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

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Abstract

Keywords:

- Green ammonia
- Green hydrogen
- Decarbonisation
- Techno-economic analysis
- LCOA (Levelized Cost of Ammonia)
- Sustainability

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$NH_{3\text{-grey}}$

1. Introduction

Hydrogen (H_2) is one of the most promising energy vectors within the energy transition with enormous potential to decarbonise high-energy consuming sectors. Although the projections and expectations of green H_2, produced from renewable energy sources, for the medium-term are high, currently more than 99% of it is produced from fossil fuels [1], being therefore a high-priority sector to be decarbonized. 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 ammonia (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 H_2-derived fuels projects were on pilot stages consuming a negligible amount of green H_2. However, 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 [2]. This trend is set to continue through 2030, with NH_3 accounting for roughly 90% of the announced production. 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 H_2-based fuels. Moreover, its capacity 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.

1.1 Ammonia State-of-the-Art

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 and currently relies more than 99% on fossil fuels, specifically from natural gas (72%) and coal (22%) [3]. Thus, it is 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 [4].

NH_3 is produced by the combination of 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 [3]. It has been used as feedstock for the fertilizer industry since the beginning of the 20th century when the Haber-Bosch process was developed. 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 since approximately 10% of the global NH_3 produced is seaborne traded, 20 Mton/year [3].

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.

1.2 Green Ammonia Market Assessment

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. The main projections for 2030 and 2050 can be observed in Figure 1. Green NH_3 demand is expected to surge from almost zero in 2023 to 20 Mton/year by 2030 and over 350 Mton/year by 2050.

Existing Markets (Fertilizer, Industry) are 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.

Emerging Markets (Marine Fuel, Power Generation, H_2 Carrier) are expected to be largest long-term market for green NH_3 with required technological advances, accounting for over 250 Mton/year consumption by 2050.

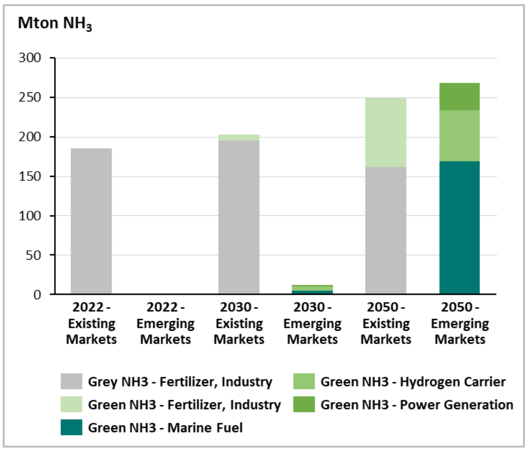


Figure 1: Grey & green NH_3 demand in existing and emerging markets by 2030 and 2050. Source: own elaboration based on [3] [5]

2. Techno-Economic Assessment

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. The case study considers the key metrics to be analysed in order to assess the viability of these projects and its potential as a decarbonisation pathway and comprises:

- **Methodology development to define renewable energy in specific high-potential regions** and its suitability to establish green H_2 and NH_3 production facilities.

- **Specific operational mode definition**, adapted to the existing resources and characteristics of the identified location, alongside the main equipment and technologies required.

- **Financial metrics definition,** to provide a detailed assessment of the viability of these projects and its potential as a decarbonisation pathway versus grey NH_3

2.1 Methodology development to define renewable energy in specific high-potential regions

2.1.1 Green Ammonia Production 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 it Calculates present value of the total CAPEX and OPEX of an asset (NH_3 plant, power plant, electrolyzer…) over an assumed lifetime. Several reports have recently assessed the LCOA in a country-wise overview for different configurations ([6], [7]) 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. 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 and with an impressive 84% of energy mix coming from renewables [8], 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, as observed in Figure 2.

From these figures 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, Rio Grande do Norte, Paraiba, Pernambuco 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.

- **Electricity transmission network**: the North-East region has a well interconnected network due to the presence of numerous wind farms and populated cities [9].

- **Export facilities**: 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 [10] while Brazil only has 3 NH_3 facilities in operation with a combined capacity of 1.2 Mton/year [11]. 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. From the existing industrial ports with export capabilities in the targeted states, the Port of Pecém (Ceará) has been defined as preferred location for production, as it is acquiring worldwide relevance and attention due to the development of a H_2 and NH_3 production hub [12] .

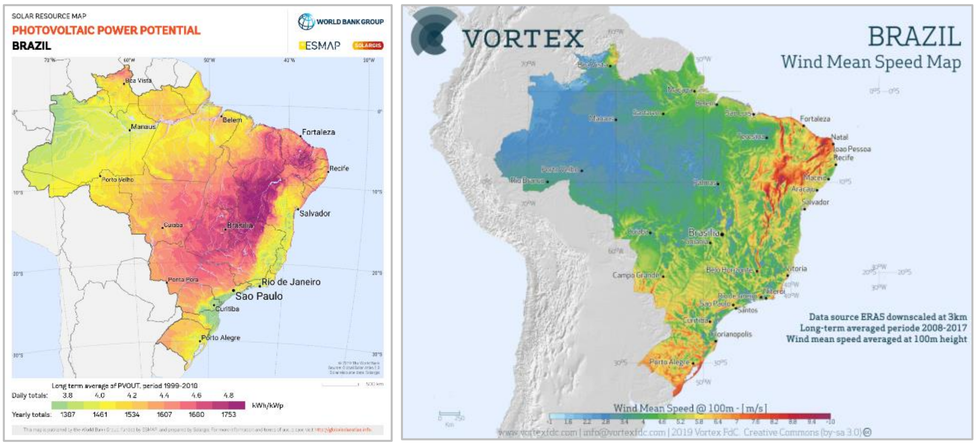


Figure 2: Left - Solar PV power potential in Brazil, long term average period 1999-2018. Source: [13]; Right - Wind mean speed map in Brazil, long term average period 2008-2017. Source [14]

Regarding NH_3 plant sizing, 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 [15]. 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.

Based on the technological maturity and market development reasoning, the green NH_3 plant sizing has been established at 200 kton/year production.

2.1.2 Renewable Energy Production Location Definition

The methodology for determining the potential best location for renewable power plants within the state of Ceará has involved the following steps:

- **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

- **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.

- **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.

- **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.

Two optimal locations have been obtained from this methodology, with the coordinates and wind farm references stated in Table 1.

Table 1: Selected locations for power profile analysis within Ceará state

Location	Latitude	Longitude	Wind Farm Reference	Height (meters above sea level)
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
Tianguá, **north-west**	-3° 52' 44.1" -3.890	-41° 11' 33.7" -41.182	Ventos de Tianguá, 141MW (Echoenergia)	600 m

2.1.3 Renewable Generation and Power Profile in Selected Sites

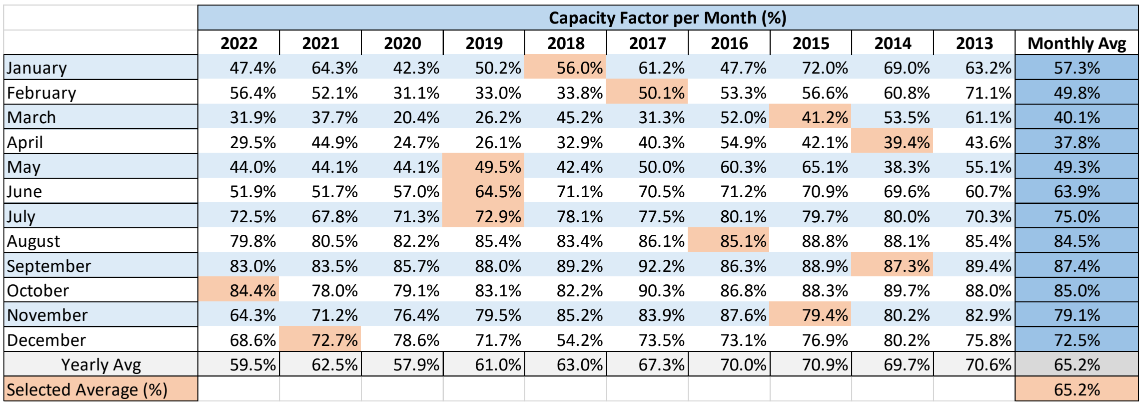
Assessing renewable energy production and the power profiles in the most precise manner has great impact on green H_2 and NH_3 operation mode and production costs. The methodology proposed involves several key steps:

- **Open Data Source Eligibility:** Renewables Ninja has been used, an open-source web tool that provide users with a platform to estimate and analyze solar PV and wind hourly energy production for any location. The tool works by taking weather data from global reanalysis models and satellite observations such as NASA's MERRA-2 [16] [17].

- **Load Profile Generation Assumptions:** To obtain the hourly energy production profiles, several inputs and assumptions should be inserted in Renewables Ninja web-tool both for wind energy and solar PV. In case of wind energy, the turbine model is the main input to be included. Vestas V150/4200 has been chosen (4,200 kW, 145m hub height), as it is the most representative turbine installed recently in Brazil. For solar PV, it has been 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.

- **Representative Year Selection – P50 approach:** the energy yield differs yearly and therefore a representative year has been selected over a significant 10-year analysis using the P50 approach. The P50 figure is the annual average level of generation, and the representative year profile combines the mean monthly data from individual years (2013–2022). The selection process involves:
1) Calculating the total electricity for each month
2) Calculating the mean capacity factor (CF) for each month
3) Identifying the year whose month's CF is closest to the mean monthly value for the established period. This is exemplary represented on Figure 3, which shows the representative year selection in orange for Trairí location, and the mean CFs selected for each month. 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.

- **Power Profile in Selected Sites:** Table 2 below shows the results of the representative year selection and the P50 approach to calculate the annual average CF both for wind and solar PV in the selected renewable energy locations.



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

Table 2: P50 wind and solar PV capacity factors in selected locations

Location	Latitude	Longitude	P50 Wind Capacity Factor (CF)	P50 Solar PV CF
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%

Solar PV resource is almost equal between the sites, while wind CF 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. Wind power seasonal variability as well as the daily power profiles have been obtained for the selected representative year in each location.

Trairí: large wind seasonal variability comprising a high-wind season (July-December) with CF averaging >80% and a low-wind season with CF averaging <50% (January-June), as seen in Figure 4. In terms of daily variability, Trairí presents an extraordinary stable wind generation profile (Figure 5), while solar PV is only available from 09:00-19:00.

Tianguá: the seasonal variability follows the same profile than in Trairí, with higher resource during July-December and lower in January-June period. It can be noticeable that the wind resource is lower than in Trairí, as seen in Table 2. 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.

Therefore, Trairí has been identified as the best location in this case study and only wind power generation will be considered in the operational mode definition due to its stability and high resource

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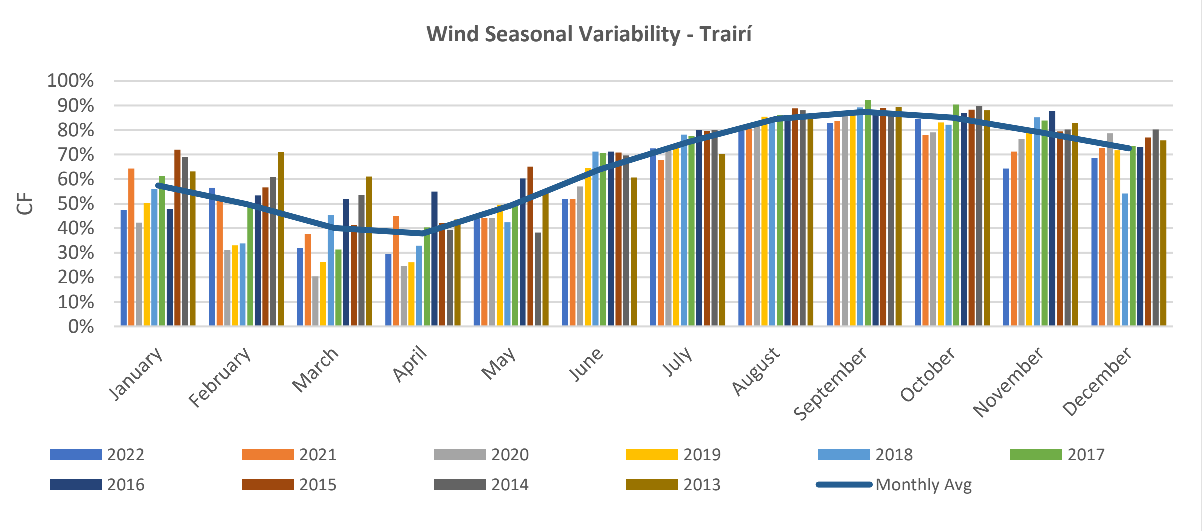

Figure 4: Wind seasonal variability in Trairí for period 2013-2022

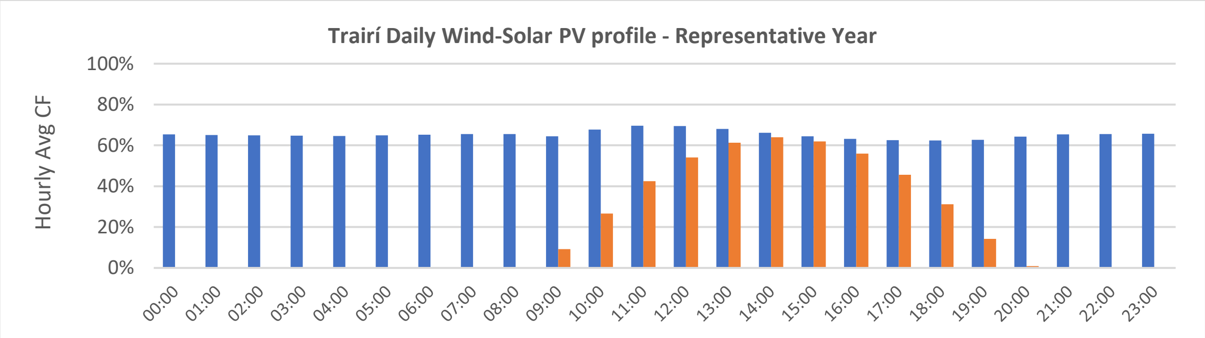

Figure 5: Trairí daily wind and solar PV profile for the representative year

2.2 Operational mode definition

The proposed scenario for defining the operational mode is illustrated with the main system components on Figure 6. The reasoning of the suitability of each of the main system blocks are stated within this section. while the main techno-economic parameters of this case study are reflected in Table 3.

- **Energy Generation Block**: Trairí has been chosen as the best location and only wind power generation will be considered due to its stable profile alongside the year.

- **Back-Up Energy Adequation Block**: 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. Moreover, the system will be able to withdraw electricity from Brazilian grid to ensure minimum operation, as back-up.

- **Green Technologies Block**: 1) PEM electrolyzers have been selected due to higher dynamic performance allowing better integration with variable energy input, high-pressure production and expected cost reduction [2], [18].

2) Flexible NH_3 production has been considered. Existing fossil-based Haber-Bosch plants for NH_3 production are inflexible and designed to run uninterrupted at high capacity [19]. 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 are developing flexible NH_3 synthesis technology that can operate down to 5 – 10% of nominal load [20]. Although nowadays no commercial flexible NH_3 plant is in operation, in the short-term (2025) several projects are expected to be operational.

3) H_2 storage has been added as back-up due to the flexibility assumed in the green NH_3 plant to smooth the fluctuation from renewables and has only been considered in the economic parameters. NH_3 storage has been sized accordingly to NH_3 shipping potential and expected yearly production.

- **Complementary Systems Block**: comprised of air separation unit (ASU) to supply N_2 to the NH_3 plant and desalinization unit to supply water to the electrolyzers.

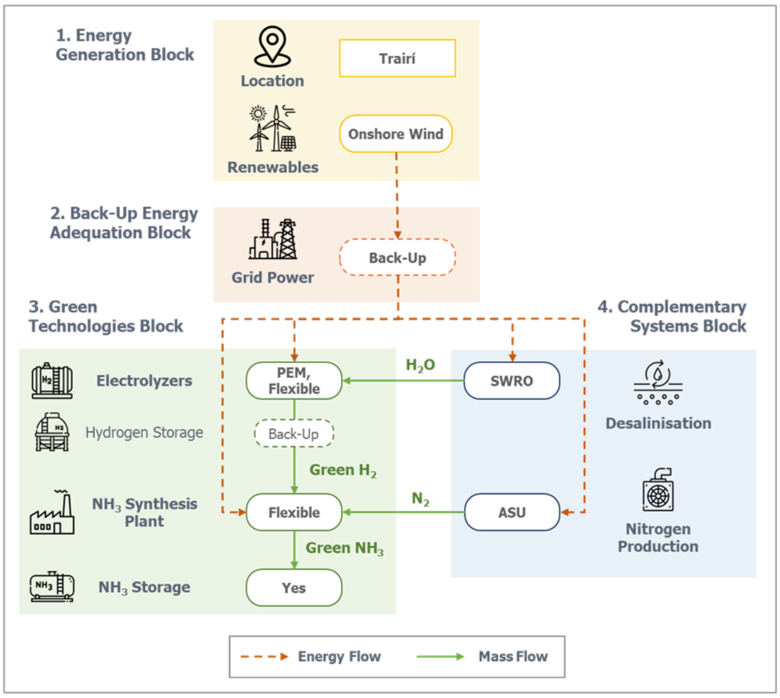

Figure 6: Optimization model key blocks and components, energy, and mass flow representation. Source: own elaboration

Table 3: Techno-economic and environmental parameters

Block	Nature	Parameter	Value	Unit	Source
Energy Generation	Technical	Wind Turbine Rated Power	4.2	MW	Vestas
		Total Wind Turbine Fixed Losses	10.5%	%	
	Economical	CAPEX – Installed Costs	1,052	$/kW	IRENA
	Economical	OPEX – Full Service	22	$/kW/year	
	Environmental	Equivalent CO_2 emissions	7.3	g CO_2-e / kWh	Vestas
Energy Adequation – Grid BZ	Technical	Renewable % in NE Grid – Average 2022	95%	%	CCEE Brazil
	Economical	Hourly Average Energy Price in NE Grid (Oct 2021- Oct 2023)	63.67 12.38	R$/MWh $/MWh	
	Environmental	Equivalent CO_2 emissions	52.05	g CO_2-e / kWh	
Energy Adequation – Transmission	Technical	Distance between Trairí and Pecém Port	70	km	Maps
		Transmission Losses	1.1%	% energy transported / 100km	Guidehouse
		Substation Losses	1%	% energy converted	
	Economical	Transmission Line CAPEX	190,000	EUR/km/GW	

		Transmission Line Fixed OPEX	0.2%	% CAPEX	
		Renewables substation CAPEX	124,000	EUR/MW	
		Renewables substation Fixed OPEX	2%	% CAPEX	
Green Technologies – PEM Electrolyzer	Technical	Specific Energy Consumption (2025)	51	kWh/kg	IEA
		System Operational Range	10-100%	%	
		Stack Lifetime (until replacement)	80,000	h	
		System Lifetime	20	Years	
	Economical	System CAPEX	1,000	$/kW	
		Fixed OPEX	15	$/kW/year	
		Variable OPEX - Stack Replacement	400	$/kW	
	Environmental	Equivalent CO_2 emissions	72	g CO_2-e / kg H_2 / stack	Industry
Green Technologies – NH_3 Synthesis	Technical	Operational Range	10-100%	%	[19], [20]
		Specific Energy Consumption	0.65	kWh / kg NH_3	[6]
	Economical	CAPEX	3,450,000	\$ / (ton NH_3/hour)	
		OPEX	2%	% CAPEX	
Green Technologies – H_2, NH_3 Storage	Technical	Green H_2 Storage days at full load	0.5	days	Assumption
		Green NH_3 Storage Required for Export	40	kton NH_3	Assumption
	Economical	Green H_2 Storage CAPEX	961	\$ / kg H_2	Industry
		Green NH_3 Storage CAPEX	0.81	$ / kg NH3	Industry
Complementary Systems – ASU	Technical	Operational Range	70-100%	%	Industry
		Specific Energy Consumption	0.265	kWh/kg N_2	[6]
	Economical	CAPEX	1,500,000	\$ / (ton N_2/hour)	
		OPEX	2%	% CAPEX	
Complementary Systems – Desalinization	Technical	Electrolyzer water requirement	15	m^3 / kg H_2	[6]
		Specific Energy Consumption	3	kWh / m^3	Industry
	Economical	CAPEX	5.72	\$/m^3/year	Industry
		OPEX	2%	% CAPEX	Assumption

2.3 Financial metrics definition

The financial analysis extends throughout the full value chain of the project, from electricity generation to green NH_3 delivery, with the following key metrics considered.

- **LCOx**: The levelized cost of a product (energy, H_2, NH_3) is a metric widely used by the industry, as it calculates present value of the total CAPEX and OPEX of an asset over an assumed lifetime.

- **WACC**: The cost of capital becomes an important parameter in assessing a firm’s potential for net profitability. For green H_2 and derivates such as NH_3 it reflects their risk profile, including local regulatory and political risks, with an estimated 8.5% [21].

- **Project lifetime**: Fixed at 20 years, in line with electrolyzers lifetime, although a 25-year lifetime is expected for renewable assets such as wind turbines.

- **Cost Estimate Classification System**: Class 5 estimate AACE has been considered, as it is in concept screening and has a low level of engineering and design. 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 (-30% to +50%).

3. Results and Discussion

3.1 Project Sizing and Optimization

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 ammonia yearly production target.

The 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 70% net CF, accounting with the assumed wind power losses. 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.

The Excel-based model employs then 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 control loop operates as follows:

- **Net Energy 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

- **Net Energy 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 hydrogen and ammonia synthesis processes continue operating at 10% load while the air separation unit keeps operating at 70% load to provide the flexibility required in the ammonia synthesis

- **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.

This has led to a project size comprising 407.4 MW wind energy, 305.5 MW electrolyzers and 21.6 MW ammonia synthesis, with a nominal capacity of 33.3 kton NH_3/hour. Other relevant results are the minimum amount of wind energy curtailed (0.06%) and energy withdraw from the grid (0.14%), which show the effectiveness of the wind energy resource with the optimization established. The main technical KPIs results can be seen in Table 4.

3.2 Financial Analysis

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 [7], [6]. 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 reach the billion dollar, reflecting the high necessary investment behind the green ammonia opportunity. The main financial KPIs results can be seen in Table 4.

Table 4: Technical and Financial KPIs Results

KPIs	Block	Section	Parameter	Result	Unit
Technical	Energy Production	Wind Turbines	Nº Turbines	97	Nº
			Installed Capacity	407.4	MW
			Annual Net Energy Production	2,028,265	MWh/year
		Wind Energy Curtailment	Energy Curtailed	1,198	MWh/year
		Energy Withdraw from BZ Grid	Energy Withdrawn	2,870	MWh/year
	Energy Consumption	Electrolyzers	Installed Capacity	305.5	MW
			Energy Consumption	91.06	%
			H_2 Production	36,246	tons/year
		ASU	Installed Capacity	7,2	MW
			Energy Consumption	2.48	%
			N_2 Production	190,321	tons/year
		NH_3 Synthesis Plant	Installed Capacity	21.6	MW
			Energy Consumption	6.46	%
			NH_3 Production	201,366	tons/year
Financial	Energy Production	LCOE	LCOE_Wind	30.0	$/MWh
		LCOE	LCOE_Wind_GridInfrastructure	34.0	$/MWh
		LCOE	LCOE_Wind_GridInfrastructure_BZGrid	34.1	$/MWh
	Energy Consumption	LCOH	LCOH_PEM_SWRO	3.4	$/ kg H_2
		LCOH	LCOH_PEM_SWRO_Storage	3.7	$/ kg H_2
		LCOA	LCOA_Synthesis	770.5	$/ ton NH_3
		LCOA	LCOA_Synthesis_Storage	789.3	$/ ton NH_3
		LCOA	LCOA_Synthesis_Storage_Shipping	831.3	$/ ton NH_3
	CAPEX		Total Project CAPEX	1,263.8	M$
	OPEX		Total Project OPEX	905.3	M$

The LCOA breakdown, illustrated in Figure 7 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.

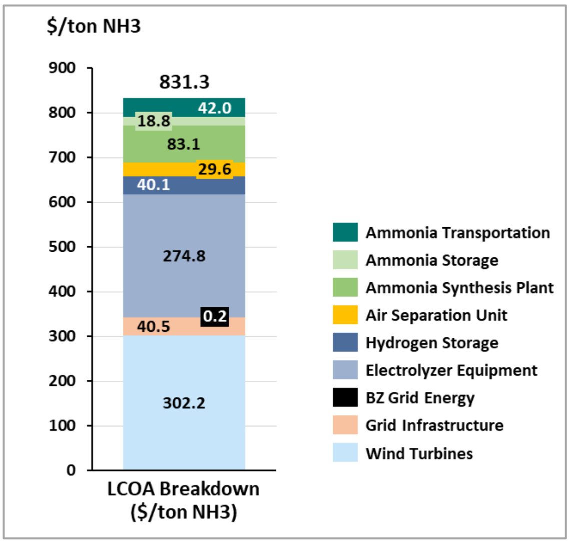

Figure 7: LCOA breakdown by system component

3.3 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 ammonia with green ammonia 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 ammonia 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.

To analyse grey ammonia production it is then imperative to reflect the main techno-economic and environmental parameters of this production route, stated in Table 5 below and mostly obtained from Yara, one of the largest ammonia producers and traders worldwide with 7.7 million tons/year NH_3 production [22].

- **Economic Comparison**: When comparing the green NH_3 LCOA with the grey NH_3 production pathway, variable NG TTF ($/MWh) prices as well as several potential carbon taxes ($/ton CO_2) have been considered, as observed in Figure 8.

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 electrolyzer, an optimistic LCOA 654$/ton$NH_{3\text{-green}}$ would be competitive with grey when NG and carbon taxes prices reach 50$/MWh and 50$/tonCO_2 respectively.

Table 5: Grey ammonia production from SMR, Techno-Economic and Environmental Parameters

Block	Nature	Parameter	Value	Unit	Source
Grey NH_3 Production - SMR	Technical	SMR Gas Consumption	36	mmbtu/ton NH_3	Yara
			10.55	MWh/ton NH3	
			37.98	GJ/ton NH3	
	Economical	Gas Price (OPEX – Fuel)	Variable	$/MWh	
		Other Production Cost (OPEX)	29	$/ton NH_3	
	Environmental	Equivalent CO_2 emissions	1.92	ton CO_2-e / ton NH_3	Industry

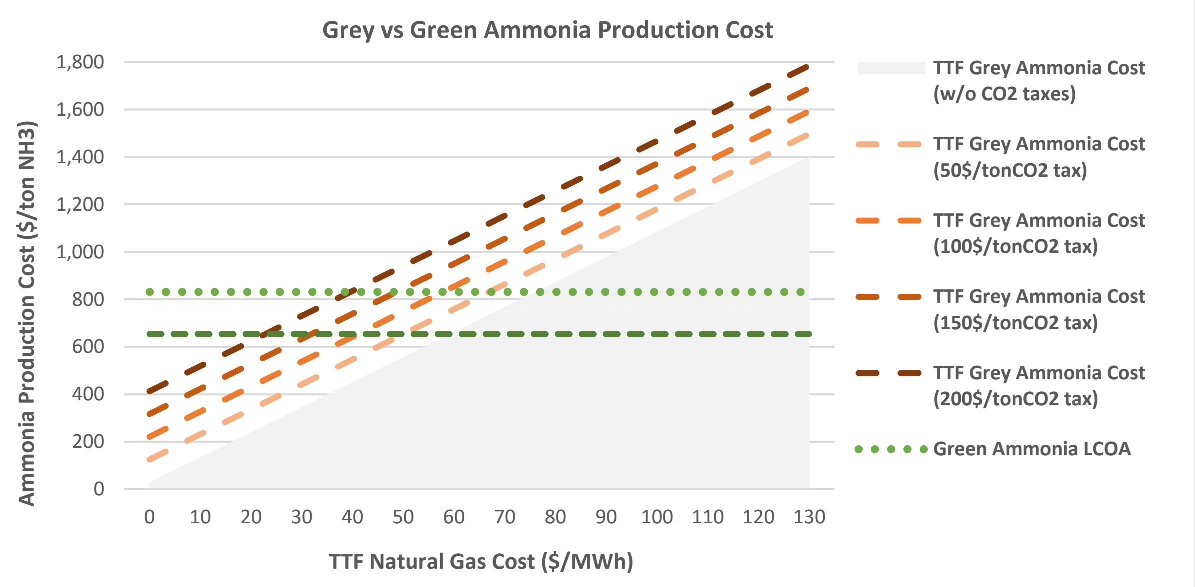

Figure 8: Grey vs green ammonia production cost, based on TTF natural gas cost

When comparing the energy intensity both production pathways are quite balanced, although being more energy-consuming the grey ammonia 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 ammonia having an almost insignificant 0.22 tonCO_2-eq/tonNH_3 versus the 1.92 tonCO_2-eq/tonNH_3 from the grey production.

4. Conclusions

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 NG and carbon taxes prices. However, the investment behind the opportunity is impressive and project financing and ensuring offtake play a relevant role. The deployment of green NH_3 projects worldwide could be accelerated by the successful application of carbon taxes and through 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.

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