right) \times 1{,}000\left(\frac{kg}{ton}\right) \times 1 hour$ $\times Minimum\ Operational\ Range\ (\%)$

B) Control Loop Assessment

Scenario	Parameter	Unit	Formula
All	**Gross Wind Energy Production – Gross Energy Output**	kWh	$\text{Hourly Wind Energy Production from Representative Year (kWh)} \times \text{Number of Wind Turbines}$
All	**Net Wind Energy Production – Net Energy Output**	kWh	$\text{Hourly Wind Energy Production from Representative Year (kWh)} \times \text{Number of Wind Turbines} \times \big(1 - \text{Total Wind Turbine Fixed Losses (\%)}\big) \times (1 - Transmission\ \&\ Conversion\ Losses\ (\%))$
1) Net Energy Output Exceeds Nominal System Requirements: <u>Wind Curtailment</u>	**Net Energy Input**	kWh	$Nominal\ Hourly\ Operation\ Consumption$
	<u>Curtailed Energy</u>	kWh	$Net\ Energy\ Output - Nominal\ Hourly\ Operation\ Consumption$
	Net Energy to H_2	kWh	$Nominal\ Hourly\ H_2\ Operation\ Consumption$
	Net Energy to N_2	kWh	$Nominal\ Hourly\ N_2\ Operation\ Consumption$
	Net Energy to NH_3	kWh	$Nominal\ Hourly\ NH_3\ Operation\ Consumption$
2) Net Energy Output Falls Below Minimum System Requirements: <u>Grid Backup</u>	**Net Energy Input**	kWh	$Minimum\ Hourly\ Operation\ Consumption$
	<u>Grid Energy</u>	kWh	$Minimum\ Hourly\ Operation\ Consumption - Net\ Energy\ Output$
	Net Energy to H_2	kWh	$Minimum\ Hourly\ H_2\ Operation\ Consumption$
	Net Energy to N_2	kWh	$Minimum\ Hourly\ N_2\ Operation\ Consumption$

	Net Energy to NH_3	kWh	$Minimum\ Hourly\ NH_3\ Operation\ Consumption$
3) Variable Operation: 10-70% Operational Range	**Net Energy Input**	kWh	$Variable\ Hourly\ Operation\ Consumption$
	Net Energy to N_2	kWh	$Minimum\ Hourly\ Operation\ Consumption$ (70% Minimum Operation Range)
	Net Energy to H_2	kWh	$\frac{(Net\ Energy\ Input - Net\ Energy\ to\ N_2) \times\ Nominal\ Hourly\ H_2\ Operation\ Consumption}{Nominal\ Hourly\ H_2\ Operation\ Consumption +\ Nominal\ Hourly\ NH_3\ Operation\ Consumption}$
	Net Energy to NH_3	kWh	$\frac{(Net\ Energy\ Input - Net\ Energy\ to\ N_2) \times\ Nominal\ Hourly\ NH_3\ Operation\ Consumption}{Nominal\ Hourly\ H_2\ Operation\ Consumption +\ Nominal\ Hourly\ NH_3\ Operation\ Consumption}$
4) Variable Operation: 70-100% Operational Range	**Net Energy Input**	kWh	$Variable\ Hourly\ Operation\ Consumption$
	Net Energy to N_2	kWh	$\frac{Net\ Energy\ Input \times\ Nominal\ Hourly\ N_2\ Operation\ Consumption}{Nominal\ Hourly\ Operation\ Consumption}$
	Net Energy to H_2	kWh	$\frac{Net\ Energy\ Input \times\ Nominal\ Hourly\ H_2\ Operation\ Consumption}{Nominal\ Hourly\ Operation\ Consumption}$
	Net Energy to NH_3	kWh	$\frac{Net\ Energy\ Input \times\ Nominal\ Hourly\ NH_3\ Operation\ Consumption}{Nominal\ Hourly\ Operation\ Consumption}$