Port of Itaqui Decarbonization Plan

April/2025

FUNDACIÓN VALENCIAPORT

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ACRONYM	DESCRIPTION
BaU	Tendential, or Without Mitigation Actions (Business as Usual)
BID	Inter-American Development Bank
Bio-GNL	Gás Natural Liquefeito → Liquefied Natural Gas (LNG)
BlueBARGE	Unidade flutuante de fornecimento de energia → Energy Barge Solution
BT	Low Voltage (LV)
CO_2	Carbon Dioxide (CO_2)
CO_2eq	Carbon Dioxide Equivalent (CO_2eq)
Drop-in	Drop-in Alternative Fuel
EIA/RIMA	Environmental Impact Assessment (EIA) / Environmental Impact Report (EIR)
EMAP	Maranhão Port Administration Company (EMAP)
Fuel Cells	Fuel Cells
GEE	Greenhouse Gases (GHG)
GLP	Liquefied Petroleum Gas (LPG)
GNC	Compressed Natural Gas (CNG)
H_2	Hydrogen (H_2)
H_2PORTS	Hydrogen Use in Ports Project
HVO	Hydrotreated Vegetable Oil (HVO)
Hz	Frequency Unit (Hertz – Hz)
IFC	International Finance Corporation (IFC, World Bank Group)
IMO	International Maritime Organization (IMO)
ISP	Port Sustainability Index (PSI)
kg	Kilogram (kg)
kgCO_2/t	Kilogram of CO_2 per Ton Transported
kVA	Kilovolt-Ampere (kVA, apparent power)
kW	Kilowatt (kW, active power)
kWh	Kilowatt-hour (kWh, consumed electricity)
kWp	Kilowatt-peak (kWp, installed solar capacity)
k€	Thousand Euros (€k)
M€	Million Euros (€M)
MW	Megawatt (MW)
MWh	Megawatt-hour (MWh)
MVA	Megavolt-Ampere (MVA)
m^2	Square Meter (m^2)

ACRONYM	DESCRIPTION
OPS	Onshore Power Supply (OPS)
RTG	Rubber-Tired Gantry (RTG)
SBTi	Science Based Targets initiative (SBTi)
SCC	Social Cost of Carbon (SCC)
Stillstrom	Floating Power Barge Solution
TGL	Maranhão Grain Terminal (TEGRAM)
TEQUIMAR	Aratu Chemical Terminal (TEQUIMAR)
tCO_2eq	Ton of Carbon Dioxide Equivalent (tCO_2eq)
US$	United States Dollars (USD)
V	Volt (V)
VPL	Net Present Value (NPV)
VTMIS	Vessel Traffic Management Information System (VTMIS)
W	Watt (W)
°C	Degrees Celsius (°C)

EXECUTIVE SUMMARY

This document presents the Decarbonization Plan of the Port of Itaqui, a strategic roadmap designed to progressively reduce Greenhouse Gas (GHG) emissions associated with its activities. The plan is framed within the global commitment to tackling climate change and is aligned with international initiatives, proposing concrete actions to decarbonize the Port of Itaqui by 2050.

The Decarbonization Plan is based on the carbon footprint calculation carried out for the Port of Itaqui, with 2022 as the baseline year. For this purpose, the specific current and future context of the port was analyzed, considering operational characteristics, planned expansions, and energy transition trends in the port sector. The adopted methodology combines a technical approach with a participatory process, relying on direct collaboration with EMAP. The plan was built on quantitative analyses that allow estimating the impact of different measures on emissions reduction, supported by specific models and by current and projected port traffic data.

These elements, together with the definition of the plan's target year and the estimated carbon price, enabled the evaluation of future scenarios for the Port of Itaqui, with the objective of guiding decision-making towards a realistic and effective energy transition.

The Plan establishes decarbonization targets based on the current and projected emissions profile and provides a detailed analysis of the technologies available for different transport modes and actors in the port ecosystem: vessels, tugboats, port terminals, trucks, railways, as well as energy solutions such as photovoltaic generation and renewable hydrogen. Based on this foundation, a structured action plan is proposed, with specific measures for each actor involved, presenting their respective potential for emissions reduction and the estimated cost of implementation. Two implementation scenarios — conservative and optimistic — are analyzed to assess different decarbonization pathways depending on the level of adoption of the proposed measures. The comparison between the two scenarios demonstrates that it is possible to achieve a significant reduction in emissions, reaching only 12 kt or even 9 kt of CO_2eq emitted in 2050, depending on the level of ambition adopted.

Finally, the document includes cost estimates associated with offsetting residual emissions that cannot be eliminated due to port activities, as well as a general economic analysis of the plan.

1. Introduction

Climate change is one of the major challenges of the 21st century. According to climate records, each of the last four decades has been progressively warmer than any previous decade since 1850. Global warming caused by human activity is undeniable, and every ton of GHG emissions contributes to this phenomenon, driving rapid and widespread changes in the atmosphere, oceans, cryosphere, and biosphere.

At the global scale, decarbonization efforts have intensified in response to the growing urgency of mitigating the impacts of climate change. International agreements, such as the Paris Agreement, have set clear goals to reach the global peak of GHG emissions as soon as possible, with rapid reductions based on the best available scientific evidence. In Brazil, climate change policies have encouraged the transition to renewable energy sources, the electrification of strategic sectors, and the decarbonization of logistics and transportation. In particular, the country seeks to strengthen initiatives in ports, promoting more sustainable practices to reduce emissions associated with maritime and land-based operations.

Ports are essential infrastructure for global trade, enabling the transportation of goods. However, their activities also generate a significant amount of GHG emissions. Cargo handling operations, inland transportation, navigation, and the use of equipment and machinery in the port environment, along with the infrastructure itself and the growing demand for logistics services, still rely heavily on fossil fuels, contributing substantially to climate change and raising the sector’s carbon footprint.

In this context, calculating a port’s carbon footprint is the first step in identifying and quantifying the sources of GHG emissions associated with its operations. This assessment allows the port authority to understand the extent of its environmental impact and establish specific strategies to reduce it. Based on this information, the implementation of decarbonization plans becomes a fundamental tool to promote the transition to a more sustainable operational model.

By reducing GHG emissions and optimizing resource use, ports contribute effectively to addressing the climate crisis while also increasing their operational efficiency and competitiveness in the global market.

This report is based on the carbon footprint calculation of the Port of Itaqui, conducted with 2022 as the baseline year, and defines a decarbonization plan aimed at promoting a transition to more sustainable operations, aligned with global emission reduction commitments and improved port efficiency.

2. Context of the Port of Itaqui

2.1. Location and general characteristics

The Port of Itaqui is located in São Luís, Maranhão, Brazil, and is one of the country's main ports for handling solid and liquid bulk. Its strategic position on the Atlantic coast facilitates connections with both domestic and international markets, making it a key logistics hub for agribusiness, mining, and fuels.

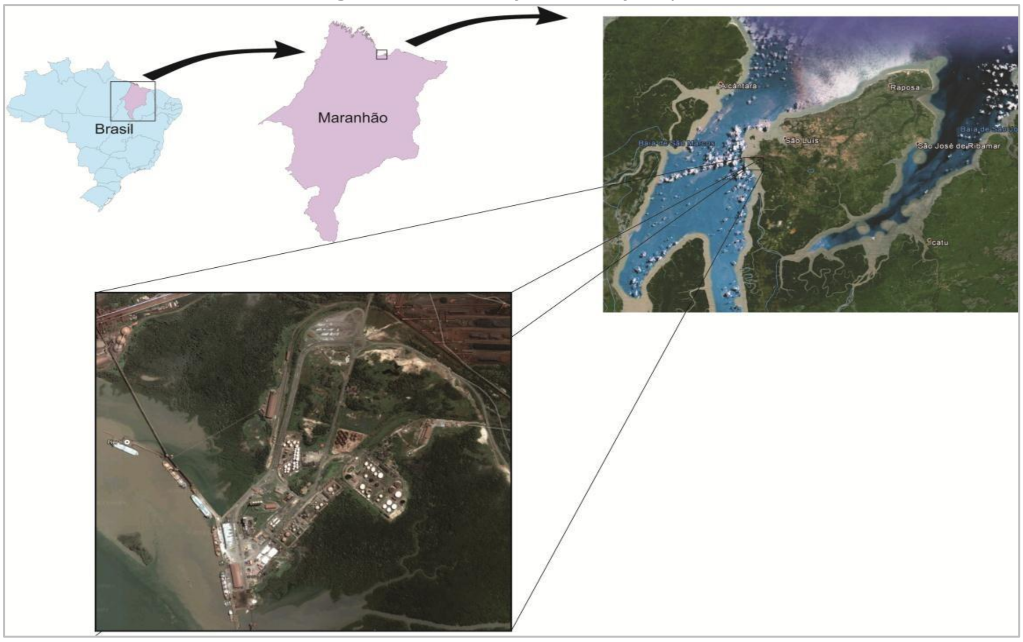
1. Berths and Terminals

The port has nine operational berths, designed for handling various types of cargo, including:

- Solid Agricultural Bulk (soybeans, corn, soybean meal, wheat, rice);
- Solid Mineral Bulk (fertilizers, pig iron, coal, slag, clinker, limestone, copper concentrate);
- Liquid Bulk — fuels and chemicals (petroleum derivatives — fuel and LPG);
- General Cargo (pulp).

Its modern infrastructure **allows the docking of large vessels**, optimizing port operations and ensuring high logistical efficiency.

Figure 1– Location of the Port of Itaqui.



Source: EMAP.

2. Access and Connectivity

The Port of Itaqui has intermodal access routes that ensure efficient and integrated transportation:

- **Railway:** connected to the North-South Railway, enabling the transport of agricultural and mineral production from the Brazilian hinterland.
- **Highway:** linked to major federal highways, facilitating inland cargo transportation.
- **Maritime:** access channel with sufficient depth to accommodate large-draft vessels.

Figure 2 Intermodal access at the Port of Itaqui.

Source: EMAP

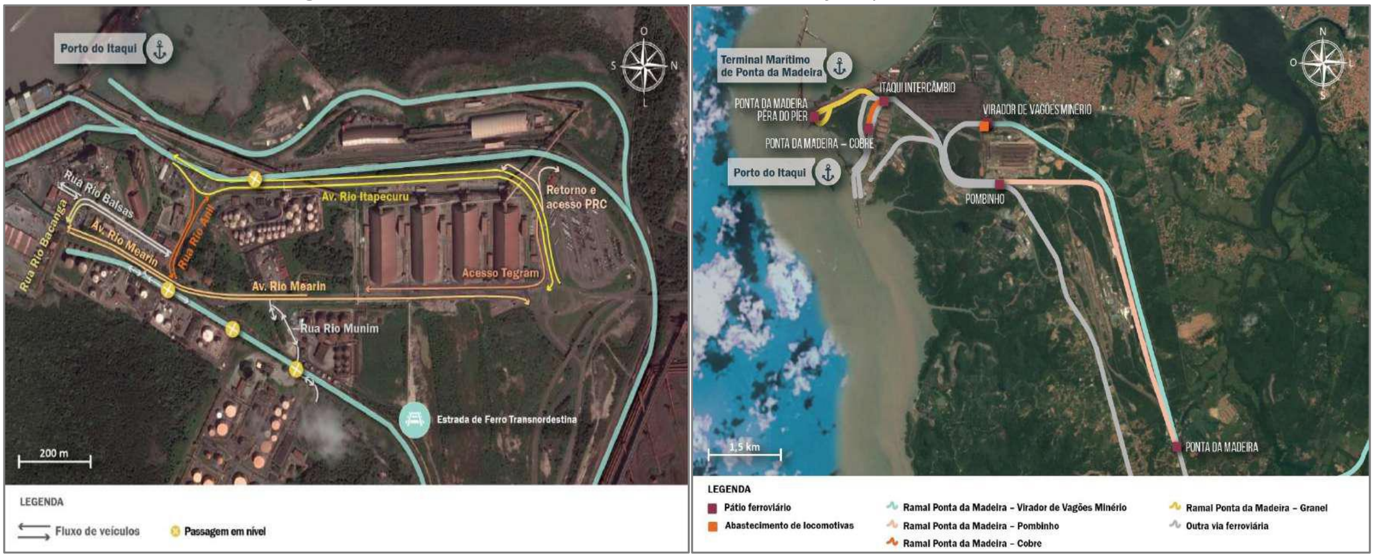
3. Connection with the Hinterland

The Port of Itaqui is connected to its hinterland through the BR-135 and BR-222 highways, as well as railway lines.

Trucks: with access to the port via Av. dos Portugueses or Av. Eng. Emiliano Macieira, trucks serve the Tegram, VLI, Ultracargo, Eneva, Moinhos, DATA, COPI, Pedreiras, and Transpetro terminals.

Railways: with one inbound and one outbound branch line, trains serve the VALE, Tegram, Granel Química Ltda., Petrobras, Ultracargo, and Itacel terminals.

Figure 3 - Road and rail connections between the Port of Itaqui and its hinterland.



Source: EMAP

The medium-voltage grid (13,800 V) that supplies the Port of Itaqui is owned by the local power utility (Equatorial Energia) up to the property boundary of the Port Authority. From that point onward, the grid continues underground to the receiving substation, and this section is owned by the Port Authority. The contracted demand for the port area (the primary port area) with the utility is 400 kW.

The berths are supplied through a Low-Voltage (LV) network. There is also a medium-voltage network extending to the existing substations: the receiving substation, located near the water tower; SE-01 (electrocenter), near berths 101/102; SE-02 (electrocenter), near berths 103/104; and SE-03, near berth 105. **The grid voltage level is 13,800 V.**

Rated Power:

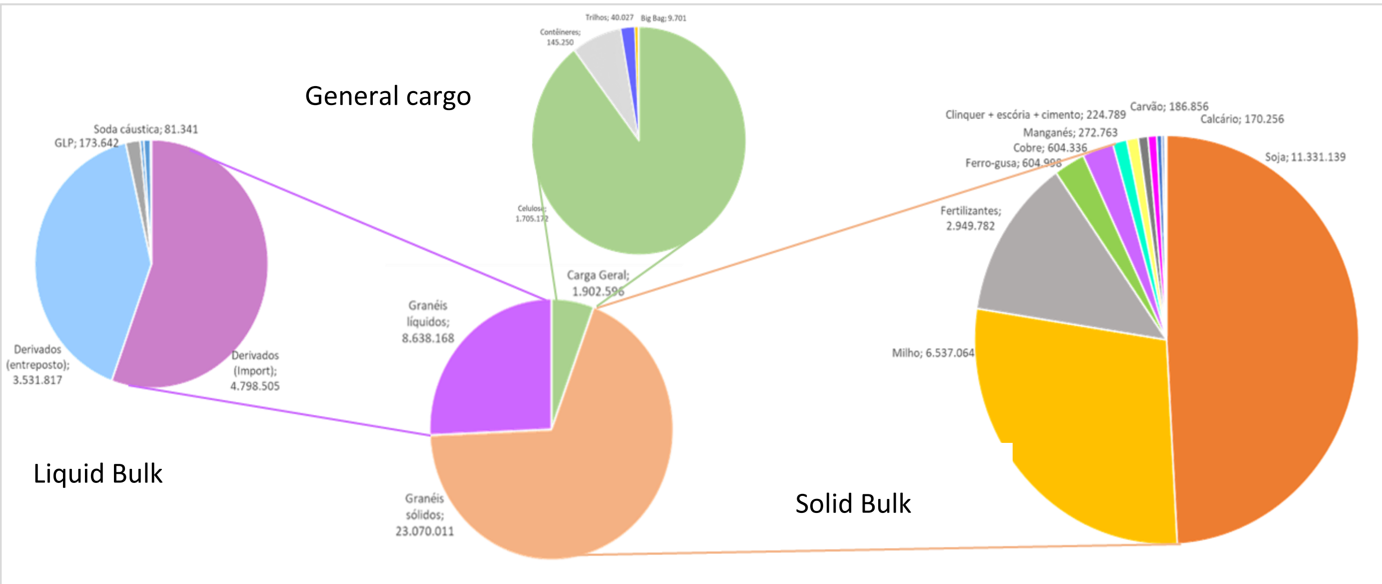
- **Receiving Substation:** 500 kVA
- **Substation 01:** 500 kVA (lighting and power) / 300 kVA (firefighting system)
- **Substation 02:** 500 kVA
- **Substation 03:** 500 kVA (lighting and power) / 300 kVA (firefighting system)

Figure 4 - Location of electrical substations within the port.

Source: EMAP.

In 2022, the port handled around 34 million tons, with the main type of cargo being solid bulk (69%), followed by liquid bulk (26%) and general cargo (5%). Solid bulk traffic is dominated by soybeans (33% of the port's total traffic), corn (20%), and fertilizers (9%). The main liquid bulk commodity is imported petroleum derivatives (14%), followed by hydrocarbons for transshipment (10%). Pulp traffic accounts for 5% of the total volume handled at the port.

Figure 5 - Distribution of cargo volumes handled at the Port of Itaqui in 2022, by type and product.



Source: Fundación Valenciaport.

2.1. Current Situation

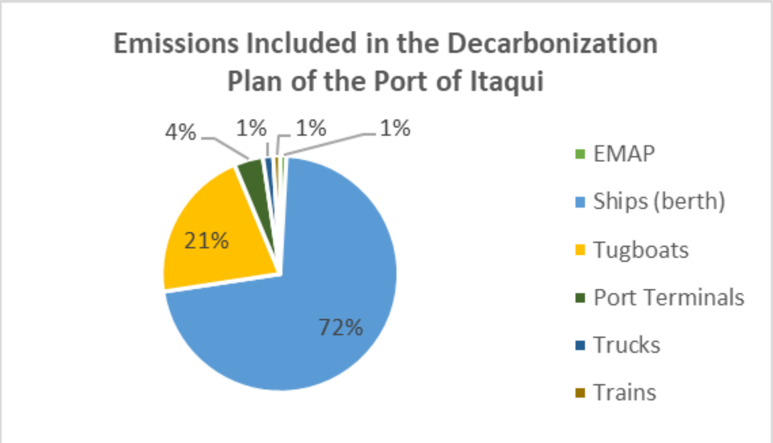
At the Port of Itaqui, 189 ktCO_2 were emitted in 2022, of which 82 ktCO_2 are attributed to port activities themselves, including vessels berthed (at berth), while 107 ktCO_2 correspond exclusively to navigation, anchorage, and maneuvering operations of vessels. In relative terms, port activity presents an emission intensity of 5.63 kgCO_2 per ton of cargo handled.

Table 1 – Results of the carbon footprint of the Port of Itaqui in 2022.

Scope	Area	Emissions (tCO_2eq)
Scope 1	Fixed sources	67.33
	Mobile sources	96.94
	Refrigerant gases	437.05
	Fire extinguishers	0.22
	Total	**601.54**
Scope 2	Electricity at EMAP facilities	110.83
	Total	**110.83**
Scope 3	Ships (navigation)	5,948.91
	Ships (maneuvering)	5,529.55
	Ships (anchorage)	95,790.91
	Ships (at berth)	58,789.68
	Tugboats	17,289.50
	Terminals	3,243.92
	Trucks	1,156.57
	Trains	763.98
	Total	**188,513.02**
Port Total		
Port Total (ships at berth only)		

Source: Fundación Valenciaport.

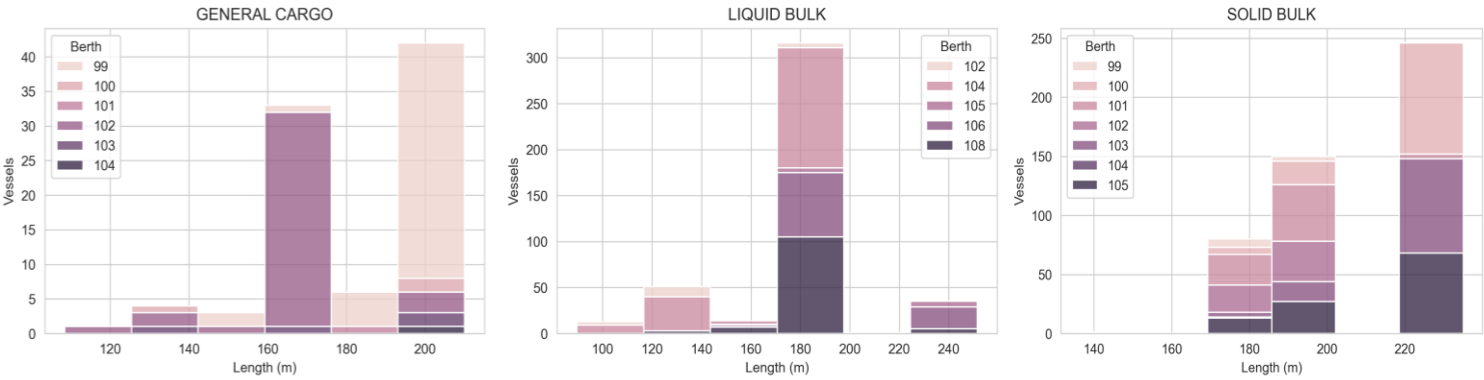
Figure 6 –Emissions accounted for in the Port of Itaqui Decarbonization Plan



Source: Fundación Valenciaport.

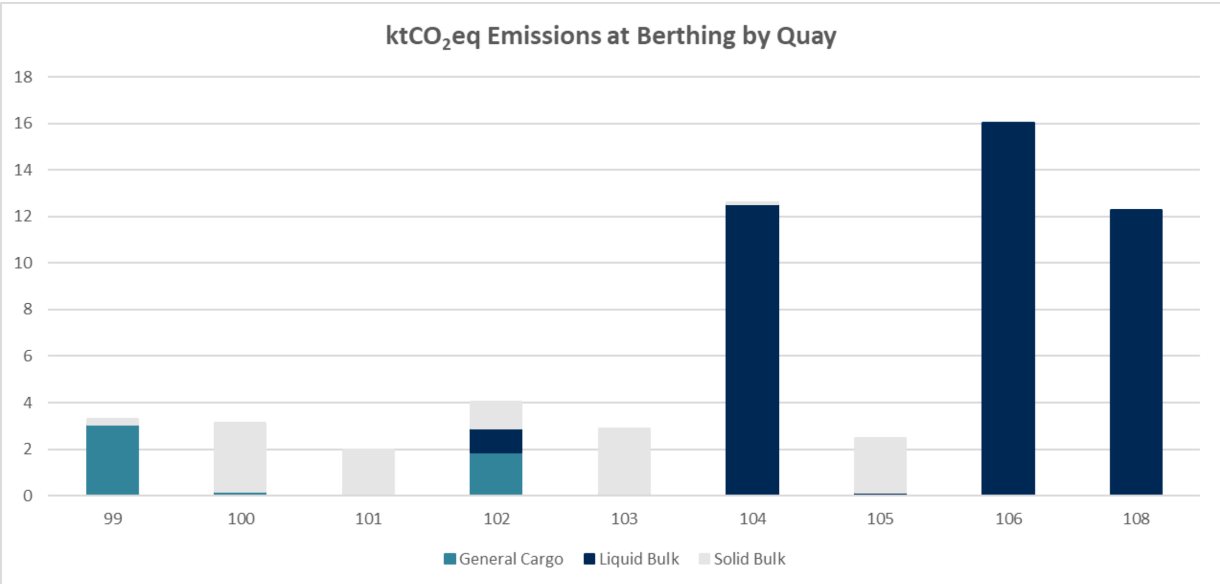
The highest CO_2 emissions during berthing come from liquid bulk vessels, which are allocated at berths 104, 106, and 108. The largest number of calls corresponds to dry bulk, mainly distributed across three size ranges. In the case of liquid bulk, most vessels are concentrated around a single size class. The highest number of general cargo calls refers to cellulose, within a specific size range, at berth 99.

Figure 7 - Record of vessel calls in 2022, by cargo type, berths, and vessel length.



Source: Fundación Valenciaport.

Figure 8 - Vessel emissions at berth, by cargo type and berth.



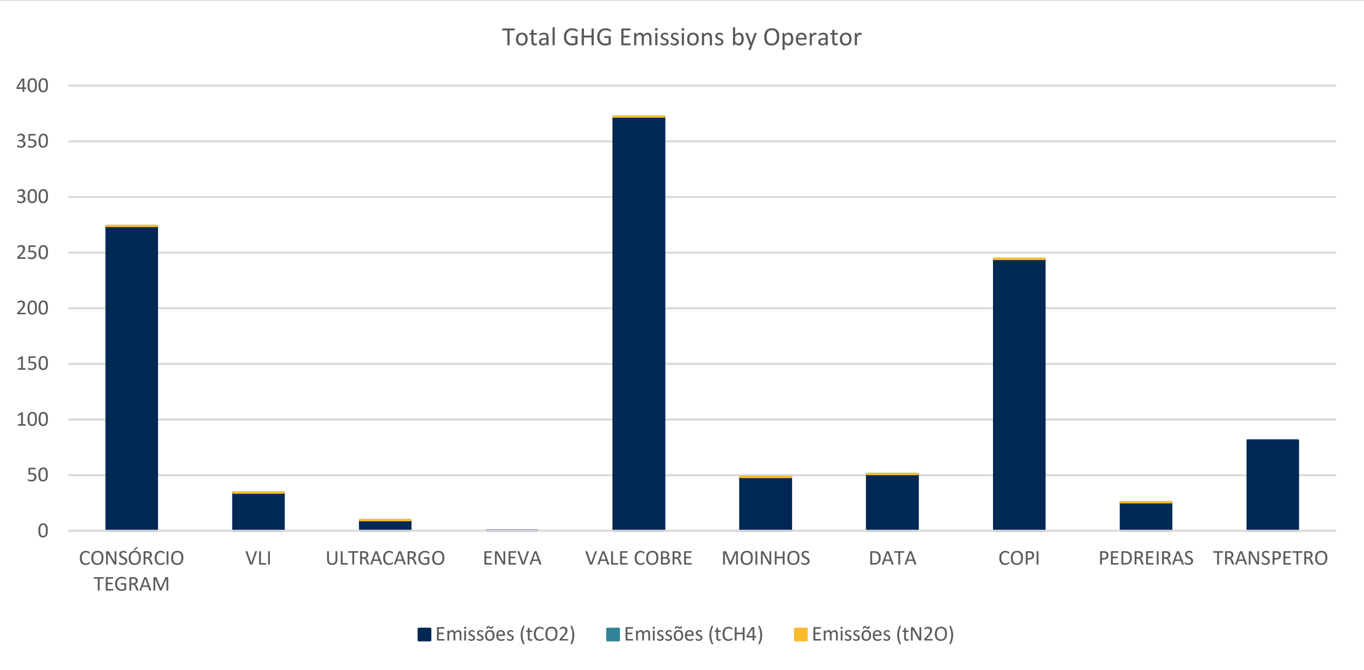
Source: Fundación Valenciaport.

With regard to the inbound and outbound flows of goods by land at the Port of Itaqui, the mode of transport used is directly related to the type of cargo. Pulp is predominantly received by rail, while mineral dry bulk and liquid bulk are mostly transported by trucks. Agricultural dry bulk, the main cargo handled at the port, shows an estimated modal split of 60% by road and 40% by rail.

Road operations are concentrated mainly at the Maranhão Grain Terminal (TEGRAM) and in the primary port area. On the rail side, operations also stand out at TEGRAM and in pulp reception activities.

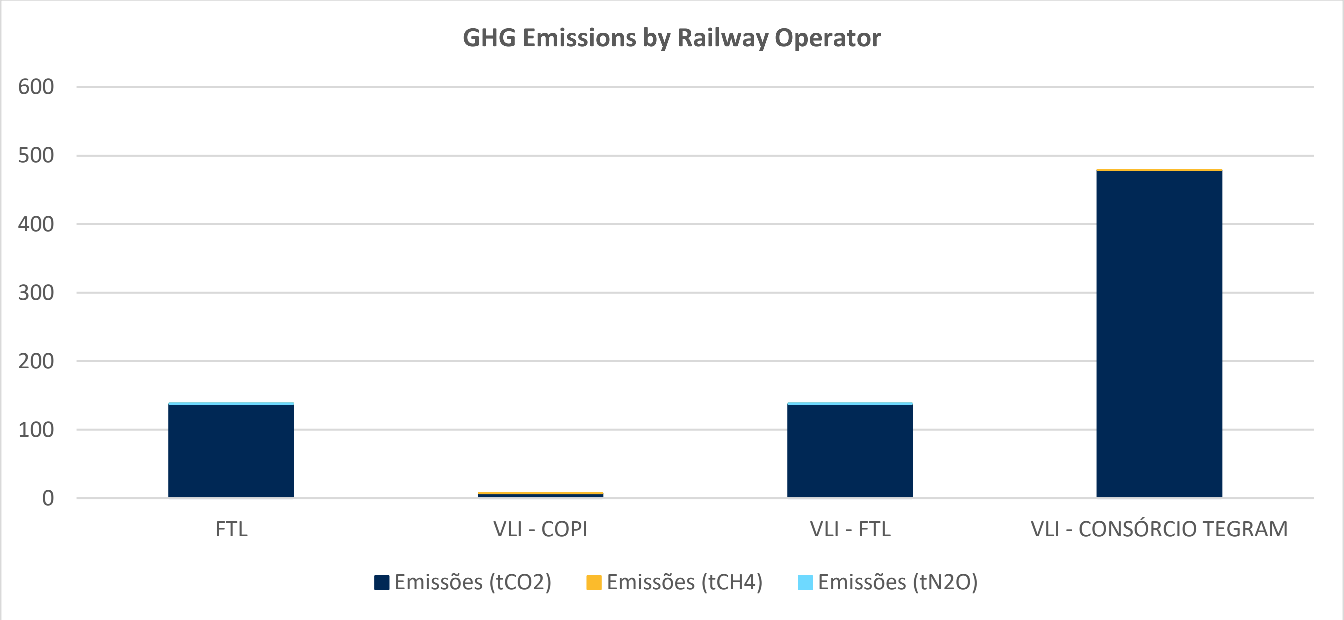
Additionally, the use of the pipeline system deserves special mention, as it connects specialized berths — such as berths 104, 106, and 108 — to storage facilities and processing units. Pipelines are widely used for the handling of liquid bulk, providing a safe, efficient logistics solution with lower environmental impact. This mode significantly contributes to operational optimization, enabling continuous and automated transfers while reducing operation time and the risks associated with truck transport.

Figure 9 - Emissions from cargo transported by truck.



Source: Fundación Valenciaport.

Figure 10 - Emissions from cargo transported by railway.



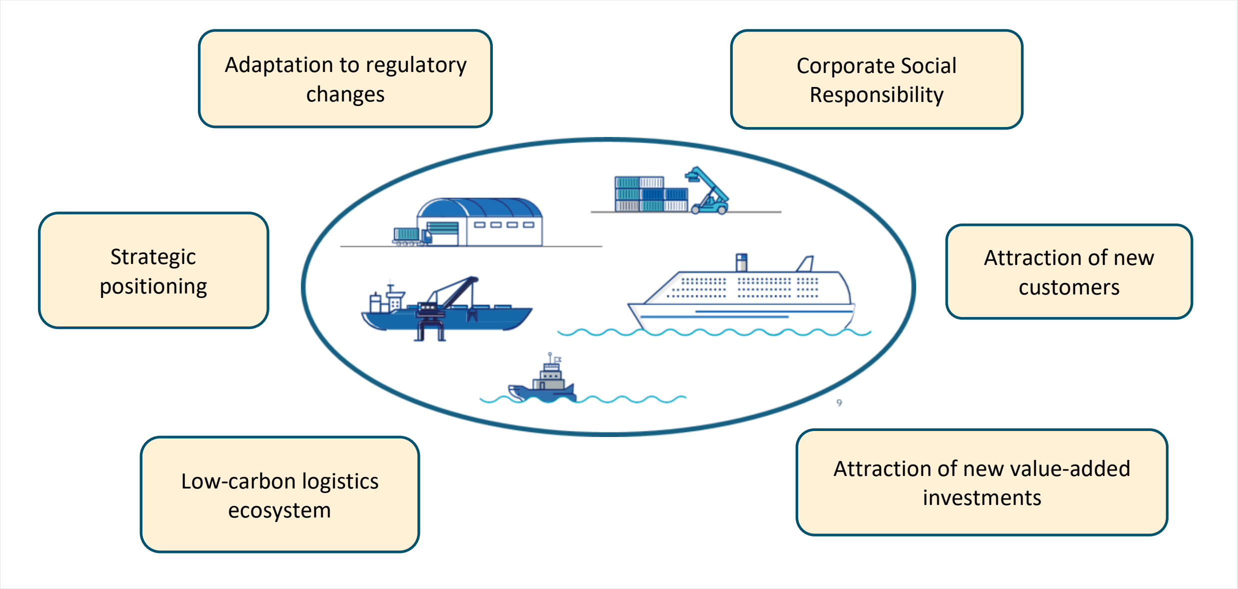
Source: Fundación Valenciaport.

2.2. Motivation

Although the outcomes of a port's decarbonization process have a positive impact on society and are therefore aligned with the port authority's corporate social responsibility strategy, the main benefits lie in readiness and positioning, and are thus directly related to the port's competitiveness on a global scale.

The implementation of low-carbon practices strengthens the port's ability to meet international regulatory requirements, expands its access to more demanding markets, and makes it more attractive to new clients and investors committed to sustainability criteria. In addition, it consolidates the port's strategic role as a logistics platform of reference in environmental excellence, integrating technological innovation, operational efficiency, and socio-environmental responsibility as competitive differentiators.

Figure 11 - Strategic benefits of decarbonization for port competitiveness.



Source: Fundación Valenciaport.

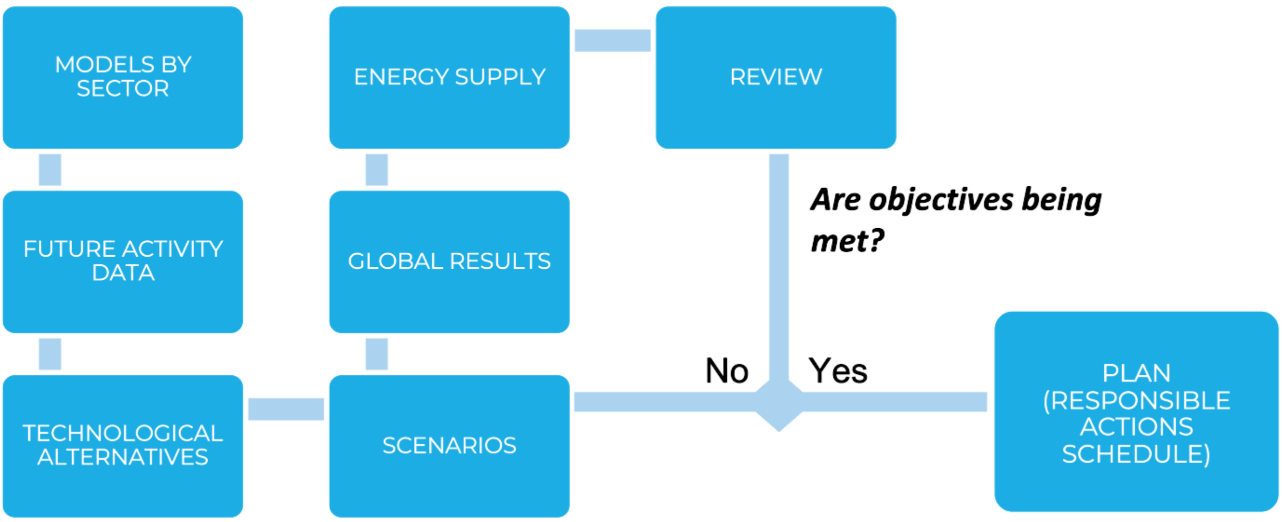
3. Methodology

The methodology used for developing the decarbonization plan is based on a technical and participatory approach, combining quantitative analyses with the direct collaboration of EMAP.

First, specific models are developed to quantify the potential impact on CO_2 emission reductions resulting from the implementation of different technologies or other mitigation measures. These models make it possible to simulate, based on real data and projections, how each action can contribute to port decarbonization over time. For each measure considered, a preliminary budget is also estimated, enabling an assessment of its technical and economic feasibility. These two tools — estimated emission reductions and approximate cost — are integrated with traffic growth forecasts and operate within the local port context, taking into account particularities such as current operational patterns and growth projections. This makes it possible to build realistic and consistent future scenarios.

The final definition of the actions to be included in the plan is carried out collaboratively with EMAP, ensuring alignment with institutional strategies, the port's sustainability objectives, and the real possibilities for implementation.

Figure 12 - Methodology adopted for the development of the Decarbonization Plan of the Port of Itaqui.



Source: Fundación Valenciaport.

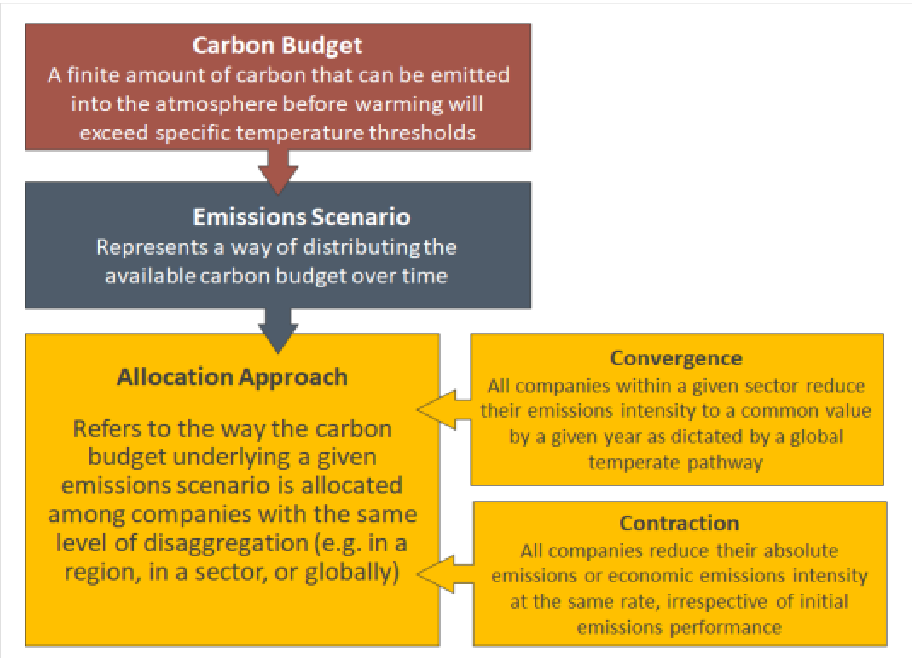
3.1. Alignment with the SBTI

Science-Based Targets (SBTi) require that the objective be aligned with a global temperature increase of less than 2 °C, with efforts to limit it to 1.5 °C. To define concrete targets, the initiative requires three elements:

- Defining a specific carbon budget,
- Developing scenarios, and
- Applying an allocation approach.

The methodology proposed in this study provides tools (scenarios) to achieve this objective, although it is considered that, when selecting concrete actions, pursuing a realistic goal is more important than simply meeting the CO_2 budget defined by SBTi.

Figure 13 - Elements for defining science-based targets.



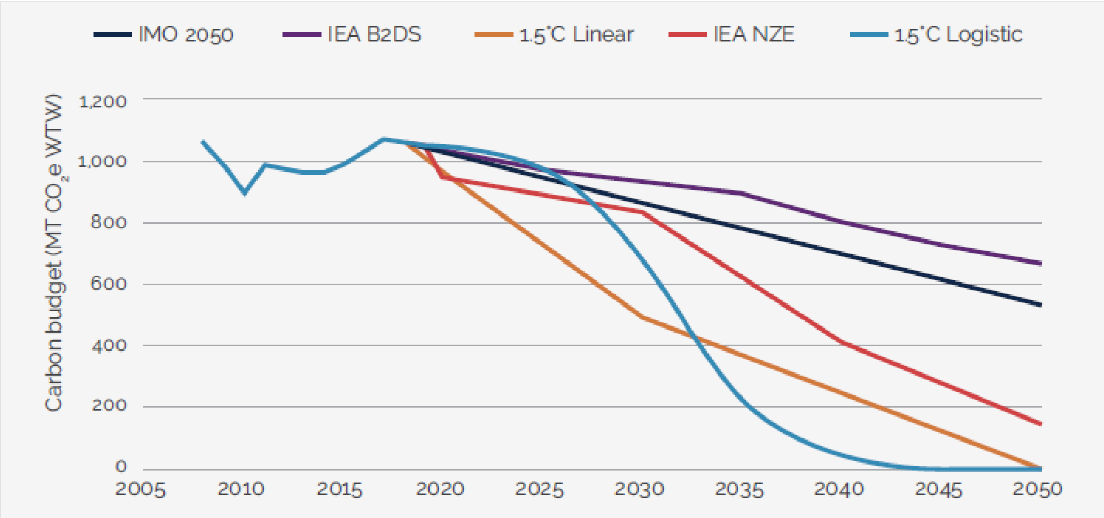
Source: SBTi.

3.2. Decarbonization Targets

The initial decarbonization target is that established by the SBTi methodology. In the case of the Port of Itaqui, considering that more than 93% of emissions come from maritime sources (cargo vessels and tugboats), the Science Based Target Setting for the Maritime Sector guide was applied, which indicates that reductions should reach 96% by 2040.

If the IMO strategy is adopted instead, the expected reduction would be 70% by 2040. In any case, the defined plan must remain realistic and applicable.

Figure 14 - Emission pathways for the maritime sector.

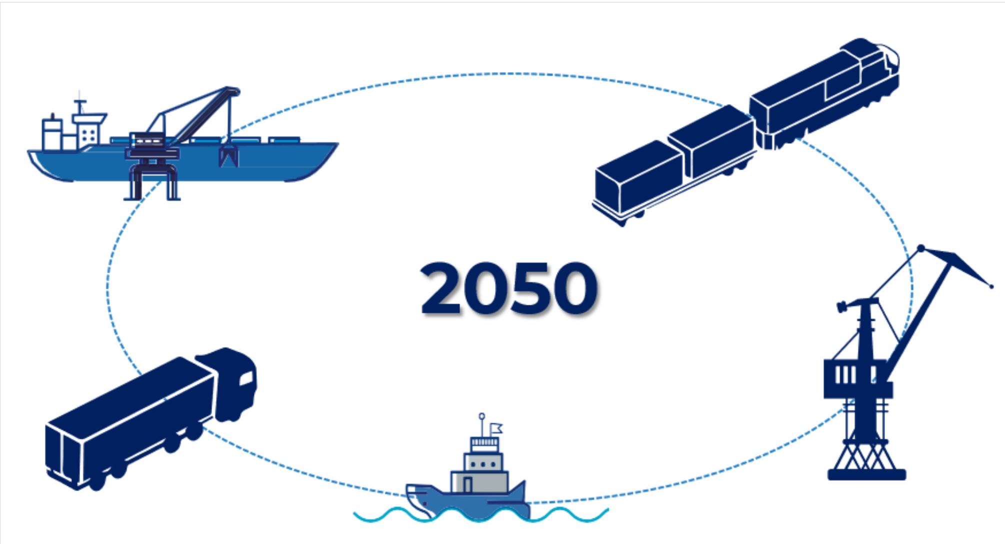


Source: Science Based Targets initiative.

3.3. Target Year

Considering that the main sources of emissions are cargo and service vessels, it is advisable to set a target year for decarbonization in line with the IMO strategy, i.e., 2050. The scope of action includes the same scope as the average carbon footprint, namely: berthed vessels, tugboats, tenants, concessionaires and operators, as well as land transport by truck and rail. In the case of vessels, only the berthing phase is considered, since it is the only stage in which EMAP can implement interventions.

Figure 15 - Definition of the target year for the Decarbonization Plan of the Port of Itaqui.

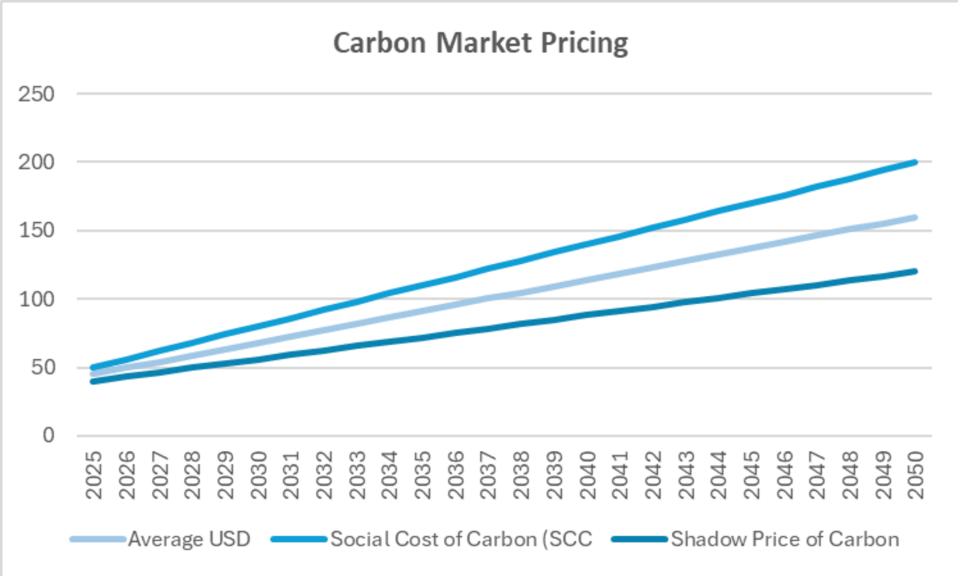


Source: Fundación Valenciaport.

3.4. Carbon Price

For the economic benefit analyses and investment evaluation, the average between the expected future values of the Social Cost of Carbon and the Carbon Shadow Price was considered.

Figure 16 - Estimativa futura USD tCO2.



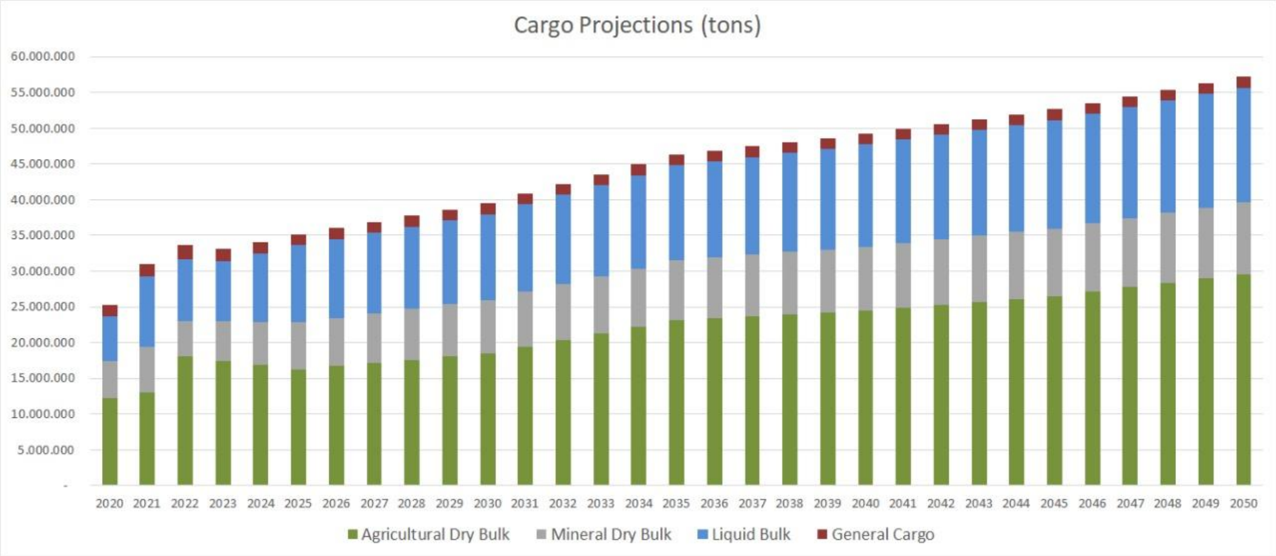
Source: Fundación Valenciaport.

Social Cost of Carbon (SCC). Represents the real economic and environmental impact of emitting one ton of CO_2. Carbon Shadow Price. Used by multilateral organizations (IDB, World Bank, IFC) and large companies to simulate future regulatory scenarios.

4. Future Scenarios

In the year 2050, demand at the Port of Itaqui is estimated to reach 57.2 million tons in the baseline scenario. Agricultural dry bulk will account for the largest share, with 29.6 million tons; 16.1 million tons will correspond to liquid bulk; 10 million tons to mineral dry bulk; and 1.5 million tons to general cargo.

Figure 17 - Cargo forecasts (tons)



Source: Fundación Valenciaport.

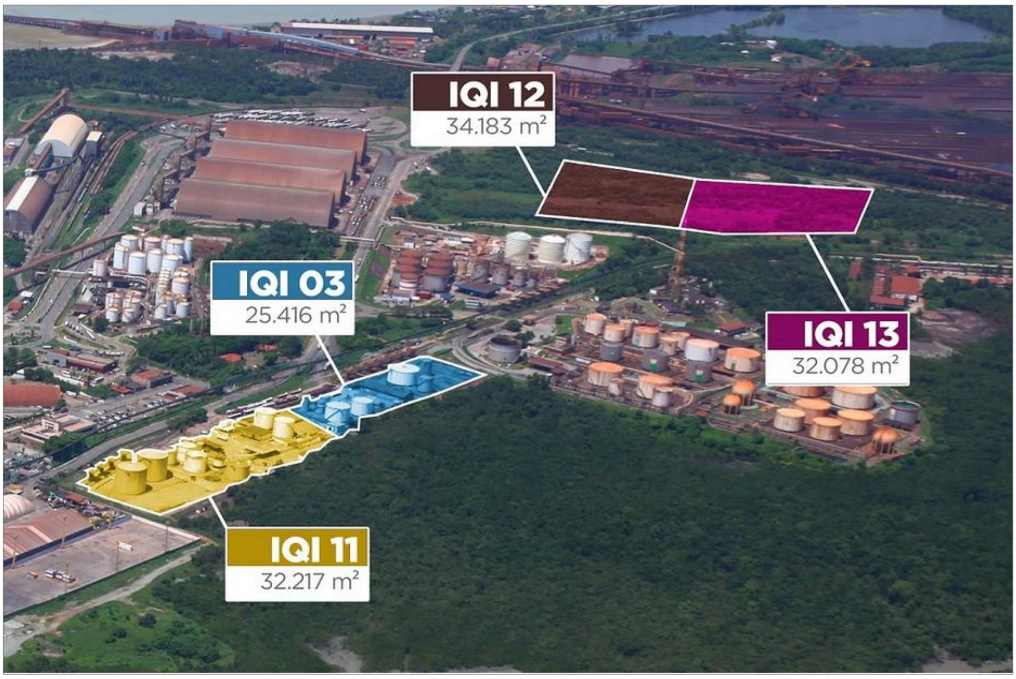
Berth 98 will be completed by the end of 2026. Berths 97 and 96 already have demand and are expected to become viable within a maximum of five years. Berths 95 and 94 are scheduled for a maximum timeframe of ten years. Over the next ten years, five new berths will be built, which, together with the nine already existing, will total 14 berths. Details on port planning and the associated environmental studies are described in the full EIA/RIMA report, available on the port's official website.

Figure 18 - Expansion of the port infrastructure of the Port of Itaqui: forecast of new berths until 2035.

Source: Fundación Valenciaport.

A new terminal operated by Santos Brasil, a company specialized in port operations and logistics, has been in operation at the Port of Itaqui since the end of 2022. The company has started its expansion plan for the fuel terminals TGL 1 and TGL 3 in the public port of Maranhão. The ongoing works include the construction of new tanks for the reception, dispatch, and storage of diesel, gasoline, and biofuels.

Figure 19 - Leased areas and expansion plan of Santos Brasil for fuel terminals at the Port of Itaqui.



Source: Fundación Valenciaport.

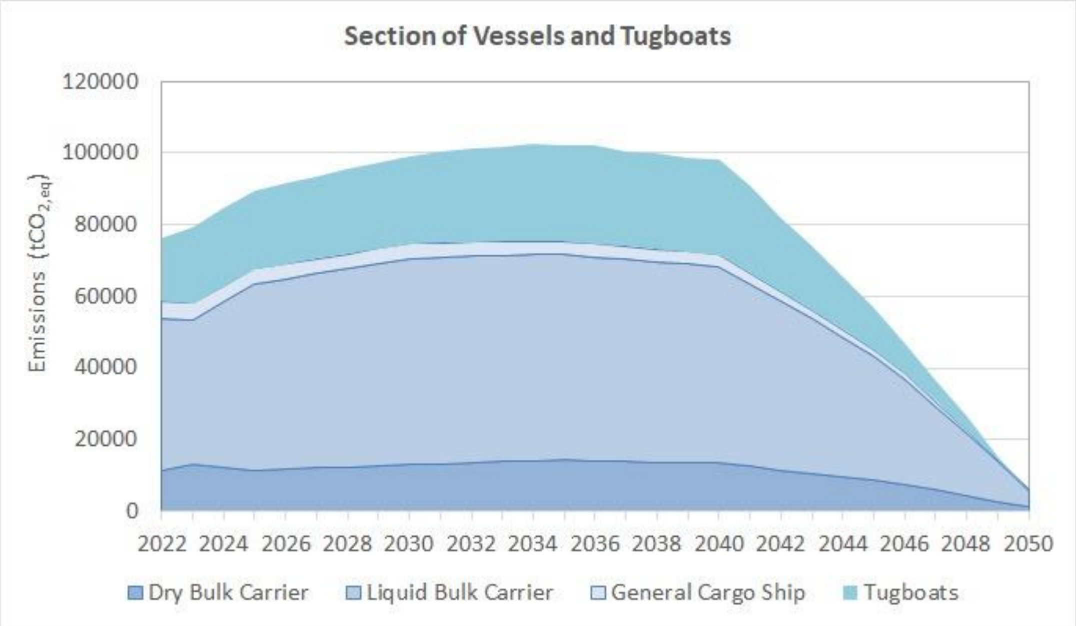
Santos Brasil has leased the following areas: IQI-03, IQI-11, and IQI-12. Area IQI-13 has been leased by the Aratu Chemical Terminal (TEQUIMAR).

4.1. Towage and vessels projections

In the period from 2022 to 2050, under the scenario without EMAP's decarbonization actions, two trends can be observed. Until 2040, there is a slight increase in which part of the growth in activity is offset by some decarbonization actions in the sector. From 2040 onwards, the maritime sector is expected to align with the IMO strategy, which will imply a significant reduction in overall emissions.

By 2050, total emissions are estimated at 6 kt CO_2, a value representing 8% of 2022 emissions. However, in 2050 they will still remain the main source of emissions at the Port of Itaqui, accounting for 41% of total global emissions.

Figure 20 - Projection of Ships and Tugboats



Source: Fundación Valenciaport.

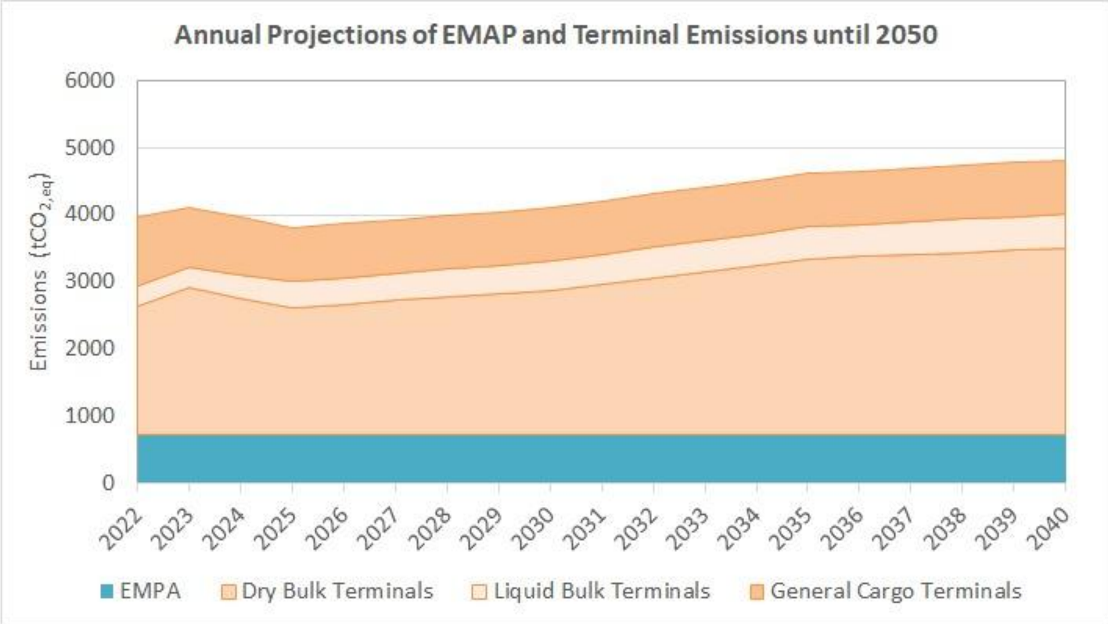
4.2. Terminals and EMAP projections

Between 2022 and 2050, with regard to the terminals, it was assumed that, without technological changes, emissions per unit of cargo handled would remain constant. Emission projections up to 2050 for operators and terminals were calculated considering traffic projections by cargo type (solid bulk, liquid bulk, and general cargo) and the emission index per ton of each type of cargo ($kgCO_2eq$/ton for solid bulk, liquid bulk, and general cargo).

Figure 21 presents the projection of annual Greenhouse Gas (GHG) emissions associated with the activities of EMAP and the leased terminals in the period from 2022 to 2050. As in the carbon footprint inventory, the projection considers emissions from stationary sources, mobile sources, refrigerant gases, fire extinguishers, and electricity consumption, generated both by EMAP's facilities and by the terminals located within the port's geographical boundaries.

It is observed that most emissions come from solid bulk terminals, which follow a gradual growth trajectory over the years. This segment concentrates the highest emission intensity, reflecting the dominant operational profile of the port complex. Liquid bulk and general cargo terminals show more modest but stable emissions, with a slight upward trend through 2050. Emissions directly attributable to EMAP remain practically constant throughout the entire period, considering that any growth in the coming years may be offset by currently planned decarbonization measures (replacement of the fleet with hybrid and electric vehicles, fuel substitution prioritizing ethanol and biodiesel, installation of solar panels). Thus, emissions remain below 1,000 tCO_2eq per year, which indicates a lower relative impact of the port authority compared to private operations.

Figure 21 - Annual emission projections of EMAP and the terminals until 2050.

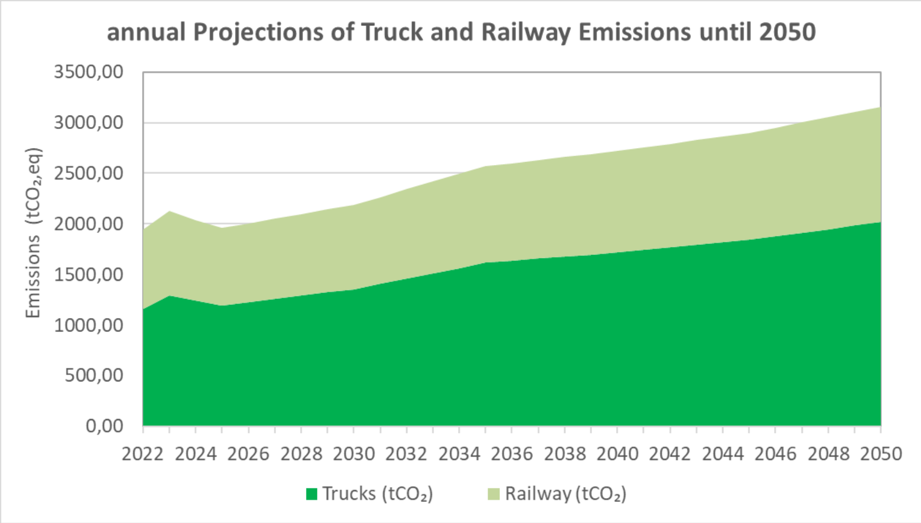


Source: Fundación Valenciaport.

4.3. Railways and trucks projections

In the period between 2022 and 2050, in the scenario without decarbonization actions, truck and rail emissions are expected to increase by 62%, a rise consistent with the increase in traffic. The distribution of emissions by mode remains reasonably constant, with a slight increase in the contribution of trucks, reaching 64% of this section.

Figure 22 - Annual emission projections of trucks and railways until 2050.



Source: Fundación Valenciaport.

4.4. Global Projections

Considering the traffic projections and assuming that no decarbonization measures are implemented by EMAP (BAU – Business as Usual scenario), a progressive increase in emissions is estimated until 2040. From that year onward, the maritime sector is expected to align with the International Maritime Organization (IMO) strategy, resulting in a significant reduction in emissions associated with ships and tugboats.

In this scenario, total emissions will reach around 105 thousand tons of CO_2 equivalent ($ktCO_2eq$) in 2040, with a sharp reduction to 14.6 $ktCO_2eq$ by 2050, due to the technological renewal of the fleet. Nevertheless, the main sources of residual emissions will remain associated with ships at berth, cargo handling operations, and road freight transport (trucks), requiring special attention in long-term mitigation strategies.

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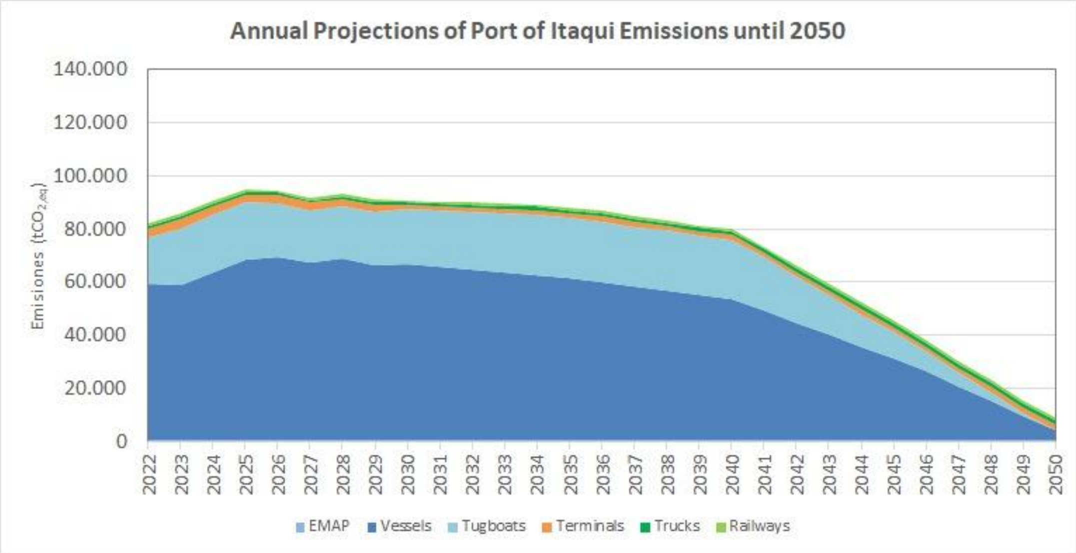
Figure 23 - Annual emission projections of the Port of Itaqui until 2050.



Source: Fundación Valenciaport.

5. Technologies Availability

The decarbonization of the port sector requires a transformation of current processes, equipment, and energy sources. In recent years, several technologies have emerged with the potential to significantly reduce Greenhouse Gas (GHG) emissions associated with port and logistics operations.

These solutions range from the electrification of vehicles and operational equipment, the use of low-emission alternative fuels, to the implementation of management systems and digitalization aimed at improving energy efficiency. Although many of these technologies are already available on the market and have shown positive results, their large-scale implementation still faces technical, economic, and regulatory challenges, which must be analyzed based on the specific characteristics of each port, its operational context, and territorial conditions.

The following sections present the main technological options currently available for the decarbonization of the different segments of the port environment.

5.1. Vessels

The technologies that can be applied are mainly three:

- **Onshore Power Supply (OPS):** consists of providing electrical power to ships while they are anchored or berthed, allowing them to switch off their auxiliary generators.
- **Use of alternative propulsion technologies:** such as hybridization with batteries or fully electric vessels.
- **Use of synthetic fuels, biofuels, or low-emission fuels.**

Figure 24 - Installation of a medium-voltage OPS system for cruise ships, Altona Terminal, Hamburg.

Source: Hamburg Port Authority.

Figure 25 - Example of low-emission alternative fuel (ammonia) (a), and hybrid propulsion with batteries (Ro-Ro, Grimaldi) (b).

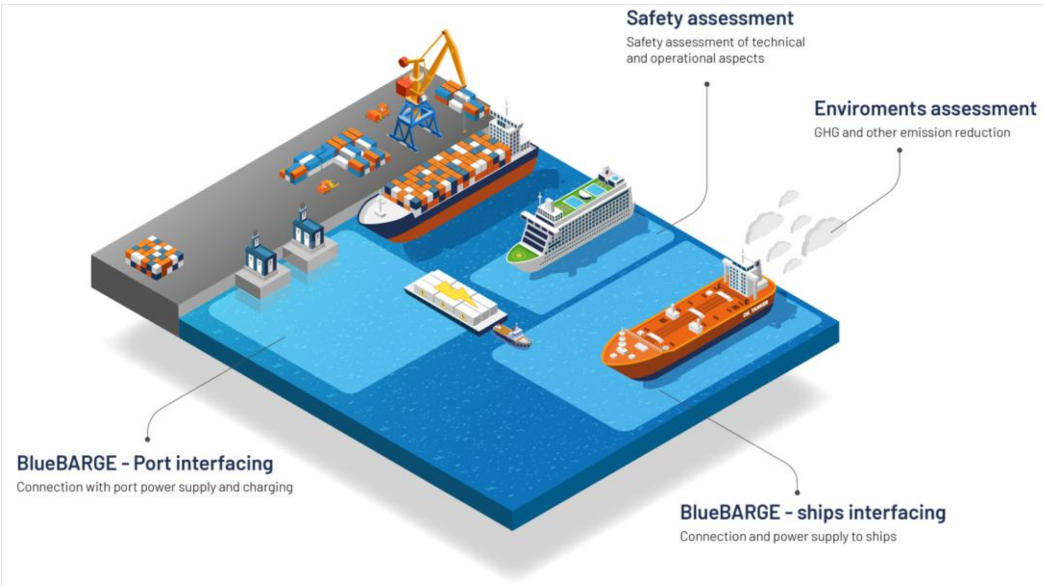
(a)
Source: Bioenergy International[1]

(b)
Source: Cadena de Suministro[2].

In the case of locations with difficult electrification, conventional OPS technology cannot be used, and the available alternatives are the use of supply barges (solutions such as BlueBARGE or Elemanta) or the deployment of submarine power cables (Stillstrom solution).

BlueBARGE: an innovative, optimized power-barge solution with energy supply modules in containers, designed to achieve at least 3 MW of discharge power and 35 MWh of energy capacity. Storage technology: battery energy storage systems based on lithium-ion and vanadium redox flow.

Figure 26 - Conceptual image of the BlueBARGE solution.



Source: Projeto BlueBARGE.[3]

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[1] *https://bioenergyinternational.com/ihi-jera-commence-worlds-first-large-scale-ammonia-co-firing-demo/*
[2] *https://www.cadenadesuministro.es/noticias/grimaldi-incorpora-a-su-flota-el-eco-malta_1393546_102.html*
[3] *https://bluebarge.eu/*

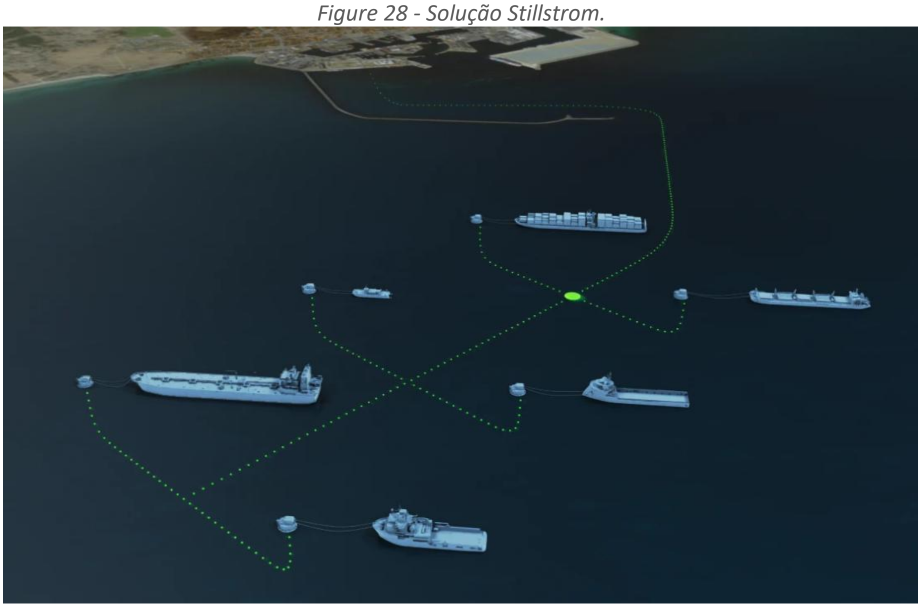
Elemanta: hydrogen fuel cell–based power barge designed to deliver between 1 and 5 MW of discharge power and up to 48 hours of autonomous energy capacity. Equipped with a 1 MW fuel cell and 1.5 tons of H_2 stored on board.

Figure 27 - Solução Elemanta (Hydrogen power Barge).

Source: HDF Energy[4]

Stillstrom: connection to the onshore grid or direct electrification, ensuring a reliable, sustainable, and constant power source for anchored vessels. It can be deployed to anchorage areas 2 and 3, providing simultaneous power supply to all vessels at anchor.

Figure 28 - Solução Stillstrom.



Source: Stillstrom.[5]

[4] *https://hdf-energy.com/*
[5] *https://stillstrom.com/*

5.2. Towage

One of the main strategies to advance the decarbonization of the maritime tugboat service is to improve the energy efficiency of existing vessels. This can be achieved through the hybridization of propulsion systems or the application of antifouling coatings that optimize hydrodynamic performance. To reach higher levels of emission reduction, it is necessary to consider the use of alternative fuels or even a complete transformation of propulsion systems.

- **Fuel consumption reduction:** Operational optimization and efficient maintenance directly contribute to reducing fuel consumption.
  - **Hybridization:** the integration of hybrid systems, combining diesel engines with batteries or electric motors, can reduce energy consumption by up to 18%, especially in low-demand operations or during short-duration maneuvers.
  - **Antifouling coatings:** these treatments applied to the hull prevent marine organism fouling, reducing water friction. Depending on the type of coating used, efficiency gains between 5% and 15% can be achieved.
- **Use of drop-in fuels:** These fuels can be used in existing engines with minimal adaptations, facilitating short-term implementation.
  - **Biodiesel and HVO:** when produced from waste oils, they can provide significant emission reductions, up to 90%. Brazil, with its strong agricultural capacity, especially in soybean and palm, has great potential for the production of these alternatives.
  - **Pyrolytic fuels:** produced from biomass. These are not yet commercially available.
- **New propulsion systems:** The feasibility of these technologies depends on the operational profile of each tugboat and its navigation patterns.
  - **Bio-LNG:** can provide emission reductions of up to 90%. In Brazil, initiatives in this direction are already being led by companies such as Petrobras and Raízen.
  - **Fully electric:** ideal for port operations or restricted areas, where travel distances are short, and adequate charging infrastructure is available.
  - **Hydrogen:** can be used both in combustion engines and in fuel cells, offering a zero-emission option at the point of use.
  - **Methanol:** a liquid alternative that allows relatively simple implementation and facilitates storage and handling.

- **Ammonia:** promises significant emission reductions, although it requires specific handling and safety systems due to its toxicity.

Currently, there is no alternative fuel that surpasses traditional fuels in all aspects; therefore, each option must be evaluated according to its specific application. FAME (Fatty Acid Methyl Ester) and HVO (Hydrotreated Vegetable Oil) are already commercially available options, although their higher cost requires technical and economic justification for use. In the case of the Port of Itaqui, ethanol — which already has a consolidated distribution chain — may represent a particularly attractive alternative. For other future initiatives with potential synergies, such as local production of ammonia or biomethane, specific feasibility studies are recommended for their use in tugboats.

5.3. Terminals

In the case of Itaqui, terminal operators mainly use equipment powered by diesel engines and, to a lesser extent, electric engines, with some of this equipment operating on non-renewable electricity. In addition, there is limited consumption of gasoline, LPG, and ethanol. All these energy sources generate Greenhouse Gas (GHG) emissions, contributing to climate change and the deterioration of air quality in the region.

The main strategies to reduce emissions from port equipment include the use of renewable electricity and fuel-related actions. This can be achieved in several ways, such as improving efficiency to reduce consumption, using "drop-in" fuels, or even proposing the complete replacement of the propulsion system or the type of equipment used.

Some options are:

- **Renewable electricity:**
  - Electric conveyor belts, refrigerated containers (reefers), and cranes operating with renewable electricity.
  - Electrically powered quay cranes of the MHC (Mobile Harbor Cranes) type.
- **Drop-in fuels:**
  - Biodiesel and HVO: Ideally produced from residual oils (up to 90%). Brazil is a major producer of soybean and palm.
  - Bio-LNG: Renewable-origin liquefied natural gas.
  - Pyrolytic fuels: Biomass-derived, not yet commercially available.
  - Ethanol: Used in blends such as E10 gasoline (with 10% ethanol).
- **Higher efficiency and new propulsion:**
  - Energy certification systems.
  - Hybridization of propulsion systems.
  - LPG (Liquefied Petroleum Gas).

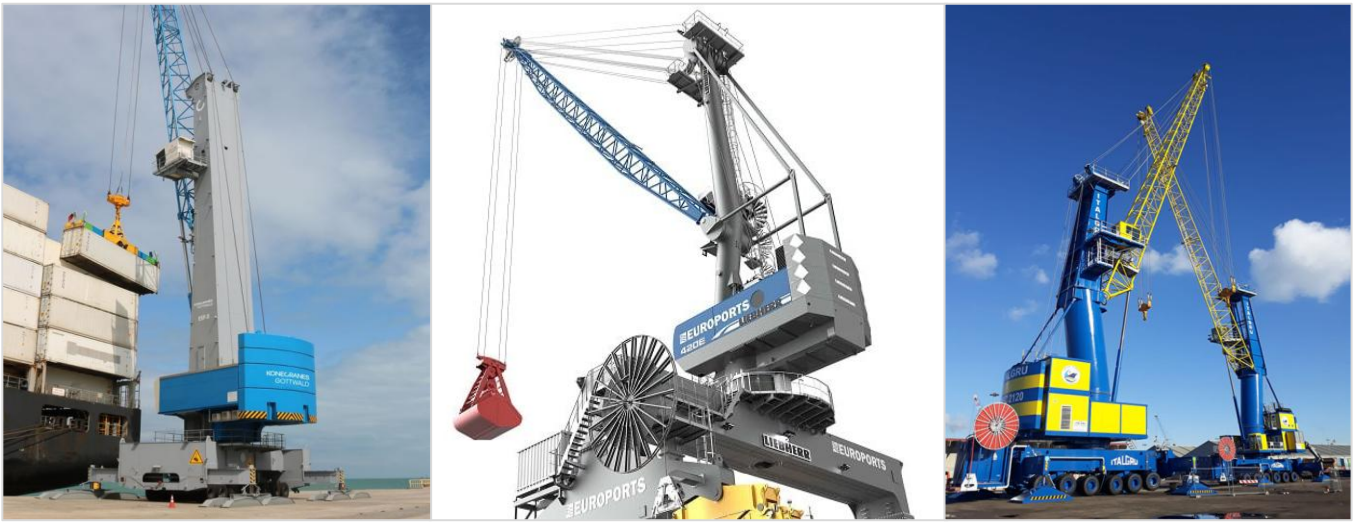
- Fully electric systems.
- Hydrogen (H_2) and Fuel Cells.

Below is an analysis of the main port equipment used in Itaqui from the perspective of low-emission alternatives.

Mobile Harbor Cranes

Since 2020, electrically powered Mobile Harbor Cranes (MHCs) have been made available by several major manufacturers and specialized companies in this type of equipment, such as Liebherr, Konecranes, Gottwald, Sennebogen, Italgru, and Palfinger Marine, among others. Some of the ports that already use electric MHCs are: Los Angeles (USA), Antwerp (Belgium), Rotterdam (Netherlands), Durres (Albania), Dar es Salaam (Tanzania), and Mormugao (India).

Figure 29 - Electric Mobile Harbor Cranes (MHCs).



Source: Konecranes[6] Liebherr [7] Italgru.[8]

Forklifts

Forklifts are mainly used for handling and storing general cargo in warehouses, depots, and cargo areas in ports, as well as for moving equipment or accessories such as generators or grabs.

Some alternative models to diesel-powered units are:

- **Toyota:** Model with electric battery (lithium-ion or lead-acid).
- **Hyster:** Electric model. Versions powered by hydrogen (H_2) are under development.
- **Still GmbH:** Electric model with lithium battery.
- **BYD:** Electric model with lithium iron phosphate batteries.

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[6] *https://www.marinelink.com/companies/konecranes-83436*
[7] *https://www.liebherr.com/es-int/gruas-maritimas/productos/equipamiento-de-puerto/gr%C3%BAas-p%C3%B3rtico/liebherr-portal-slewing-electric/lps-420-e-5391558*
[8] https://italgru.it/en/electric-port-cranes/mobile-harbour-cranes/imhc-2120-e

Figure 30 - Hyster electric forklift.

Source: Hyster.[9]

Reach Stackers (Container Handlers)

Reach stackers are forklifts specifically designed for handling containers. They are traditionally powered by diesel.

Some alternative models to diesel-powered units are:

- **Kalmar (Cargotec Group):** Electric version (batteries). They also offer hybrid and HVO options.
- **Hyster:** Electric version with lithium batteries or hydrogen (fuel cell).
- **Liebherr:** Electric version (plug-in or batteries).

Figure 31 - Kalmar battery-electric reach stacker

Source: Kalmar.[10]

Front-End Loaders (Wheel Loaders)

They are used in bulk solids operations for cereals and minerals. Traditionally, they are powered by diesel engines.

Some low-emission alternatives are:

- **Volvo CE:** Electric model (battery).
- **Caterpillar (CAT):** Battery-electric model (CAT is also testing hydrogen in other equipment).
- **Komatsu:** Electric model (battery).
- **John Deere:** Electric model (battery).

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[9] *https://www.hyster.com/es-es/emea/carretillas-elevadoras-electricas-de-4-ruedas/j10-18xd/*
[10] *https://www.kalmarglobal.com/news--insights/press_releases/2023/kalmar-hands-over-its-first-fully/*

Figure 32 - Volvo electric wheel loader.

Source: Volvo.[11]

Backhoe Loaders

Backhoe loaders are versatile equipment used in civil construction works, earthmoving, and handling of bulk solids. Traditionally, they operate with diesel engines, but lower-emission alternatives are available.

- **JCB:** Electric model. It also has a hydrogen-powered model.
- **CASE Construction:** Electric model.
- **Volvo CE:** Electric model under development.

Figure 33 - JCB hydrogen mini backhoe loader

Source: JCB.[12]

Other Port Equipment

Operators also need to perform other tasks and use other types of equipment that also have low-emission alternatives.

[11] *https://www.volvoce.com/espana/es-es/products/electric-machines/l120-electric/*
[12] *https://tinyurl.com/58baaphj*

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- **Konecranes:** Electric RTG (Rubber-Tired Gantry) and HVO/biodiesel.
- **Terberg:** Electric terminal tractor.
- **MAN Truck & Bus:** Electric trucks for ports.
- **Scania:** Trucks with biogas (Bio-LNG) or HVO engines.

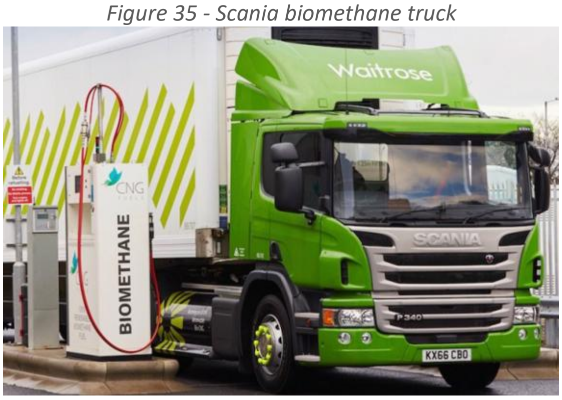
Figure 34 - Terberg electric truck

Source: Terberg.[13]

Finally, as a summary, the alternative fuels that can be used in cargo handling operations in ports include biodiesel, liquefied natural gas (LNG), hydrogen, pyrolytic fuels, and renewable electricity. These fuels contribute to the reduction of greenhouse gas (GHG) emissions and to improving sustainability in port operations. Some manufacturers that already have commercially developed equipment for these fuels include Liebherr, Konecranes, Kalmar, Scania, and others:

- **Electric (batteries):** Most common option (e.g., Kalmar, Volvo, CAT).
- **Hydrogen (H_2):** Under development (Hyster, JCB).
- **With HVO/Biodiesel:** Used in modified diesel-powered equipment (Kalmar, Konecranes).
- **Bio-LNG:** For trucks and heavy machinery (Scania, IVECO).
- **LPG/CNG:** Less common in ports, but used in some forklifts.

Figure 35 - Scania biomethane truck



Source: Interchange UK [14]

[13] *https://www.terbergtaylor.com/assets/TTA_PRODUCT_LINE.pdf*
[14] *https://www.interchange-uk.com/news/stbs-launch-alternative-fuels-strategy-for-the-south-west*

5.4. Trucks

In the short term, it is strategic to prioritize actions aimed at improving fleet characterization and increasing the operational efficiency of the sector. Next, it is recommended to move forward with the progressive replacement of fuels and, finally, to assess the adoption of low- or zero-emission truck technologies.

Fuel consumption reduction

- Better sector characterization.
- Business Assistance Program.
- Truck Certification Systems.
- Triple trailer.

Drop-in fuels

- Biodiesel and HVO.
- Ideally from used oils (up to 90%).
- Brazil is a powerhouse in soybean and palm.

New propulsion

- Bio-LNG. Requires a refueling network. IVECO S-Way Natural Power and Scania CNG/LNG. (20%).
- Fully electric. Short distances. Volvo, Mercedes-Benz, and Scania.
- Refueling networks.

Assistance services are an option that allows significant reductions without major investments by transport companies. This tends to have good social acceptance and interesting results: for example, the French program "Objectif CO_2.

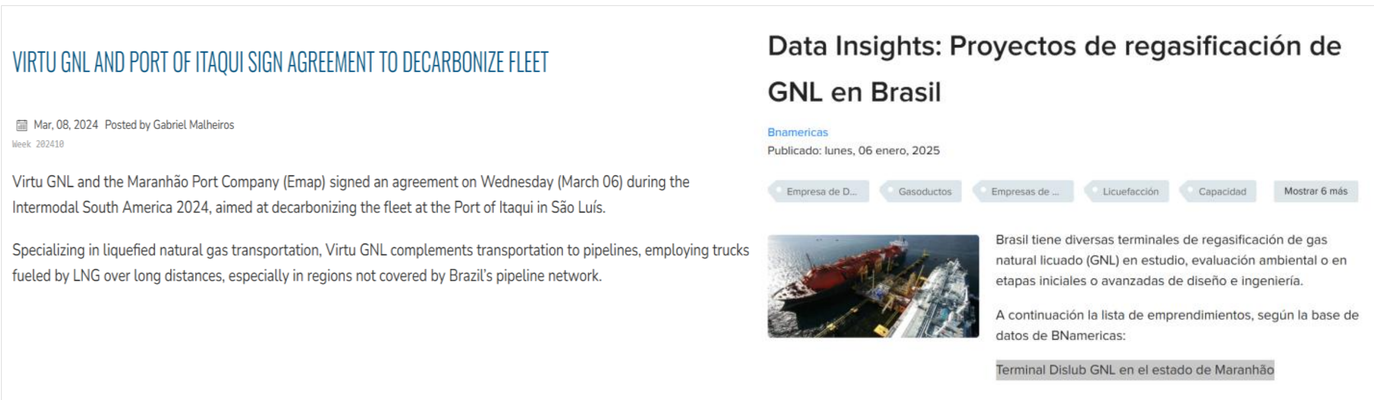
Figure 36 - French program Objectif CO_2.

Source: Objectif CO_2

Currently, the infrastructure of Liquefied Natural Gas (LNG) refueling stations for trucks in Brazil is under development and remains limited. There is no exact number of LNG stations in operation in the country, as public information is scarce and projects are at different stages of implementation.

In the state of Maranhão, specifically, there are currently no LNG refueling stations for trucks in operation. However, there are ongoing initiatives that may change this scenario in the future. For example, the company Virtu LNG has acquired 30 LNG-powered trucks to operate in the state, which indicates a possible expansion of the refueling infrastructure in the region.

Figure 37 - Decarbonization initiatives with LNG.



VIRTU GNL AND PORT OF ITAQUI SIGN AGREEMENT TO DECARBONIZE FLEET

Mar, 08, 2024 Posted by Gabriel Malheiros
Week 202410

Virtu GNL and the Maranhão Port Company (Emap) signed an agreement on Wednesday (March 06) during the Intermodal South America 2024, aimed at decarbonizing the fleet at the Port of Itaqui in São Luís.

Specializing in liquefied natural gas transportation, Virtu GNL complements transportation to pipelines, employing trucks fueled by LNG over long distances, especially in regions not covered by Brazil's pipeline network.

Data Insights: Proyectos de regasificación de GNL en Brasil

Bnamericas
Publicado: lunes, 06 enero, 2025

Empresa de D... | Gasoductos | Empresas de ... | Licuefacción | Capacidad | Mostrar 6 más

Brasil tiene diversas terminales de regasificación de gas natural licuado (GNL) en estudio, evaluación ambiental o en etapas iniciales o avanzadas de diseño e ingeniería.

A continuación la lista de emprendimientos, según la base de datos de BNamericas:

Terminal Dislub GNL en el estado de Maranhão

Source: World Cargo News; BNAmericas.

5.5. Railways

Actions related to the decarbonization of trains have three main axes: operational improvement, fuel and efficiency, and electrification. Considering the low degree of electrification of the external rail network, the electrification of the railway network does not present significant interest. The options with greater potential would be operational improvement, hybridization, and the use of renewable fuels.

Operation

- Optimization of rail traffic with artificial intelligence.
- Reduction of locomotive idle time.
- Real-time characterization of locomotive fuel consumption and emissions.

Fuels and efficiency

- Implementation of hybrid locomotives with lithium batteries for operations within the port area.
- Use of regenerative braking for battery recharging.
- Biodiesel and HVO, ideally from residual oils (up to 90%). Brazil is a powerhouse in soybean and palm.

New propulsion

- Electrification of the railway network within the port, with public-private partnerships to finance electrification.
- Use of Bio-LNG.
- Tests with locomotives powered by green hydrogen, integrating H_2 production into the energy matrix of the Port of Itaqui.

5.6. Photovoltaic potential and storage study

The specific objectives of this study are to identify the areas within the port with the greatest potential for the installation of solar panels, quantify the solar power generation capacity, and define the technical parameters for its implementation. In addition, the short- and long-term energy storage needs will be assessed to optimize the use of the generated energy.

Finally, the potential for local hydrogen production will be analyzed, and technological and infrastructure solutions for its storage and use will be proposed, in line with the energy needs of this energy vector foreseen in the present Decarbonization Plan of the Port of Itaqui.

5.6.1. Solar potential

The objective of this study is to analyze the potential for photovoltaic solar generation at the Port of Itaqui and in its areas of influence, specifically considering the feasibility of installing solar systems on administrative building rooftops, parking areas under renovation, and other areas managed by Empresa Maranhense de Administração Portuária (EMAP) outside the port perimeter, such as the passenger terminal or adjacent land.

Given the high solar irradiation characteristic of the state of Maranhão and the port's commitment to decarbonization and energy sustainability, this analysis aims to identify concrete opportunities for the use of solar energy as a clean and strategic source for supplying its operations.

To estimate the solar generation potential in the identified areas of the Port of Itaqui, a methodology was applied based on the analysis of available surface area, average annual solar irradiation data, and photovoltaic system efficiency. First, a preliminary estimate of the usable surfaces on administrative building rooftops, parking structures, and viable external land plots was carried out using satellite images and port layouts. Subsequently, the average annual solar irradiance in São Luís was considered, ranging from 3.03 (March) to 5.49 (August) kWh/m²/day, with an annual average of 4.366 kWh/m²/day [1], as well as an average system efficiency between 15% and 18% [2], taking into account losses due to temperature, orientation, shading, and conversion. These parameters allow for the calculation of the theoretical annual energy production for each type of area and the assessment of its potential contribution to the port's electricity consumption.

Figure 38 - Irradiation considered for the Port of Itaqui.

Daily Total Averages of the Direct Normal Irradiation for the State of MARANHÃO

(Wh/m².day)

Show 10 entries — ---- Insert ID ---- Search: 61200

ID	Lon	Lat	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
61200	-44.249	-2.5005	4355	3902	3487	3032	3105	3804	4679	4990	5496	5378	4722	4804	4863
ID	Lon	Lat	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

Source: Fundación Valenciaport.

Identification of Areas Suitable for the Installation of Photovoltaic Panels

Three main categories of spaces were considered:

- Administrative building rooftops: Flat or slightly inclined surfaces, generally free of obstructions and with nearby electrical infrastructure. Priority was given to the rooftops of central administrative buildings, technical rooms, and logistics warehouses.

- Parking areas under renovation: The installation of carport-type photovoltaic structures in parking areas is doubly efficient, as it generates renewable energy while also providing shade and thermal comfort for vehicles. The selected areas include parking lots for operational staff, visitors, and service fleets, currently undergoing renovation or expansion.

- Areas outside the port perimeter: Land outside the immediate port boundary, but under the management of EMAP or the Government of the State of Maranhão, such as decommissioned logistics areas, railway yards, or adjacent plots. These locations represent opportunities for the deployment of larger-scale solar plants.

Initial Planning: Internal Areas

The procedure for sizing the areas followed a sequential process. First, the available area in zones under the direct control of EMAP was determined. These zones were classified as typologies 1 and 2 and define the space available for the installation of photovoltaic generation in the short term.

Figure 39 - Available area in controlled zones.

Source: Fundación Valenciaport.

After a detailed analysis of the infrastructures and available surfaces within the Port of Itaqui premises, it was determined that the potentially usable area for the installation of photovoltaic panels is 14,810 m². This surface is distributed between 7,320 m² corresponding to administrative and logistics building rooftops, and 7,490 m² in parking areas currently undergoing renovation.

To more accurately reflect the truly usable fraction, adjustment factors of 80% were applied to rooftops (considering obstacles, slopes, or inaccessible zones) and 90% to parking areas (due to structural layout and spacing between rows).

As a result, the estimated net usable surface for the installation of solar panels is 12,597 m², which constitutes the basis for sizing the photovoltaic plant within the port perimeter.

Expanded Planning: External Areas Outside the Port Perimeter

Following the analysis of the available surface within the Port of Itaqui premises, it was estimated that it is possible to install a photovoltaic system of approximately 6.7 MWp over a total of 12,597 m² of usable area, distributed between building rooftops and parking areas.

However, this capacity represents only a fraction of the technical injection potential allowed by the existing electrical infrastructure, in particular the substation equipped with a Schneider Electric SM6 medium-voltage modular cell, configured to operate at 13.8 kV with a rated current of 630 A.

Therefore, this study proposes, as a first step, maximizing photovoltaic generation until exhausting the capacity of the internal distribution network of the Port of Itaqui.

By combining the already identified internal surfaces with new complementary external areas, it becomes possible to reach this capacity without the need to modify the existing medium-voltage infrastructure. This design strategy not only maximizes the use of already available assets but also optimizes the energy and economic return of the system, by spreading the fixed infrastructure investment over a larger volume of renewable generation, thus avoiding higher investments in internal grid upgrades.

Requirements for External Areas

These external areas must meet a series of technical, operational, and legal requirements, including the following:

- **Public ownership or availability of use:** Priority should be given to land belonging to the Government of the State of Maranhão or managed by EMAP, such as former logistics areas, decommissioned rail yards, or areas near the passenger terminal.
- **Proximity to the port's electrical infrastructure:** To minimize losses and facilitate connection to the common delivery point at the SM6 substation, it is recommended that the external plant be within a maximum distance of 1.5 to 2 km from the load center.

- **Topographic and irradiation conditions:** The land must have low slope, shadow-free orientation, accessibility for installation machinery, and low exposure to flooding, which is common in some areas near the port.
- **Connection feasibility:** It will be necessary to design a medium-voltage connection, preferably overhead or underground depending on technical feasibility, to the available cell of the existing substation, adequately sizing protections and sectionalizers in accordance with NBR 14039 (medium-voltage electrical installations).

The table below presents a summary of the technical characteristics of the proposed installations.

Table 2- Technical characteristics of the proposed installations.

Parameter	Internal installation	External installation
Effective available surface area (m²)	12.597	14.340
Maximum installed capacity (kWp)	6.676	7.600
Number of modules (550 W)	12.138	13.818
Estimated minimum annual production (kWh)	3.011.168	3.427.812
Estimated maximum annual production (kWh)	3.613.402	4.113.375

Source: Fundación Valenciaport.

The estimated maximum production is **7,726,777 kWh per year.**

5.6.2. Storage Need

During 2022, EMAP recorded a total energy consumption of 2.6 GWh, according to data provided by the port authority. This value corresponds to the set of operational and administrative facilities within the premises served by EMAP.

This consumption volume makes it possible to establish a first approximation of the energy magnitude of the complex, which can be considered moderate in industrial terms, opening the way for a strategy of partial or even total coverage through renewable generation sources.

The photovoltaic system proposed for installation at the port, with a total capacity of 14.3 MWp, was modeled with site-specific climatic data using the PVGIS software. Based on this model, an annual production between 6,438,848 and 7,726,618 kWh was estimated, depending on the effective system efficiency (estimated range between 15% and 18%).

The direct comparison between the estimated production and the recorded consumption allows for the extraction of some key conclusions:

- The projected plant would generate between 2.47 and 2.97 times the port’s current consumption.
- This implies a significant energy surplus, which will require careful evaluation of surplus management scenarios.

- Under a direct self-consumption scheme, the installation could cover 100% of the current demand managed by EMAP, including during the months of lower solar irradiation.

Technical study on storage potential (Scenarios)

With the objective of rigorously and realistically assessing the techno-economic feasibility of harnessing photovoltaic solar energy at the Port of Itaqui, this study was structured into two differentiated case studies.

This division responds to the need to compare the performance, impact, and profitability of different renewable generation implementation strategies, taking into account both the physical limitations of the port environment and the current tariff and technological framework.

Based on generation profiles and considering the reference demand (initially assumed as uniformly distributed), the economic optimization of battery sizing will be carried out, under the following assumptions:

- The projected generation in this case allows covering a substantial portion of the port's current electricity consumption through direct self-consumption, significantly reducing the energy bill, with an estimated avoided energy cost of R$ 0.711 per kWh, according to the industrial tariffs in force in the State of Maranhão.
- However, due to the limitation of available surface area, this solution does not allow for the full use of the photovoltaic potential of the site, nor the complete coverage of port demand in certain periods. Additionally, the hourly generation curve does not always coincide with the consumption curve, highlighting the need to consider complementary energy storage options to improve the self-sufficiency index.
- Given the current cost of stationary battery storage, estimated at R$ 2,000 per kWh installed [13], this case analyzed the optimal battery capacity that allows shifting solar energy from peak generation hours to peak demand hours, without incurring unjustified oversizing.
- The balance between the investment cost in storage and the savings generated by the reduction of grid energy consumption is crucial to determine the final feasibility of this scenario.
- The optimization goal is to maximize the Net Present Value (NPV) of the investment, considering an internal discount rate of 4%.

To carry out the optimization, a battery optimization tool developed by Fundación Valenciaport was used.

Case Study 1: photovoltaic installation on EMAP-owned buildings and parking areas

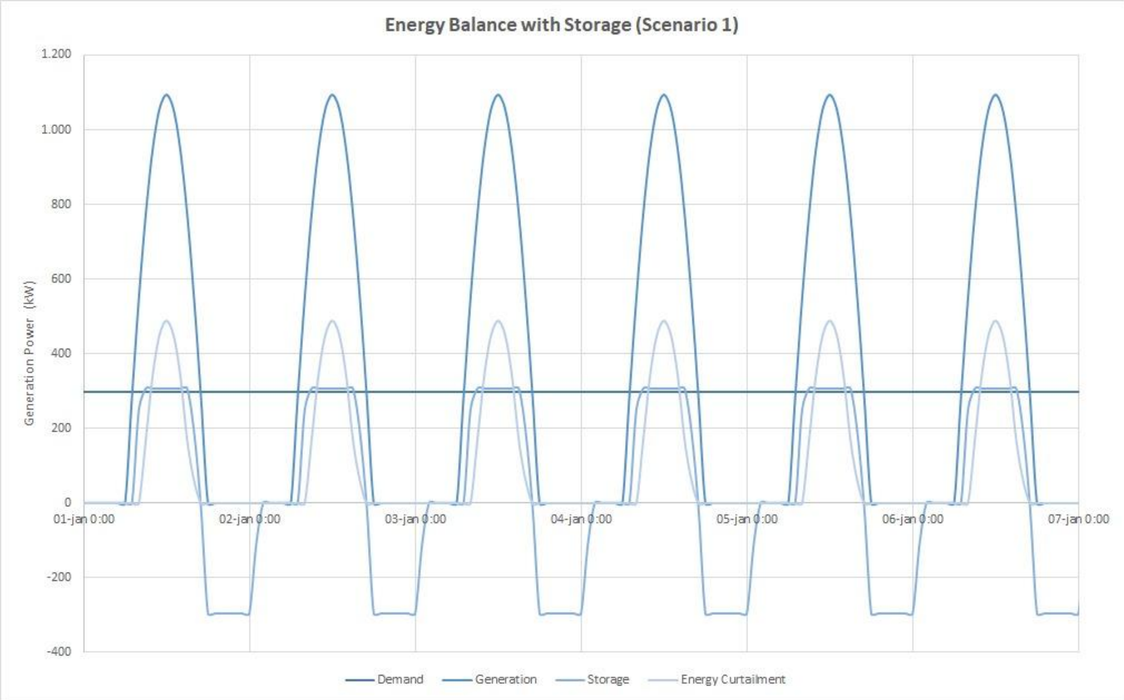
In this first scenario, only the installation of photovoltaic systems on the rooftops of administrative buildings and in the parking areas previously identified as technically feasible within the port premises is considered. This option represents a strategy of using already urbanized areas, with minimal soil impact, lower licensing complexity, and maximum architectural integration.

For the first case study, we obtained an optimized storage capacity of 307 kW, which implies an investment of R$ 614,559 for battery acquisition. This generates an annual saving on electricity purchases of R$ 565,458.

In addition, there is a reduction in renewable energy curtailment (due to the inability of the grid to absorb all generation), decreasing from 2,030 MWh (equivalent to 63% of generation) to 1,094 MWh (34%). Installation maintenance costs are estimated at R$ 21,249.

The following chart presents the projected energy balance for the first week of the base year considered:

Figure 40 - Energy balance with storage (Scenario 1).



Source: Fundación Valenciaport.

Case Study 2: photovoltaic installation considering full-scale deployment

In the second scenario, the scope of the photovoltaic installation is expanded with the inclusion of an additional ground-mounted plant, located in areas outside the immediate port premises but still within the management area of the port authority or the State Government, such as adjacent yards or logistics expansion zones.

This alternative makes it possible to achieve a significantly higher installed capacity, which not only ensures full coverage of the port’s current consumption but also enables new vectors of energy use, such as:

- Green hydrogen production.
- Electrification of port equipment.
- Power supply to third parties.

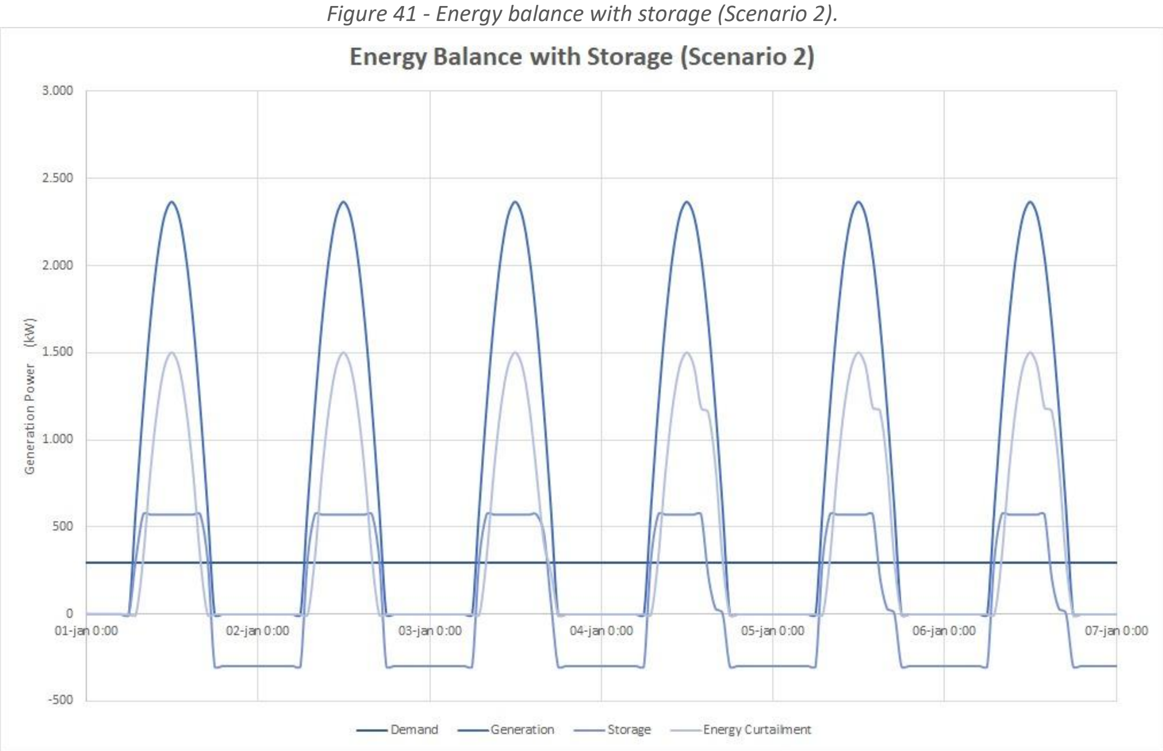
This greater generation capacity inevitably produces a higher volume of daily solar surpluses, making the need for electrical storage more relevant. However, the possibility also arises of using part of this additional energy for flexible uses such as hydrogen production, nighttime charging, or refrigeration systems, which reduces pressure on the battery system.

Thus, this case allows not only the assessment of a large-scale energy utilization strategy but also progress toward a model of integral energy self-sufficiency and distributed generation with added value.

For the second case study, an optimized storage capacity of 568 kW was obtained, implying an investment of R$ 1,136,227 for battery acquisition. This generates annual electricity savings of R$ 996,755. Renewable energy curtailment (due to the grid's inability to absorb all generation) is reduced from 5,757 MWh (equivalent to 82% of generation) to 4,105 MWh (59%). Installation maintenance costs are estimated at R$ 46,041, proportional to the scale of the proposed solution.

This result shows that, even with optimized storage, a significant portion of the renewable energy generated cannot be utilized without adopting new system flexibility measures. The following chart presents the projected energy balance for the first week of the base year considered:

Figure 41 - Energy balance with storage (Scenario 2).



Source: Fundación Valenciaport.

In comparative terms, the first case presents better relative efficiency in energy utilization, with lower investment and a higher proportion of self-consumption.

On the other hand, the second case, although less efficient from the standpoint of relative energy use, makes it possible to achieve higher absolute volumes of energy utilized and greater total savings, thanks to the larger scale of installed solar generation.

Both scenarios demonstrate the technical and economic feasibility of combining solar generation with electrical storage in the port environment. However, they also highlight the need to develop complementary strategies, such as the use of green hydrogen, the electrification of equipment, or the implementation of microgrids, to take advantage of the renewable energy surplus that cannot be absorbed by the grid or efficiently stored.

5.7. Renewable hydrogen

The study on local renewable hydrogen production at the Port of Itaqui made it possible to size a 1 MW electrolysis plant partially powered by solar energy, capable of producing up to 450 kg of green hydrogen per day. This production is proposed as a strategic solution to decarbonize logistics operations, supply port machinery, and generate a new complementary energy vector, making use of photovoltaic surpluses not directly consumed by the grid.

Figure 42 - Hydrogen refueling station of the H2Ports project located at the Port of Valencia

Source: Fundación Valenciaport.

The system includes low-pressure storage to cover a full day of operation, as well as a replicable refueling station based on the H2PORTS model. The economic analysis, considering local electricity prices and the estimated investment, places the Levelized Cost of Hydrogen (LCOH) between R$ 48 and R$ 60 per kg.

Table 2 - Technical Parameters of Hydrogen Production

Parameter	Value
Electrolyzer capacity	1 MW
Maximum hydrogen production	450 kg/day
Specific electricity consumption	12.138
Improvement in electricity utilization	+14.9% / +21.4%
Estimated LCOH (Levelized Cost of Hydrogen)	R$ 48 – R$ 60

Source: Fundación Valenciaport.

5.8. Compensation

Once mitigation measures are applied, a residual volume of emissions may remain which, due to the specific characteristics of port activities, is difficult to eliminate. In such cases, compensation mechanisms can be considered.

Emission offsetting refers to the process of acquiring carbon credits generated by projects that absorb or avoid the emission of Greenhouse Gases (GHG), with the aim of offsetting the emissions that an organization cannot reduce.

Each carbon credit represents 1 metric ton of CO_2 equivalent (tCO_2eq) that has been avoided or absorbed through a certified project. If an organization offsets the entirety of its carbon footprint for a given year, it may be considered carbon neutral for that period.

There are different levels of commitment that a port authority can assume in relation to emission offsetting, depending on the role it plays—from facilitating access to carbon credits for the various organizations operating in the port, to generating its own offset credits.

Table 3 - Roles of a Port Authority in Emission Offsetting

Role	Promoter	Aggregator	Facilitator
Description	**Investment in absorption projects outside the port area**	Intermediary between project developers/brokers and the port community	Maintenance of a CO_2 credit trading portal for port users
Activities	- Project identification - Investment and maintenance - Certification	- Identificação de projetos - Cessão/venda de créditos - Criação e manutenção de plataforma de compra e venda	- Criação e manutenção de plataforma de compra e venda

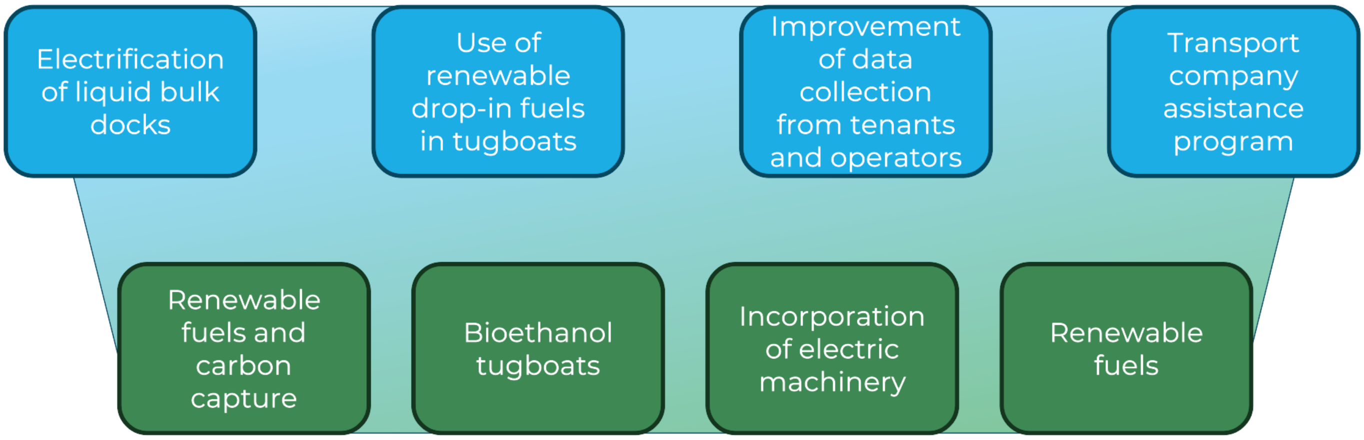
Role	Promoter	Aggregator	Facilitator
	- Assignment/sale of credits - Creation and maintenance of trading platform		
Resources	- Full-time port authority team - Tenders: • Audits • Platform	- Part-time port authority team - Tenders: • **Promoter/broker** • **Platform**	Tender for market development

Source: Fundación Valenciaport.

6. Action Plan

The decarbonization plan of the Port of Itaqui establishes a strategic objective of action for each of the short-term (2025–2035) and long-term (2035–2050) segments. In the short term, actions are proposed that take into account technologies already available for ships and tugboats, combined with soft measures in terminals and land transport. In the long term, the plan proposes increasing the presence of renewable fuels and electrification.

Figure 43 - Main actions suggested for the decarbonization of the Port of Itaqui.



Source: Fundación Valenciaport.

6.1. Actions Identified – EMAP

The possible actions were discussed in collaboration with various EMAP departments and were taken into consideration in the plan's actions.

• **Discount (Bonus)**

o Related to the ISP (Port Sustainability Index).

o Bonus through concession or tariff.

• Address sustainability criteria in upcoming bids.

• Implementation of systems for energy supply to berthed vessels (OPS).

• Define performance and action points aimed at sustainable improvements in the port.

• Implementation of a berth management system.

o Clear rules for berthing and operation.

o VTMIS.

• Inclusion of ferry boats in management and sustainability systems.

• Expansion of EMAP's sustainable fleet.

6.2. Vessels

OPS in liquid bulk terminals

It is recommended to electrify the liquid bulk berths. The OPS standard (IEC/IEEE 80005-1) recommends medium-voltage power supply infrastructure for power demands above 1 MVA. However, for demands above 500 kW, considering the increase in vessel size and the possible conversion of boilers to electric systems, this study recommends medium-voltage OPS supply infrastructure (6.6 kV). The following table presents the estimated power values for each berth, along with the gross tonnage (GT) and length data of the vessels that called at the port in 2022.

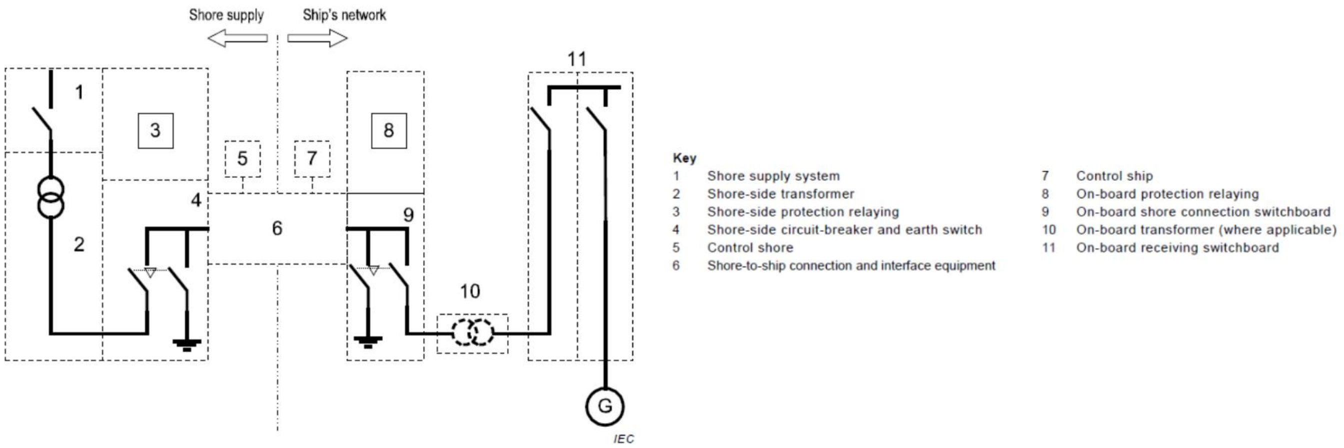
Table 4 - Data of liquid bulk vessels that called at berths 104, 106, and 108 in the year 2022.

Vessels	Calls	P_{aux} (kW)	$P_{boilers}$ (kW)	P_{total} (kW)	GT	Length (m)
104	181	790	1350	2140	14900-36200	162-184
106	97	800	4000	4800	57000-66000	243-252
108	120	790	1350	2140	12700-54100	164-230

Source: Fundación Valenciaport

The minimum total required capacity is 9.08 MW, which, considering the reactive power component, reaches a value of 9.08/0.8 = approximately 11.35 MVA.

Figure 44 - General scheme of medium-voltage OPS connection.



Source: IEC 80005-1. High Voltage Shore Connection. General Requirements.

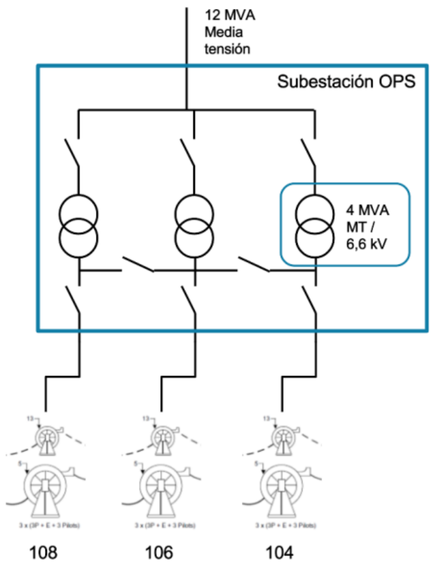
The IEC/IEEE 80005-1 HVSC (High Voltage Shore Connection) standard indicates, in its Annex F of additional requirements for tankers, that the ship connection must be made with three cables. Each cable must have three phases, ground, and three pilot lines. Each cable must also have a rated capacity of 3.6 MVA. Upstream of the connection, the transformer substation for the 6.6 kV supply must have a minimum total rated capacity of 11.35 MVA.

OPS infrastructure required for the electrification of liquid bulk docks. It is proposed to install a single OPS substation, with a rated capacity of 12 MVA, to supply OPS at the three berths (104, 106, and 108). The installation requires a medium-voltage supply line with 12 MVA of contracted power.

The following characteristics are recommended for the OPS substation:

- The substation must include at least three grounded transformers to ensure galvanic isolation in the three supply lines for the berths.
- In addition, it must include a switchboard for operation and protections.
- If the vessels' electrical network is at 60 Hz, a frequency converter is not required.
- Option to include steering to allow the total power to be used at one, two, or three berths simultaneously.

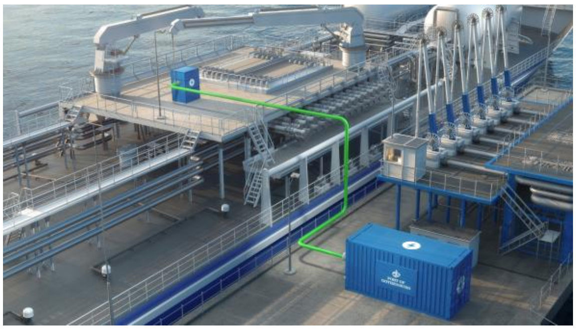
Figure 45 - Simplified diagram of electrical infrastructure for OPS supply to berths 104, 106, and 108.



Source: Fundación Valenciaport.

The emission reduction potential of the electrification of berths 104, 106, and 108 depends on the percentage of OPS installation in vessels and the electrification of boilers. Assuming that the berths in 2022 were used at their full potential, the maximum reduction potential will reach 40.2 kt (8.5 kt from auxiliary generators and 31.7 kt from boilers).

Figure 46 - Example of OPS installation for tankers: The Green Cable project for tankers at the Port of Gothenburg.



Source: Port of Gothenburg.[15]

Budget

In Europe, the cost of installing the OPS system, from the OPS substation to the cable management system on the quay, is approximately 900 thousand euros per MVA installed, including a frequency converter. If the converter is not required, the cost can be reduced by half: 450 thousand euros per MVA installed. Therefore, for the proposed installation, the budget would be:

12 MVA x 450 k€ = 5,4 M€

This calculation does not include the medium-voltage supply line. The infrastructure included is from the OPS substation to the cable management systems at the three berths.

Other Actions

It is recommended to start with the improvement of data collection in berth requests (preparation for OPS and fuel consumed) and to improve berth management. In a second stage, it will be necessary to upgrade the electrical grid with the installation of a medium-voltage network, which will require a detailed study of the grid. Finally, it is necessary to seek benefits for shipping companies that use decarbonized options or a berth priority system.

Table 5 - Lista de ações para navios.

#	Action	Budget (MR$)	Potential reduction/year (kt CO_2)	Start	End	Department
N1	Improvement in data collection of calls	0,6	0	1M26	2M26	Operations, Digitalization
N2	Implementation of a call management system	0,3	0	2M26	1M27	Operations, Digitalization
N3	Research on preparing Itaqui's power grid	2	0	2M26	1M27	Infrastructures
N4	Medium voltage grid (12 MW)	35	0	2M26	2M27	Infrastructures
N5	Electrification of liquid bulk berths	33,2	15,6	1M27	2M28	Infrastructures

[15] *https://www.portofgothenburg.com/about/projects/ops-tankers/*

#	Action	Budget (MR$)	Potential reduction/year (kt CO_2)	Start	End	Department
N6	Tariff discount for ships using renewable fuels	14	3,5	1M27	2M40	Operations
N7	Priority berthing system for low-carbon ships	0,24	1,3	1M27	2M50	Operations

Source: Fundación Valenciaport.

The actions N5 and N6 must be considered with two levels of ambition in the definition of scenarios. In the conservative scenario, action N5 will consider only the electrification of pier 104, while in the optimistic scenario both pier 104 and 106 will be electrified. For action N6, different results obtained through tariff reductions are considered. In the conservative scenario, the reductions achieved are 2.5%, while in the optimistic scenario they are 5%.

A significant part of vessel emissions comes from the anchorage area (in 2022 they amounted to 95.8 kt CO_2eq, mainly due to solid bulk). Although it is debatable whether it is an area where actions are recommended, two options are presented that may be of interest and the potential savings identified. In the case of anchorage zones 4, 5, and 7, by selecting vessels with a draft of less than 11 m, total emissions are 9.05 kt CO_2eq.

Table 6 - Proposed action for ships in the anchorage area

#	Action	Budget (MR$)	Potential reduction/year (kt CO_2)	Start	End	Department
N0	OPS for anchored ships	18/30	2,8	1M40	2M50	Infrastructures

Source: Fundación Valenciaport.

For these anchorage areas closer to the port, “power-barge” based solutions are proposed:

BlueBARGE Solution:

- Maximum supply per call: energy used by anchored auxiliary generators – maximum supply capacity (35 MWh).
- One barge can only serve one vessel at a time, then recharge or swap the battery.
- The resulting emissions from auxiliary consumption for vessels with a draft of less than 11 m are 2.34 kt CO_2. The maximum that could be reduced is 2.79 kt CO_2. This is equivalent to 2.95% of the total CO_2eq emissions at the anchorage per year.

Elemanta Solution:

- Maximum supply per call: energy used by anchored auxiliary generators – maximum supply capacity (48 MWh).

- One barge can only serve one vessel at a time and then refuel H_2.

- The resulting emissions from auxiliary consumption for vessels with a draft of less than 11 m are 1.73 kt CO_2. The maximum that could be reduced is 3.46 kt CO_2eq. This is equivalent to 3.61% of the total anchorage emissions per year.

6.3. Tugboats

By promoting antifouling systems, it is possible to improve the performance of tugboats. This requires the implementation of an inspection and certification system to validate the savings obtained.

- **Monitoring**
  o Use of hull sensors to measure the accumulation of marine organisms.
  o Historical data analysis.

- **Emission Reduction**
  o Depends on the technology: 5% (basic) and 12% (low-friction silicone).
  o Savings of up to 3,700 t per year (12% of consumption).

- **Associated Costs**
  o Inspection cameras (R$ 58,000).
  o Personnel for inspection.
  o Discounts on port fees.

- **Evaluation**
  o Antifouling certification with maneuver consumption history.

It is estimated that 6 new tugboats will be needed in operation by 2040. Although the current fleet is quite numerous, which implies a low number of maneuvers per tugboat, it is necessary to consider the possibility that the tugboats will also operate at the Ponta da Madeira terminal and in Alumar, which reduces the available working hours. If it is possible to apply sustainability criteria in new port service tenders, it can be proposed that the new acquisitions be zero-emission. Based on cost data for electric tugboats acquired in 2022 by the company Saam Towage, between USD 8.8 million and USD 12 million, a value of USD 10 million per tugboat is assumed, which may imply an additional cost of 100%. The emission reduction potential would be approximately 1,000 tons per tugboat.

Table 7 - Estimate of Maneuvers/Tugboat.

Year	Calls	Tug maneuvers	#Tugs	Man./Tug
2022	997	4543	24	190
2040	1445	6584	30	220

Source: Fundación Valenciaport.

Table 8 - Estimate of Consumption with Electric Tugboats.

MDO (tn)	CO_2 (tn)	
9153,113	29344,88	Without electrification
7322,49	**23475,90**	6 electric tugboats

Source: Fundación Valenciaport.

In the short term, performance improvement is proposed through the promotion of antifouling and electrification during idling. In the medium term, the activity will be decarbonized in accordance with the IMO strategy.

Table 9 - Proposed Actions for the Decarbonization of the Sector.

#	Action	Budget (MR$)	Potential reduction/year (kt CO_2)	Start	End	Department
R8	Working group for tugboat decarbonization	0,78	0,55	2M25	2M40	Environment
R9	Biofouling monitoring programs	0,26	3,34	2M26	2M27	Environment / Operations
R10	Electricity supply during waiting	3,15	1,59	1M27	2M27	Environment

Source: Fundación Valenciaport.

6.4. Terminals

Emissions from loading and unloading operations represent a small fraction of the port's total emissions, but there is still room to reduce operator emissions. For a decarbonization plan to be successful and its actions effective, it is essential to involve the entire port community. Operators need to commit to developing initiatives that reduce emissions from their activities. In this regard, the creation of a collaborative community dedicated to improving data collection (such as fuel consumption, emissions, and equipment inventory, among others) and to disseminating the decarbonization plan is proposed. This community can also work on the development of training actions and the promotion of low-emission technological alternatives, among other initiatives.

The first phases of the process should focus on building this cooperative community, with the dissemination of the decarbonization plan as the initial stage. Actions such as training, identifying technological alternatives, and collaborating in energy procurement are more feasible within this collaborative structure. The main pillars of these actions include the creation of a participatory community, with regular meetings and annual targets, whose membership will be defined in the terms of reference. Simultaneously, it is necessary to improve monitoring and implement appropriate incentives. Finally, an interesting alternative would be the use of electric trucks in operations with frequent access to the quay, such as transport between the quay and the warehouses.

Figure 47 - Collaborative port community for port decarbonization.

Source: Fundación Valenciaport.

Table 10 - Ações propostas para operadores portuários.

#	Action	Budget (MR$)	Potential reduction/year (kt CO_2)	Start	End	Department
T11	Creation of the collaboration community (Improvement of data collection, inventory, catalog, and training)	1,3	0,2	1M26	2M50	Environment
T12	Separation of electricity meters of each terminal/operator from those of EMAP	0,2	0,01	1M26	2M26	Infrastructure

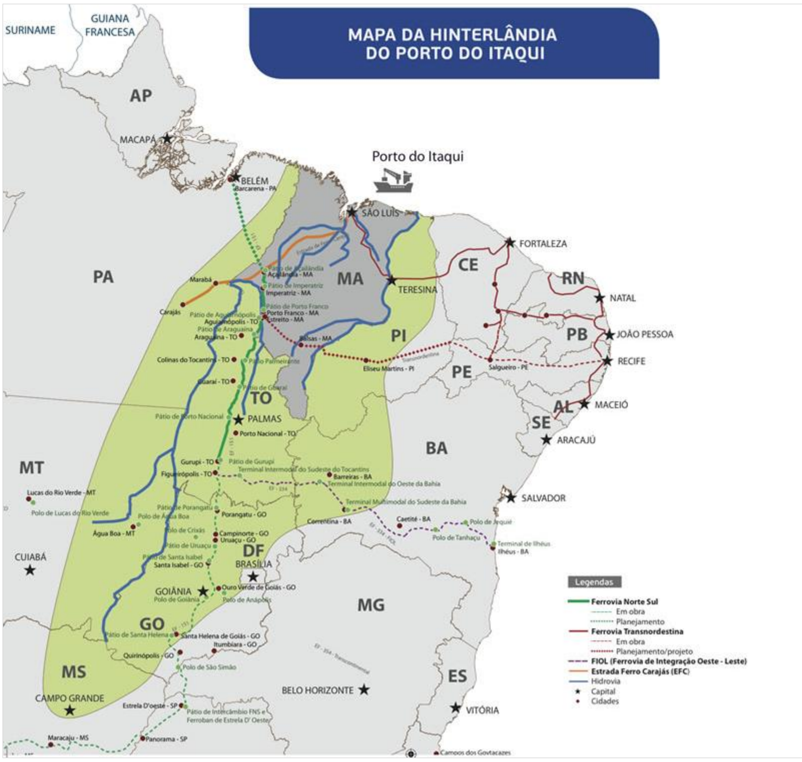
#	Action	Budget (MR$)	Potential reduction/year (kt CO_2)	Start	End	Department
T13	Incentive for the use of renewable electricity (with certificate)	57,5	0,2	1M28	2M50	Environment
T14	Economic incentives for operators and terminals (reduction of fees/tariffs) for the use of low-emission fuels	42	1,9	1M30	2M50	Environment
T15	Installation of charging point for trucks	3,3	0,2	1M28	2M28	Infrastructure and Energy

Source: Fundación Valenciaport.

6.5. Trucks

Given the relatively low impact of trucks on the total carbon footprint, combined with the lack of specific sector characterization and the complexity of the technological transition, gradual short-term actions are recommended. In parallel, the experimentation of new technologies is suggested, considering the current limitations of the refueling infrastructure.

Figure 48 - Hinterland Map of the Port of Itaqui.



Source: Porto do Itaqui.[16]

[16] *https://www.portodoitaqui.com/porto-do-itaqui/planejamento-desenvolvimento/novos-negocios*

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Figure 49 - LNG truck from Virtu GNL in operation at the Port of Itaqui.

Source: Porto do Itaqui.

The first defined steps aim to improve knowledge about the sector and the support provided by EMAP. Next, the actions will focus on facilitating access to electricity and renewable fuels. Pure electrification will be interesting for short routes, while for other routes the best option is drop-in fuels (diesel).

Table11 - Proposed actions for the decarbonization of land transport associated with the Port of Itaqui.

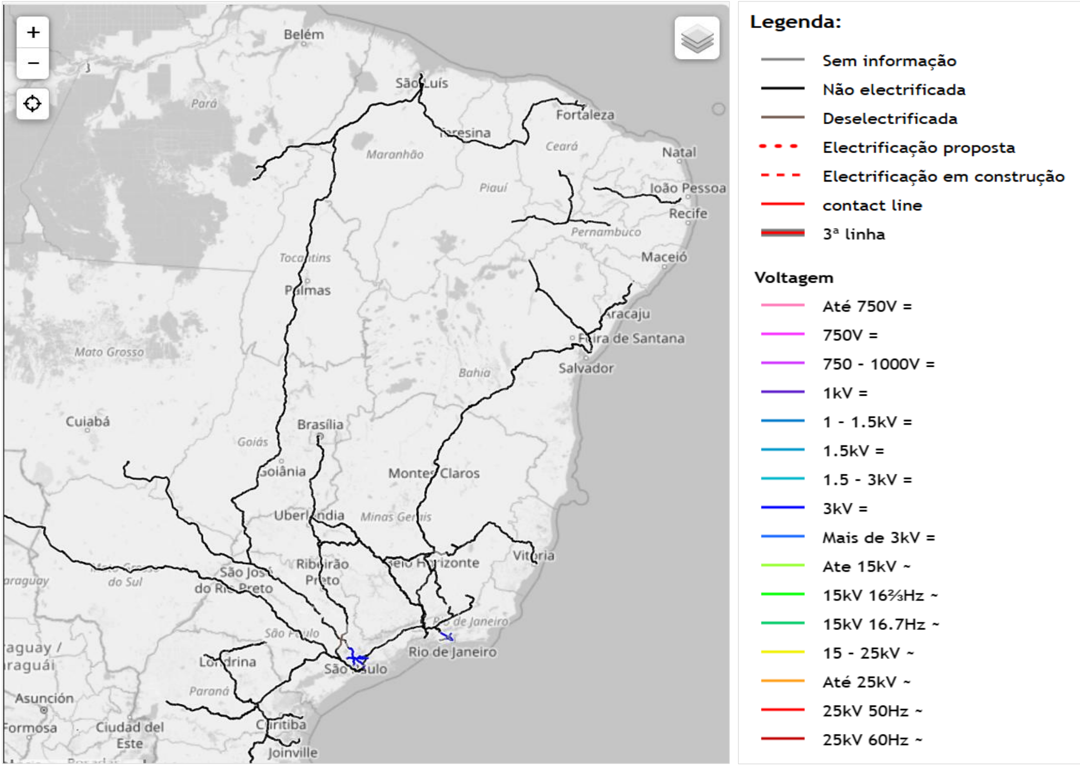
#	Action	Budget (MR$)	Potential reduction/year (kt CO_2)	Start	End	Department
C16	Working group on land transport + agricultural sector.	0,78	0,04	2M25	2M40	Logistics and Transport
C17	Study of the hinterland and potential for green corridors.	0,5	0	2M26	2M27	Strategic Planning
C18	Scheme of categorization and green labels for trucks.	1,35	0,1	1M27	2M40	Environment
C19	Agreement with an energy company for the supply of renewable fuel in the port surroundings.	288	0,1	1M27	2M30	Infrastructure and Energy
C20	Assistance office for transport companies.	5	0,23	1M27	2M30	Environment

Source: Fundación Valenciaport.

6.6. Railways

Considering the small size of the railway sector, the low degree of development of technological alternatives, and the potential to increase dialogue between operators and EMAP, it is suggested to focus efforts on communication and innovation.

Figure 50 - Map of railway electrification in Brazil.



Source:OpenRailwayMap.[17]

Figure 51 - ZTR hybrid locomotives.

Source: Union Pacific.[18]

It is proposed to work on the improvement of operations and on other decarbonization actions through the creation of a working group as a space for collaboration.

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[17] *https://www.openrailwaymap.org/*

[18] https://www.up.com/aboutup/community/inside_track/ztr-hybrid-locomotives-it-240429.htm

Table 12 - Proposed action for the decarbonization of railway operations at the Port of Itaqui.

#	Action	Budget (MR$)	Potential reduction/year (kt CO_2)	Start	End	Department
F21	Working group on logistics and digitalization of railway operations	0,75	0,06	1M26	2M40	Operations

Source: Fundación Valenciaport.

6.7. Scenarios

To assess the potential impact of the decarbonization plan, different implementation scenarios were defined, according to the degree of adoption of the proposed measures. Of the 21 actions identified, those that present a quantifiable impact on emission reduction and that allow modeling two levels of ambition were selected: a conservative scenario, which assumes a partial or more gradual adoption of the measures, resulting in moderate emission reductions; and an optimistic scenario, which contemplates the full implementation of the actions and the maximum possible reductions of GHG emissions.

In addition, 5 preparatory actions are included which, although they do not result in direct emission reductions, are necessary to enable or facilitate the adoption of more ambitious measures.

The following table lists the different actions by activity and indicates whether they were considered for the preparatory phase (PRE), for the conservative scenario (CON), and/or for the optimistic scenario (OPT).

Table 13 - Proposed decarbonization measures for the Port of Itaqui with their scenarios.

Activity	#	Action	PREP	CON	OPT
Vessels	N1	Improvement in data collection of calls			
	N2	Implementation of a call management system			
	N3	Research on preparing Itaqui's power grid			
	N4	Medium voltage grid (12 MW)			
	N5	Electrification of liquid bulk berths			
	N6	Tariff discount for ships using renewable fuels			
	N7	Priority berthing system for low-carbon ships			
Tugboats	R8	Working group for tugboat decarbonization			
	R9	Biofouling monitoring programs			
	R10	Electricity supply during waiting			
Terminals	T11	Creation of the collaboration community (Improvement of data collection, inventory, catalog, and training)			
	T12	Separation of electricity meters of each terminal/operator from those of EMAP			
	T13	Incentive for the use of renewable electricity (with certificate)			
	T14	Economic incentives for operators and terminals for the use of low-emission fuels			
	T15	Installation of charging point for trucks			
Trucks	C16	Working group on land transport + agricultural sector			
	C17	Study of the hinterland and potential for green corridors			
	C18	Scheme of categorization and green labels for trucks			
	C19	Agreement with an energy company for the supply of renewable fuel in the port surroundings			
	C20	Assistance office for transport companies			
Railways	F21	Working group on logistics and digitalization of railway operations			

Source: Fundación Valenciaport.

6.7.1. Conservative Scenario

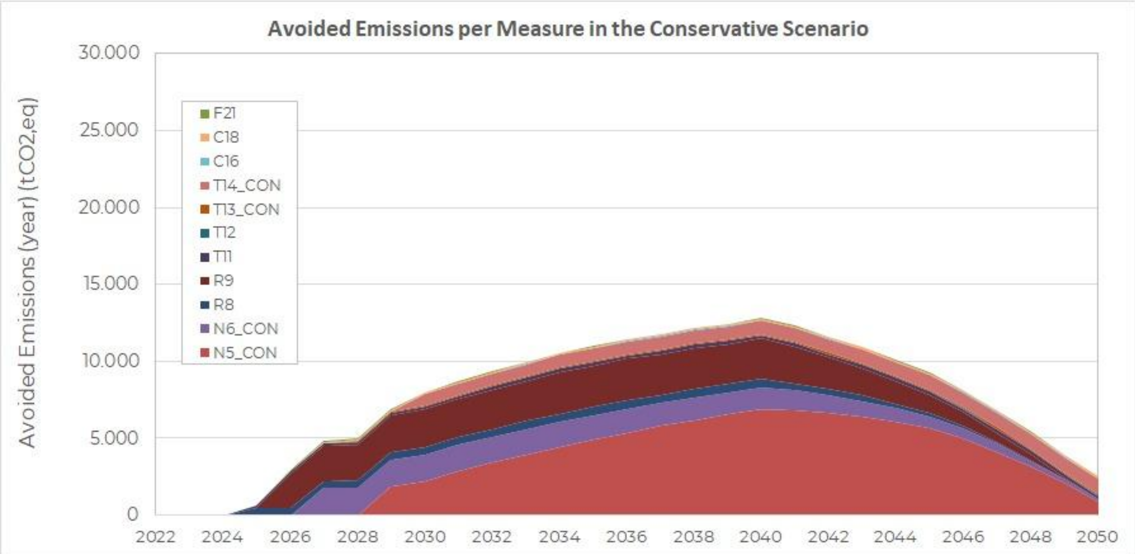
In the conservative scenario, the proposed actions result in significant annual emission reductions between 2025 and 2040, reaching a peak of more than 25 thousand tons of carbon dioxide equivalent (tCO_2eq) avoided in 2040, as indicated in Figure 53. From this milestone onward, the impact of measures aimed at vessels and tugboats tends to decrease, since most of these vessels will already have adopted low-carbon technologies, in line with the guidelines of the International Maritime Organization (IMO).

In this context, actions directed at port terminals and road transport progressively gain relevance in the Port of Itaqui's decarbonization portfolio, assuming a strategic role in continuing the port complex's emission mitigation trajectory through 2050.

This scenario represents moderate progress, but possibly a more realistic one, considering the technical, economic, or governance limitations that may delay the adoption of certain technologies or operational changes at the Port of Itaqui.

The following chart presents the annual emissions avoided by each measure in the conservative scenario:

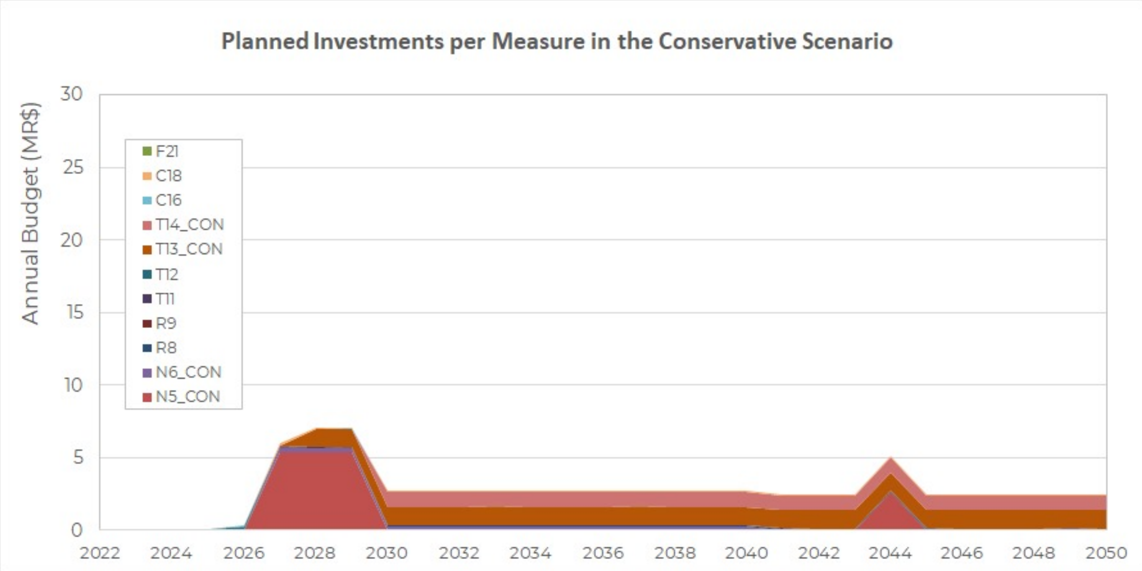
Figure 52 - Emissions avoided per measure in the conservative scenario.



Source: Fundación Valenciaport.

The largest investments are expected between 2026 and 2030, reaching BRL 8 million per year. In 2044, there is a new investment peak due to the refurbishment of the OPS installation.

Figure 53 - Planned investments per measure in the conservative scenario

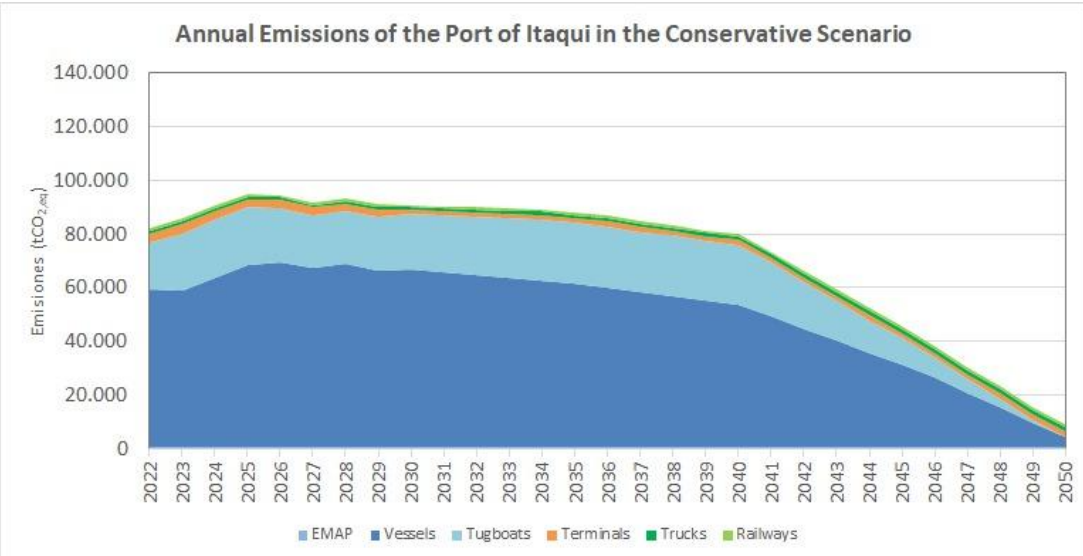


Source: Fundación Valenciaport.

As a result of the implementation of the reduction measures and the corresponding investments, in the conservative scenario it is possible to keep the annual emissions of the Port of Itaqui below 100 kt of CO_2eq at all times, even in the years of highest activity. By 2050, emissions are reduced to approximately 12 kt, which represents a 17% decrease compared to the Business as Usual scenario.

Although this scenario implies a gradual and more limited implementation of the proposed measures, it allows progress toward a more sustainable and resilient port model, establishing the foundations for future improvements.

Figure 54 - Annual emissions of the Port of Itaqui in the conservative scenario.

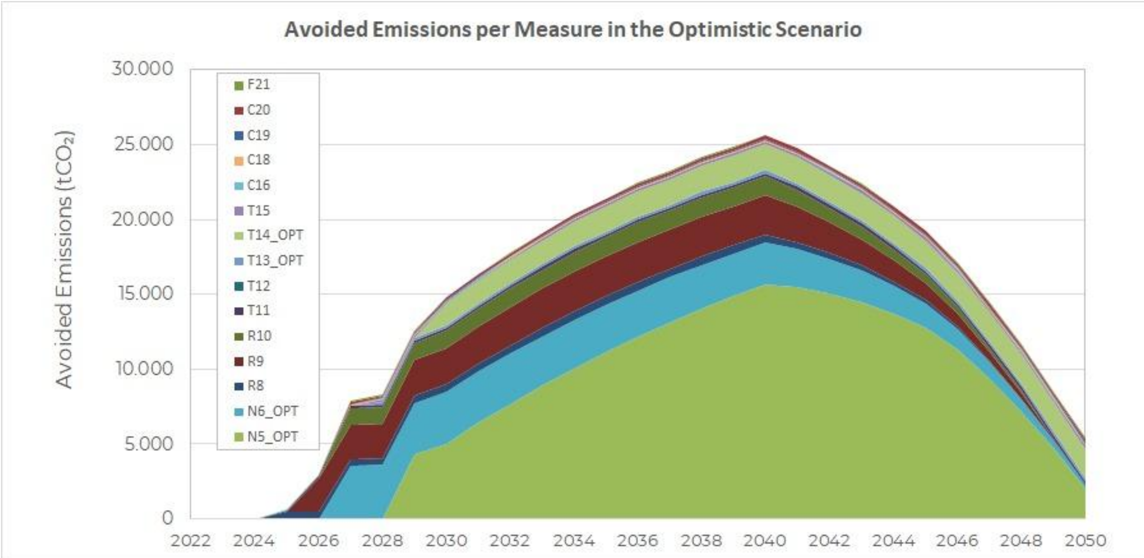


Source: Fundación Valenciaport.

6.7.2. Optimistic Scenario

In the optimistic scenario, the broad and accelerated adoption of the proposed decarbonization measures is considered, with greater ambition and efficiency in their implementation. Under these conditions, the annual reduction of GHG emissions reaches its peak around 2040, surpassing 25 thousand tons of CO_2 equivalent ($ktCO_2eq$). From that point onward, a gradual decrease in the annual abatement rate is observed, mainly due to the progressive transformation of the fleet of vessels and tugboats toward low- or zero-emission technologies, which reduces the marginal reduction potential in these categories as the main sources of emissions are replaced or optimized.

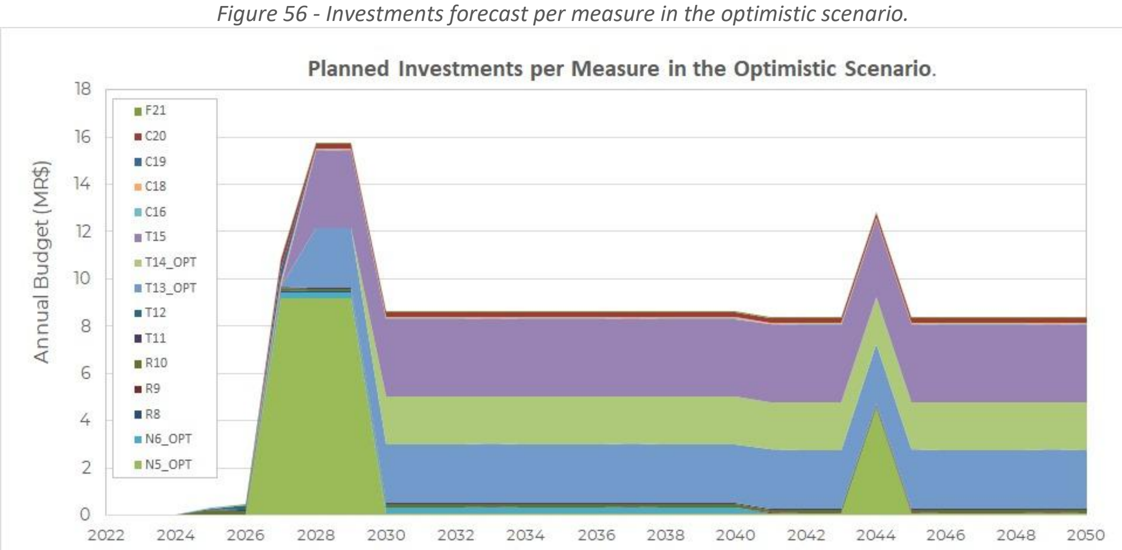
Figure 55 - Emissions avoided per measure in the optimistic scenario.



Source: Fundación Valenciaport.

The largest investments are expected between 2026 and 2030, exceeding BRL 24 million per year. In 2044, there is a new investment peak due to the refurbishment of the OPS installation. From 2026 onward, the annual investment required exceeds BRL 11 million.

Figure 56 - Investments forecast per measure in the optimistic scenario.

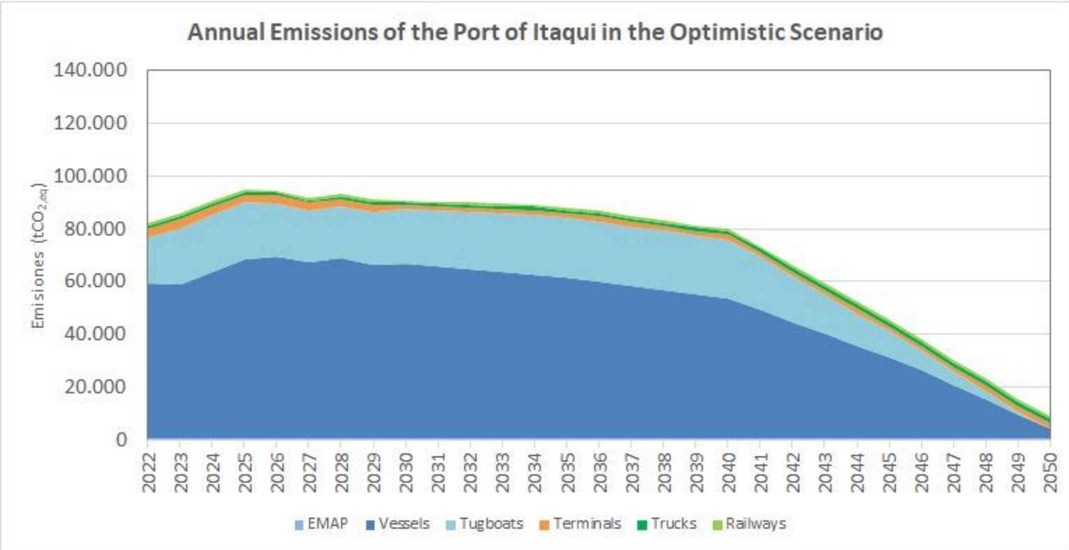


Source: Fundación Valenciaport.

As a result of a more determined implementation of the proposed decarbonization measures, the port's emissions begin to decrease continuously from 2026 onward. In 2050, annual emissions are reduced to approximately 9 kt of

CO_2eq, which represents a significant decrease compared to the Business as Usual (BaU) scenario and highlights the impact that can be achieved through an ambitious decarbonization strategy.

Figure 57 - Annual emissions of the Port of Itaqui in the optimistic scenario.

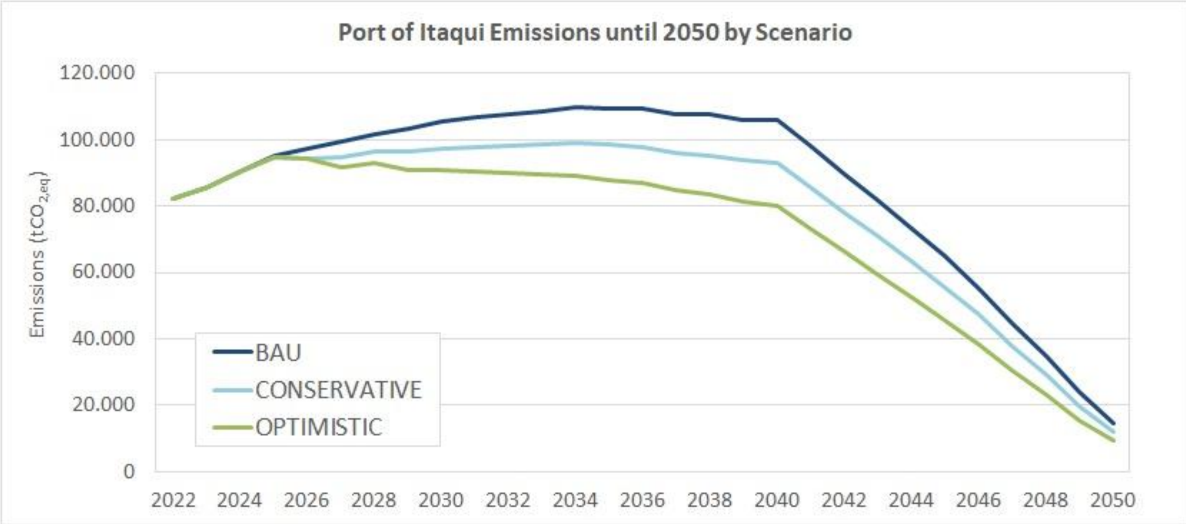


Source: Fundación Valenciaport.

6.7.3. Comparison of Scenarios

The following chart shows the evolution of the Port of Itaqui's carbon footprint according to the Business as Usual scenario, and the implementation of measures in the conservative and optimistic scenarios. It can be observed that the conservative scenario manages to maintain a constant level of emissions, despite increased activity, until 2040, the year from which a significant reduction occurs driven by the decarbonization of the maritime sector. In turn, the optimistic scenario foresees reductions starting in 2026, which will also accelerate from 2040 onward.

Figure 58 - Emissions of the Port of Itaqui up to 2050 according to the scenario.



Source: Fundación Valenciaport.

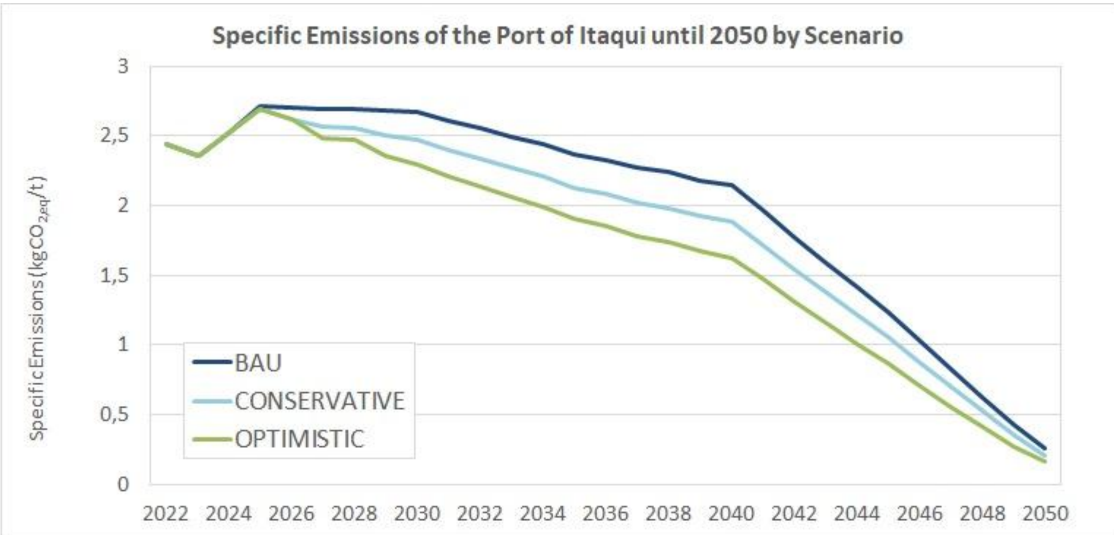
Table 14 - Emission reduction of the Port of Itaqui by scenario.

Year	% CO_2 Reduction (2022 reference)		
	BAU	Conservative	Optimistic
2035	-33,2	-19,9	-7,2
2040	-28,7	-13,1	2,5
2045	21,0	32,3	44,4
2050	82,2	85,3	88,8

Source: Fundación Valenciaport

In the scenario of maintaining current practices (BAU), a trend of emission stability is observed, with the beginning of a gradual decline starting in 2030. In the conservative and optimistic scenarios, however, the declines occur more rapidly.

Figure 59 - Emissões específicas do Porto do Itaqui até 2050 conforme o cenário.



Source: Fundación Valenciaport.

6.7.4. NPV

Eight of the actions result in a positive NPV, with those aimed at vessels and tugboats standing out as the best performers.

Net Present Value (NPV) is a widely used financial metric in investment analysis to estimate the profitability of an action or project over time. In the context of the Decarbonization Plan, NPV represents the balance between the expected economic benefits (such as fuel savings, tax incentives, or reduced operational costs) and the necessary investments, brought to present value based on a defined discount rate. A positive NPV indicates that the action generates a return greater than its cost of capital, and is therefore financially viable.

In this study, eight of the evaluated actions presented a positive NPV, with emphasis on those aimed at vessels and tugboats, which proved to be the most efficient from both an economic and climate perspective. These initiatives combine high GHG emission reduction potential with financial feasibility, positioning them as key elements of the Port of Itaqui's decarbonization strategy.

Table 15 - Positive NPV.

Scope	Action	Name	NPV (MR$)
Vessels	N5 Optimistic	Electrification of liquid bulk berths	R$ 26,14
Tugboats	R9	Working group for tugboat decarbonization	R$ 12,54
Vessels	N5 Conservative	Electrification of liquid bulk berths	R$ 8,74
Vessels	N7	Priority berthing system for ships with low-carbon technology	R$ 7,29
Tugboats	R10	Electricity supply during waiting	R$ 5,45
Vessels	N6	Tariff discount for ships using renewable fuels	R$ 5,37
Tugboats	R8	Biofouling monitoring programs	R$ 2,38
Terminais	T11	Creation of the collaboration community	R$ 0,50

Source: Fundación Valenciaport.

In the conservative scenario, adopting an average discount rate of 8% per year, it is observed that eight actions present a positive Net Present Value (NPV), indicating economic feasibility and relevant contribution to the decarbonization strategy. These actions are represented in the Marginal Abatement Cost Curve (MACC) in Figure 61, and are mostly concentrated in the scopes of vessels and tugboats.

The three most prominent initiatives in this scenario are:

• N5 – Electrification of liquid bulk berths;

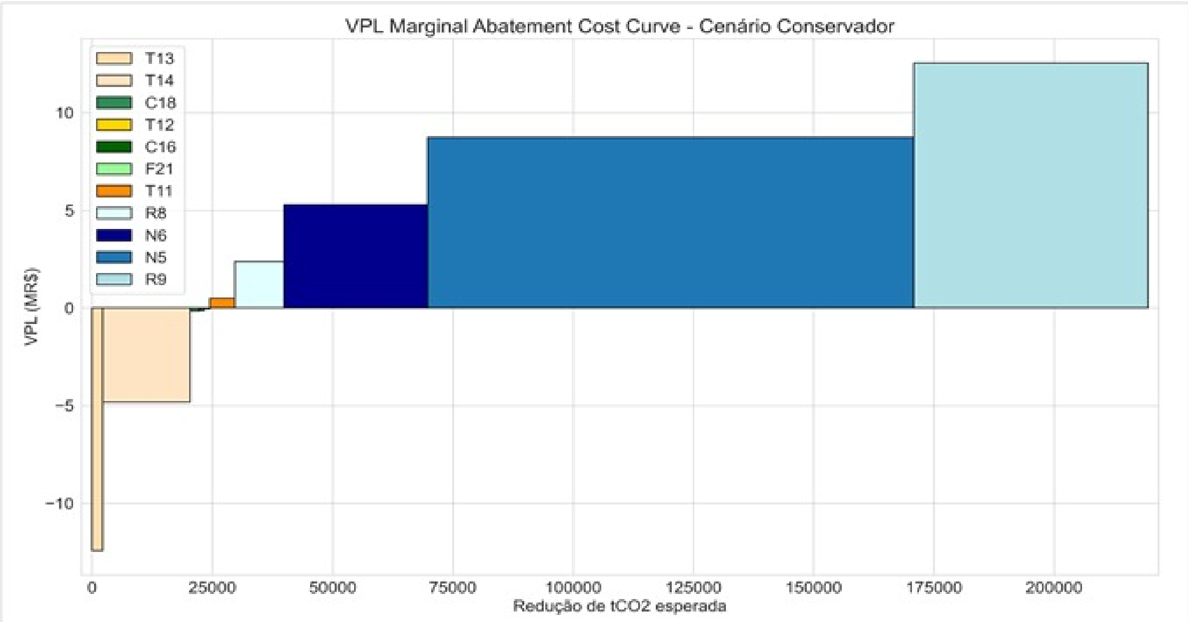
• R9 – Creation of a working group for tugboat decarbonization, with an NPV of BRL 12.54 million;

• N6 – Tariff discount for vessels using renewable fuels, with an NPV of BRL 5.37 million.

These three actions significantly concentrate both the largest volume of potential CO_2 equivalent (tCO_2eq) emission reductions and the highest estimated net financial return, positioning them as priorities for short- and medium-term implementation.

Another five actions also present a positive NPV, although with less individual impact, reinforcing the role of complementary solutions in the mitigation portfolio. The analysis shows that the maritime modes (vessels and tugboats) remain the main strategic targets for decarbonization, both due to their share in the carbon footprint and the opportunity for financial return on investments.

Figure 60 - Conservative NPV.



Source: Fundación Valenciaport.

In the optimistic scenario, which considers greater efficiency in the implementation of measures and favorable market and regulatory contexts, there is a significant increase both in the potential for GHG emission reductions and in the economic return values (NPV) of the evaluated actions.

The Marginal Abatement Cost Curve (MACC) in Figure 62 shows that, as in the conservative scenario, the actions with the greatest impact are strongly concentrated in the maritime modes – vessels and tugboats.

The five actions with the highest positive NPV in this scenario are:

• N5 – Electrification of liquid bulk berths, with the highest NPV and emission abatement potential among all evaluated measures;

• R9 – Working group for the decarbonization of the tugboat fleet;

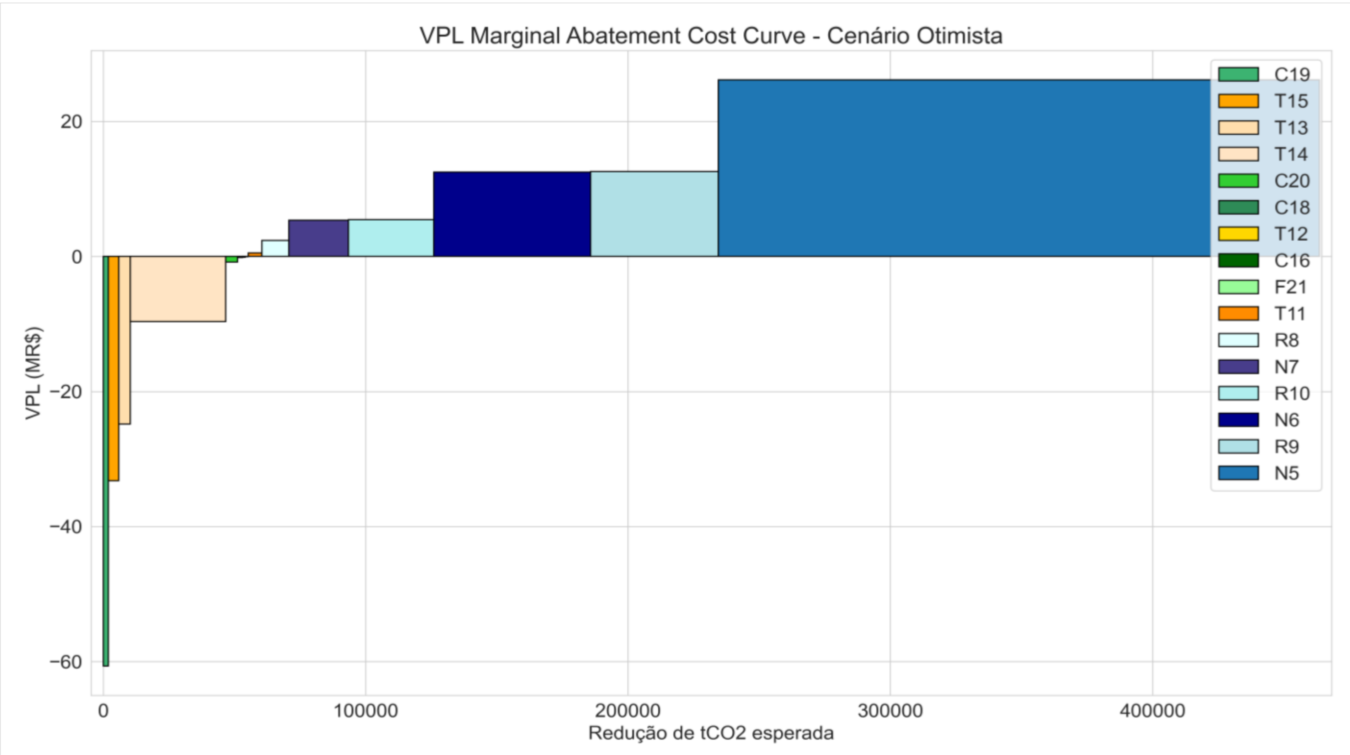
- **N6 – Tariff discount for vessels using renewable fuels;**
- **R10 – Electricity supply during tugboat idling;**
- **N7 – Berth priority system for vessels with low-carbon technology.**

These actions stand out for combining positive economic feasibility with high mitigation potential (tCO_2eq), consolidating themselves as the most effective strategies in the analyzed technical portfolio.

Unlike the conservative scenario, the optimistic scenario increases the expected abatement volume, surpassing 400 thousand tCO_2eq — and improves the financial performance of several actions, including initiatives that in the previous scenario showed neutral or negative returns.

This analysis reinforces the importance of institutional incentives, regulatory frameworks, and operational synergies to enable a more favorable environment for the adoption of these technologies, allowing the port authority and its operators to extract maximum value from decarbonization strategies.

Figure 61 - Optimistic NPV.



Source: Fundación Valenciaport.

6.8. Offsetting

Although decarbonization efforts allow for a significant reduction of emissions at the Port of Itaqui, there will always be a remainder of emissions that are difficult to eliminate, due to the operational nature of certain port activities.

For the port to achieve climate neutrality and become a **net zero emission infrastructure by 2050**, it will be necessary to complement mitigation measures with offsetting actions.

This implies investments in projects capable of avoiding or removing from the atmosphere an amount of Greenhouse Gases (GHG) equivalent to the residual emissions.

According to the analyzed scenarios, the estimated annual cost for offsetting residual emissions in 2050 would be approximately **BRL 11.6 million** in the conservative scenario and **BRL 8.8 million** in the optimistic scenario, considering the projected results of residual emissions for each scenario, as described in the previous sections, and an average price of BRL 960 per carbon credit.

It is recommended that the Port of Itaqui's offsetting strategy start gradually from 2050, initially acting as a facilitator, then as an aggregator, and eventually establishing a requirement to achieve net zero emissions. Below are the responsibilities that EMAP would have in each phase:

Facilitator

- Create and maintain a digital platform for access to reliable credits.
- Select and validate suppliers/brokers of certified credits.
- Disseminate information and raise awareness in the port community about the importance of offsetting.

Aggregator

- Create and maintain a platform for buying and selling credits.
- Connect port users to reliable suppliers/brokers.
- Identify offsetting needs and available projects.
- Promote collective purchases under advantageous conditions.
- Ensure traceability and verification of transactions.

Net Zero Emission Requirement

- Establish rules for emission neutrality in the port ecosystem.
- Include offsetting requirements in contracts, licenses, and concessions.
- Implement mandatory monitoring and verification systems.
- Apply incentives and sanctions according to the level of compliance.
- Provide training and support for reduction and offsetting measures.

7. Final Considerations

The decarbonization plan of the Port of Itaqui represents an unprecedented milestone in the Brazilian port scenario, positioning the logistics complex as the first national public port to have a decarbonization planning tool aligned with the climate requirements of the 21st century.

More than just a response to IMO targets and Brazil's commitments under the Paris Agreement, the plan establishes the technical, operational, and strategic foundations for the progressive reduction of greenhouse gas emissions across all modes and logistics chains of the port. The plan presents feasible and innovative technological solutions, such as berth electrification, solar energy potential, the use of biofuels, green hydrogen, and other renewable energies with high emission reduction potential.

The strategy combines realistic short-term actions with long-term structuring initiatives, promoting a gradual and safe energy transition across all port modes and equipment. The building of a collaborative community between EMAP, operators, and carriers ensures greater adherence to the targets, driving integrated governance for sustainability. Based on robust economic analyses, 8 actions in the plan present a positive NPV, demonstrating that decarbonization is also an opportunity for financial gains and competitiveness.

As a consequence of the decarbonization of the maritime sector, the weight of other applications will grow significantly at the Port of Itaqui; therefore, it is important to create collaboration spaces with the entire port community. Decarbonization will be led by the energy transition in the maritime sector, so it is very important that the Port of Itaqui prepares for the supply of renewable fuels in order to increase the port's commercial attractiveness. For total decarbonization, offsetting actions must be taken into account, in which, in the short term, EMAP must play the role of facilitator.

This plan reinforces the commitment of the Port of Itaqui to a low-carbon logistics ecosystem, attracting sustainable investments and consolidating its national leadership in port sustainability.

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Annex I – Detail of the proposed measures

Code	N1
Measure	Improvement in data collection of calls
Description	Implementation of standardized and automated mechanisms for the collection, consolidation, and analysis of call data from ships operating at the Port of Itaqui, including arrival and departure times, waiting times, energy consumption, fuel use, cargo type, and vessel characteristics.
Type of measure	Operations management
Scope of application	Vessels
Emission reduction potential/year (kt CO_2)	0
Additional benefits	• Improved transparency and traceability of operations. • Data-based decision-making. • Foundation for creating energy and climate efficiency indicators. • Facilitates the implementation of incentives or penalties related to the environmental performance of ships.
Budget (MR$)	0,6
Time horizon	1M26–2M26
Responsible department	Operations, Digitalization
Monitoring indicators	• % of calls recorded with complete and reliable data. • Number of key variables collected per call.
Implementation examples	Port of Los Angeles, Port of Antwerp, Port of Singapore

Code	N2
Measure	Implementation of a call management system
Description	Development and implementation of an integrated digital system to plan, coordinate, and optimize ship calls at the Port of Itaqui. The tool may include functionalities such as Just-in-Time scheduling, notifications to key stakeholders, and integration with Port Community Systems (PCS).
Type of measure	Operations management
Scope of application	Vessels
Emission reduction potential/year (kt CO_2)	0
Additional benefits	• Improved operational efficiency and reduction of bottlenecks. • Decrease in emissions associated with waiting time. • Reduction of operating costs for shipowners and terminals. • Improved transparency and coordination among port stakeholders.
Budget (MR$)	0,3
Time horizon	2M26–1M27
Responsible department	Operations, Digitalization
Monitoring indicators	• % of calls managed by the system. • Average reduction in ship waiting time. • Number of Just-in-Time events applied.
Implementation examples	Port of Rotterdam, Port of Los Angeles
Code	N3
Measure	Study on preparing Itaqui's power grid
Description	Conducting a technical study to evaluate the current capacity of the port's power grid and its potential for expansion to meet future energy demands, especially in the context of port operations electrification, Onshore Power Supply (OPS), charging of electric vehicles, and the use of renewable energy.
Type of measure	Infraestrutura portuária
Scope of application	Vessels
Emission reduction potential/year (kt CO_2)	0

Additional benefits	• Identification of opportunities to integrate renewable energy into the system. • Improved energy security and resilience of the port. • Enables proper planning of port electrification.
Budget (MR$)	2
Time horizon	2M26–1M27
Responsible department	Infrastructures
Monitoring indicators	• Identification of critical points and improvement proposals. • Number of electrification projects made feasible by the study.
Implementation examples	Port of Santos, Port of Valencia, Port of Hamburg

Code	N4
Measure	Medium voltage grid (12 MW)
Description	Implementation of a medium voltage grid (approximately 12 MW capacity) within the port area to ensure the necessary electricity supply for future demands associated with berth electrification, OPS (Onshore Power Supply), and other operations.
Type of measure	Port infrastructure
Scope of application	Vessels
Emission reduction potential/year (kt CO_2)	0
Additional benefits	• Improvement of the port's energy capacity. • Reduction of long-term operational energy costs. • Increased energy resilience against failures or overloads.
Budget (MR$)	35
Time horizon	2M26–2M27
Responsible department	Infrastructures
Monitoring indicators	• Installed capacity of the power grid (MW). • Number of enabled connection points. • % of port infrastructure supplied by the new grid. • Number of electrical projects connected to the grid.
Implementation examples	Port of Santos, Port of Valencia

Code	N5
Measure	Electrification of liquid bulk berths
Description	Installation of power supply systems at berths designated for liquid bulk operations, allowing ships to connect to the onshore power grid during their stay in the port, avoiding the use of auxiliary generators on board.
Type of measure	Port infrastructure
Scope of application	Vessels
Emission reduction potential/year (kt CO_2)	15,6
Additional benefits	• Improvement of local air quality. • Reduction of noise in the port surroundings. • Compliance with future international regulations. • Strengthening of the port's positioning as a sustainability benchmark.
Budget (MR$)	33,2
Time horizon	1M27–2M28
Responsible department	Infrastructures
Monitoring indicators	• Number of electrified berths.

	• % of calls connected to OPS. • Energy supplied to ships (MWh).
Implementation examples	Port of Rotterdam, Port of Gothenburg

Code	N6
Measure	Tariff discount for ships using renewable fuels
Description	Implementation of an economic incentive scheme that grants discounts on port tariffs to ships operating with renewable or low-emission fuels, such as green methanol, advanced biofuels, hydrogen, among others.
Type of measure	Environmental incentives
Scope of application	Vessels
Emission reduction potential/year (kt CO_2)	3,5
Additional benefits	• Attraction of maritime traffic with better environmental performance. • Improvement of the port's image as an agent committed to sustainability. • Stimulation of innovation and the use of alternative fuels in the maritime sector.
Budget (MR$)	14
Time horizon	1M27–2M40
Responsible department	Operations
Monitoring indicators	• Number of ships accessing the incentive. • % of incentivized calls using renewable fuels. • Total value of discounts granted.
Implementation examples	Port of Rotterdam, Port of Los Angeles

Code	N7
Measure	Priority berthing system for low-carbon ships
Description	Development and implementation of a system that grants berthing priority to ships using low-emission fuels or clean technologies.
Type of measure	Environmental incentives
Scope of application	Vessels
Emission reduction potential/year (kt CO_2)	1,3
Additional benefits	• Improvement of efficiency in port operations. • Acceleration of the adoption of clean technologies in maritime transport. • Strengthening of the port's image as an agent committed to decarbonization.
Budget (MR$)	0,24
Time horizon	1M27–2M50
Responsible department	Operations
Monitoring indicators	• Average waiting time vs. average berthing time for low-emission ships. • Number of ships prioritized due to environmental performance.
Implementation examples	Port of Gothenburg

Code	R8
Measure	Working group for tugboat decarbonization
Description	Creation of a permanent working group between EMAP and tugboat companies, with the objective of defining strategies and projects to reduce the emissions of tugboats operating at the Port of Itaqui.
Type of measure	Alternative fuels
Scope of application	Tugboats
Emission reduction potential/year (kt CO_2)	0,55
Additional benefits	• Promotion of public-private collaboration for the energy transition. • Improvement of the competitiveness and sustainability of port services.
Budget (MR$)	0,78
Time horizon	2M25–2M40
Responsible department	Environment
Monitoring indicators	• Number of meetings and technical proposals generated by the group. • Percentage of the tugboat fleet with low-emission technologies. • Pilot projects implemented or under development.
Implementation examples	Port of Rotterdam, Port of Los Angeles

Code	R9
Measure	Biofouling monitoring programs
Description	Implementation of programs to monitor biofouling on the hulls of tugboats at the Port of Itaqui, with the objective of identifying those with high levels of biological fouling that affect fuel consumption efficiency. Monitoring may include visual inspections, use of sensors, or analysis of energy performance data.
Type of measure	Operations management
Scope of application	Tugboats
Emission reduction potential/year (kt CO_2)	3,34
Additional benefits	• Improvement of the energy efficiency of tugboats. • Generation of useful data for ecological studies and management of invasive species.
Budget (MR$)	0,26
Time horizon	2M26–2M27
Responsible department	Environment / Operations
Monitoring indicators	• Number of tugboats assessed annually. • Percentage of tugboats with critical biofouling detected. • Application of corrective measures (cleaning, antifouling paint, etc.).
Implementation examples	Pilot initiatives in ports of Australia and New Zealand

Code	R10
Measure	Electricity supply during waiting
Description	Installation of electricity supply points at berths or docking areas of the Port of Itaqui to allow tugboats to connect to the power grid while waiting between maneuvers.
Type of measure	Port infrastructure
Scope of application	Tugboats
Emission reduction potential/year (kt CO_2)	1,59
Additional benefits	• Reduction of local emissions and improvement of air quality in the port surroundings. • Decrease in noise and vibrations in operational areas. • Fuel savings for tugboat operators. • Facilitates the progressive electrification of the auxiliary port fleet.
Budget (MR$)	3,15
Time horizon	1M27–2M27
Responsible department	Environment
Monitoring indicators	• Number of tugboats using the electricity supply system. • Average connection time per tugboat (h/year). • Avoided fossil fuel consumption.
Implementation examples	Port of Rotterdam, Port of Hamburg

Code	T11
Measure	Creation of the collaboration community (Improvement of data collection, inventory, catalog, and training)
Description	Establishment of a collaboration community between EMAP and the terminals, with the objective of improving data collection on emissions, energy consumption, and port operations. This community will also facilitate the joint development of the emissions inventory, the creation of a decarbonization measures catalog, and the implementation of training and capacity-building programs to drive port sustainability.
Type of measure	Operations management
Scope of application	Terminals
Emission reduction potential/year (kt CO_2)	0,2
Additional benefits	• Improvement of the quality and transparency of port data. • Promotion of strategic alignment among key stakeholders. • Increased technical capacity of the port ecosystem. • Facilitation of monitoring, evaluation, and continuous improvement of the decarbonization plan.
Budget (MR$)	1,3
Time horizon	1M26–2M50
Responsible department	Environment

Monitoring indicators	• Number of entities participating in the community. • Number of working sessions and activities carried out.
Implementation examples	Port of Valencia, Port of Amsterdam

Code	T12
Measure	Separation of electricity meters of each terminal/operator from those of EMAP
Description	Installation of separate electricity meters for each terminal and port operator within the management area of the Port of Itaqui, enabling precise and specific monitoring of each entity's energy consumption.
Type of measure	Operations management
Scope of application	Terminals
Emission reduction potential/year (kt CO_2)	0,01
Additional benefits	• Improved control and management of each terminal's energy consumption. • Identification of opportunities for energy efficiency at the terminal level. • Facilitation of the implementation of incentives for energy savings. • Increased transparency and accountability in energy consumption.
Budget (MR$)	0,2
Time horizon	1M26–2M26
Responsible department	Infrastructures
Monitoring indicators	• Number of terminals with independent electricity meters. • % of renewable electricity consumption used by each terminal.
Implementation examples	Port of Rotterdam, Port of Hamburg

Code	T13
Measure	Incentive for the use of renewable electricity (with certificate)
Description	Implementation of an incentive scheme for terminals that use certified renewable electricity in their operations. EMAP will offer tariff discounts, preferential access, or regulatory benefits for those using electricity from renewable sources, verified by guarantee-of-origin certificates.
Type of measure	Environmental incentives
Scope of application	Terminals
Emission reduction potential/year (kt CO_2)	0,2
Additional benefits	• Stimulus for the use of clean energy and contribution to decarbonization. • Alignment with international goals to combat climate change and reduce emissions. • Improvement of the port's competitiveness in the context of global sustainability.
Budget (MR$)	57,5
Time horizon	1M28–2M50
Responsible department	Environment
Monitoring indicators	• Number of terminals adhering to the incentive scheme. • % of renewable electricity used by terminals.
Implementation examples	Port of Amsterdam, Port of Rotterdam

Code	T14
Measure	Economic incentives for operators and terminals for the use of low-emission fuels
Description	Implementation of an economic incentive system directed at port operators and terminals that use low-emission fuels. Incentives may include discounts on port tariffs, reduction of fees for the use of sustainable fuels, or priority access to certain port infrastructures.
Type of measure	Environmental incentives
Scope of application	Terminals
Emission reduction potential/year (kt CO_2)	1,9
Additional benefits	• Improvement of air quality in the port surroundings. • Preparation for future environmental regulations. • Strengthening of institutional reputation and environmental leadership. • Attraction of sustainable terminals and operators.
Budget (MR$)	42
Time horizon	1M30–2M50
Responsible department	Environment

Monitoring indicators	• Number of operators and terminals adopting sustainable fuels. • % of low-emission fuels used by operators and terminals. • Total value of economic incentives granted for the use of low-emission fuels.
Implementation examples	Port of Rotterdam, Port of Amsterdam

Code	T15
Measure	Installation of charging point for trucks
Description	Installation of electric charging infrastructure at the terminals for trucks operating within the Port of Itaqui. EMAP may act as a facilitator through incentives, cooperation agreements, or requirements in concession contracts.
Type of measure	Port infrastructure
Scope of application	Terminals
Emission reduction potential/year (kt CO_2)	0,2
Additional benefits	• Improvement of air quality in the port surroundings. • Strengthening of the environmental image of the port and terminals. • Support for the national electromobility policy. • Attraction of sustainable terminals and operators.
Budget (MR$)	3,3
Time horizon	1M28–2M28
Responsible department	Infrastructure and Energy
Monitoring indicators	• Number of charging points installed at the terminals. • Number of electric trucks circulating in the port. • % of terminals with electric charging infrastructure.
Implementation examples	Port of Los Angeles, Port of Rotterdam

Code	C16
Measure	Working group on land transport + agricultural sector
Description	Creation of a working group composed of EMAP, logistics operators, companies from the agricultural sector, and local authorities, with the objective of analyzing and promoting the transition to more sustainable land transport solutions for moving goods between the port and agricultural areas.
Type of measure	Green logistics
Scope of application	Trucks
Emission reduction potential/year (kt CO_2)	0,04
Additional benefits	Optimization of logistics routes, increasing efficiency. Improvement of air quality. Promotion of public-private cooperation, aligned with sustainability policies.
Budget (MR$)	0,78
Time horizon	2M25–2M40
Responsible department	Logistics and Transport
Monitoring indicators	Number of meetings and projects initiated by the working group. Number of sustainable initiatives implemented. Volume of goods transported by low-emission means.
Implementation examples	Port of Rotterdam, Port of Suape

Code	C17
Measure	Study of the hinterland and potential for green corridors
Description	Conducting a study on the hinterland of the Port of Itaqui, focusing on identifying opportunities for the development of green corridors. This study will analyze current and future transport routes, assessing the potential for integrating sustainable solutions such as infrastructure electrification and the use of alternative fuels.
Type of measure	Green logistics
Scope of application	Trucks
Emission reduction potential/year (kt CO_2)	0
Additional benefits	Improvement of logistics efficiency. Reduction of air pollution. Reduction of operational costs.
Budget (MR$)	0,5
Time horizon	2M26–2M27
Responsible department	Strategic Planning
Monitoring indicators	Identification of routes and green corridors with the greatest implementation potential. Number of sustainable initiatives identified and implemented.
Implementation examples	Port of Rotterdam, Port of Hamburg

Code	C18
Measure	Scheme of categorization and green labels for trucks
Description	Implementation of a categorization and green labeling system for trucks operating in the port, based on their emission levels and use of clean technologies. This system will allow trucks to be classified into different categories according to their environmental impact, facilitating the application of incentives and discounts for low-emission vehicles. In addition, green labels will be granted to trucks that use alternative fuels or low-impact technologies, encouraging the transition toward a more sustainable fleet.
Type of measure	Green logistics
Scope of application	Trucks
Emission reduction potential/year (kt CO_2)	0,1
Additional benefits	Stimulus for the use of low-emission vehicles. Improvement of air quality. Alignment with sustainability policies.
Budget (MR$)	1,35
Time horizon	1M27–2M40
Responsible department	Environment
Monitoring indicators	Number of trucks categorized with green labels. % of low-emission trucks compared to the total operating fleet.
Implementation examples	Port of Los Angeles, Port of Rotterdam

Code	C19
Measure	Agreement with an energy company for the supply of renewable fuel in the port area
Description	Signing of an agreement between EMAP and an energy company for the supply and distribution of renewable fuels (such as biodiesel, HVO, biogas, among others) at the Port of Itaqui. The objective is to ensure that operations within the port, both in land transport and port activities, use clean energy sources, reducing dependence on fossil fuels and promoting the transition to more sustainable logistics. The agreement may also include the implementation of the necessary infrastructure for the distribution of these fuels in the port area.
Type of measure	Alternative fuels
Scope of application	Trucks
Emission reduction potential/year (kt CO_2)	0,1
Additional benefits	Boost to renewable fuel infrastructure in the port. Compliance with possible future environmental regulations. Reduction of air pollution. Attraction of sustainable operators.
Budget (MR$)	288
Time horizon	1M27–2M30
Responsible department	Infrastructure and Energy
Monitoring indicators	Amount of renewable fuel supplied to the port. Number of trucks using renewable fuels.
Implementation examples	Port of Rotterdam, Port of Los Angeles

Code	C20
Measure	Assistance office for transport companies
Description	Creation of a technical and support office within the Port of Itaqui to advise and monitor transport companies operating in the port area in their transition toward more sustainable models. This office will provide information on environmental regulations, access to incentives or financing for fleet renewal, adoption of alternative fuels, training in best practices, and technical support for the implementation of low-carbon solutions.
Type of measure	Green logistics
Scope of application	Trucks
Emission reduction potential/year (kt CO_2)	0,23
Additional benefits	Support for the modernization of the land fleet operating at the Port of Itaqui. Promotion of cooperation and strengthening of institutional relations for the energy transition. Reduction of air pollution associated with land transport. Increased environmental compliance among operators accessing the port.
Budget (MR$)	5
Time horizon	1M27–2M30
Responsible department	Environment
Monitoring indicators	Number of companies served by the office. Number of sustainable initiatives implemented by operators with the office's support.
Implementation examples	Port of Hamburg, Port of Los Angeles

Code	F21
Measure	Working group on logistics and digitalization of railway operations
Description	Creation of a technical working group composed of EMAP, railway operators, terminals, logistics companies, and governmental entities, with the objective of improving the efficiency of railway transport at the Port of Itaqui through advanced logistics solutions and digitalization tools. The group will address topics such as real-time data exchange, cargo traceability, schedule coordination, and the use of digital platforms to optimize railway management.
Type of measure	Green logistics
Scope of application	Railways
Emission reduction potential/year (kt CO_2)	0,06
Additional benefits	• Increased efficiency and competitiveness of freight railway transport. • Reduction of road traffic and associated truck emissions. • Greater integration of the railway mode into port logistics processes.
Budget (MR$)	0,75
Time horizon	1M26–2M40
Responsible department	Operations
Monitoring indicators	• Number of meetings held and actions implemented by the working group. • Increase in the volume of cargo transported by rail.
Implementation examples	Port of Rotterdam, Port of Hamburg

Annex II – Study of solar potential, storage needs, and local hydrogen production at the Port of Itaqui

1. Introdução

Context and objectives of the study

As part of the Decarbonization Plan proposed for the Port of Itaqui, developed within the framework of the collaboration between EMAP and Fundación Valenciaport, the study on the port's renewable potential and the production of renewable fuels, especially green hydrogen, is included. The study will contribute to informed decision-making regarding the necessary investments in energy infrastructure, with the objective of reducing the port's carbon footprint and improving its competitiveness in an international environment increasingly regulated in environmental terms.

The specific objectives of this study are:

• Identify the areas within the port with the greatest potential for the installation of solar panels;
• Quantify the capacity for solar energy generation and define the technical parameters for its implementation (Subtask 1);
• Assess the short- and long-term energy storage needs to optimize the use of the generated energy (Subtask 2);
• Analyze the potential for local hydrogen production and propose technological and infrastructure solutions for its storage and use, in accordance with the energy needs established in the present Decarbonization Plan of the Port of Itaqui (Subtask 3).

Scope

The scope of this study focuses on three key areas for the energy transition of the Port of Itaqui:

1. The assessment of solar potential;
2. The identification of energy storage needs;
3. The study of local hydrogen production.

The first area focuses on identifying and evaluating zones within the port suitable for the installation of photovoltaic systems, with the aim of maximizing solar energy generation. The second addresses the analysis of the most appropriate storage technologies, considering both short-term solutions (such as batteries) and long-term ones (such as hydrogen production). The third area is dedicated to studying the feasibility of on-site hydrogen production, including the location of an electrolysis plant and the assessment of its capacity based on different demand scenarios.

This study will not be limited to the technical feasibility of the proposed solutions, but will also analyze their economic profitability and the financing conditions required for their implementation. The resulting recommendations will be aligned with the sustainability objectives of the port, as well as with local and international energy and environmental policies.

The methodological approach of the study will combine qualitative and quantitative techniques, integrating technical expertise with rigorous data analysis. First, a comprehensive review of the literature and previous studies on solar generation, energy storage, and hydrogen production in similar ports will be carried out, with the aim of identifying good practices and lessons learned applicable to the Port of Itaqui.

Next, an assessment of solar potential will be conducted using geospatial analysis tools to identify the areas of the port with the greatest solar exposure. Electricity generation will be modeled based on local meteorological data, considering seasonal and daily variations, and power profiles will be simulated to assess the efficiency of different technological conFiguretions, such as panel orientation and tilt.

The analysis of energy storage needs will be based on the assessment of the storage capacity required to balance energy generation and consumption at the port. The technical and economic feasibility of various storage technologies, both short- and long-term, will be analyzed, and different storage scenarios will be designed based on projected energy demand and the variability of solar generation.

Regarding hydrogen production, the ideal location for an electrolysis plant within the port will be identified and its production capacity assessed, considering different demand scenarios, such as vessel bunkering and port operations. A cost analysis associated with the installation and operation of the hydrogen plant will be carried out, including the necessary storage technologies.

Finally, an economic-financial study will be carried out, which will include the estimation of investment and operating costs for each of the proposed solutions. Opportunities for public and private financing, as well as available tax incentives and subsidies, will be assessed. In addition, return on investment (ROI) and payback periods will be analyzed.

The validation and review of the results will be conducted in collaboration with experts and stakeholders of the Port of Itaqui, adjusting the recommendations according to the feedback received and market conditions. The final report will gather the conclusions, recommendations, and a detailed action plan for the implementation of the proposed solutions.

2. Subtask 1: Solar potential

2.1. Methodology

This study aims to analyze the potential for photovoltaic solar energy generation at the Port of Itaqui and its surrounding areas, specifically considering the feasibility of installing solar systems on the rooftops of administrative buildings, parking lots under renovation, and other areas under the management of the Maranhão Port Administration Company (EMAP), including areas outside the port perimeter, such as the passenger terminal or adjacent land.

Given the high solar irradiance characteristic of the state of Maranhão and the port's commitment to decarbonization and energy sustainability, this analysis seeks to identify concrete opportunities for the use of solar energy as a clean and strategic source to supply its operations.

To estimate the solar generation potential in the identified areas of the Port of Itaqui, a methodology was adopted based on the analysis of available surface area, average annual solar irradiance data, and the efficiency of photovoltaic systems. First, a preliminary estimate of usable surfaces was made for the rooftops of administrative buildings, parking structures, and viable external land, based on satellite images and port blueprints.

Next, the average solar irradiance in São Luís was considered, ranging between 3.03 (March) and 5.49 (August) kWh/m²/day, with an annual average of 4.366 kWh/m²/day [1], as well as an average system efficiency between 15% and 18% [2], taking into account losses due to temperature, orientation, shading, and conversion. These parameters allow the theoretical annual energy production to be calculated for each type of area and assess its potential contribution to the port's electricity consumption.

Figure 62 - Irradiation considered for the Port of Itaqui.

Daily Total Averages of the Direct Normal Irradiation for the State of MARANHÃO

(Wh/m^2.day)

Show 10 entries — ---- Insert ID ---- Search: 61200

ID	Lon	Lat	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
61200	-44.249	-2.5005	4355	3902	3487	3032	3105	3804	4679	4990	5496	5378	4722	4804	4863
ID	Lon	Lat	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

Source: Fundación Valenciaport.

2.2. Identification of Areas with Potential for Photovoltaic Panels

The identification of suitable areas for the installation of photovoltaic systems at the Port of Itaqui was based on criteria of physical availability, accessibility, orientation, absence of significant shading, and public ownership. Three main categories of spaces were considered, all under the management of EMAP or linked to the Government of the State of Maranhão:

1. **Administrative building rooftops:** flat or slightly inclined surfaces, generally without obstructions and with nearby electrical infrastructure. Priority was given to the rooftops of the headquarters, technical rooms, and logistics warehouses.

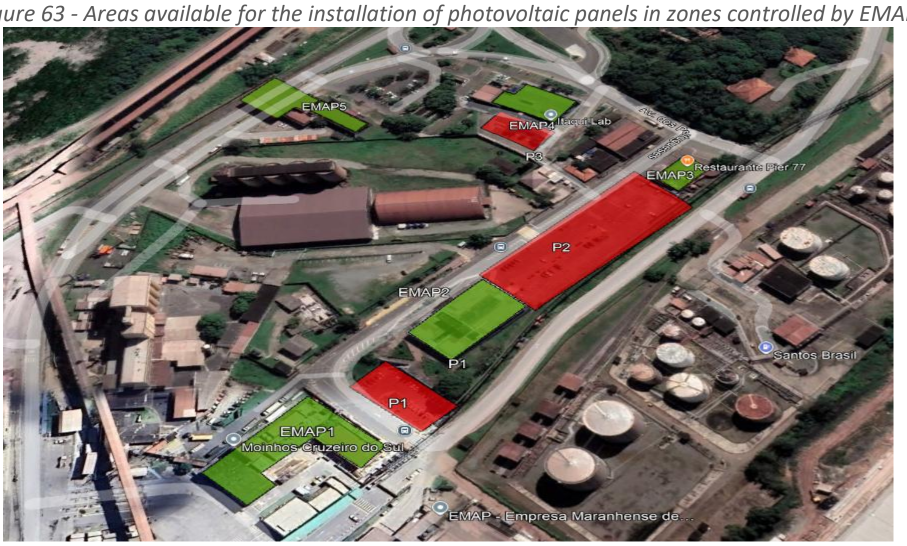
2. **Parking areas under renovation:** the installation of carport-type photovoltaic structures over parking lots represents a doubly efficient solution, as it not only generates renewable electricity but also provides shade and thermal comfort for vehicles. The selected areas include parking lots for employees, visitors, and service fleets, currently undergoing renovation or expansion.

3. **Areas outside the port polygon:** zones with potential to host larger-scale solar plants, especially land without defined use or with low occupation. These were indicated as potential areas, depending on EMAP's final decision regarding the concrete use of the land.

2.3. Initial Proposal: Internal Areas

The area sizing procedure followed a sequential process. First, the available area in zones under the direct control of EMAP was determined. These areas were classified as typologies 1 and 2 and define the space available for short-term installable photovoltaic generation.

Figure 63 - Areas available for the installation of photovoltaic panels in zones controlled by EMAP.



Source: Fundación Valenciaport.

After a detailed analysis of the infrastructures and surfaces available within the Itaqui Port area, it was determined that the potentially usable area for the installation of photovoltaic panels amounts to 14,810 m². This surface is divided between 7,320 m² of administrative and logistics building rooftops, and 7,490 m² in parking areas currently under renovation.

To more accurately reflect the effectively usable fraction, adequacy factors of 80% were applied to the rooftops (considering obstacles, inclination, or inaccessible zones) and 90% to the parking areas (due to structural layout and spacing between rows). As a result, the estimated net usable surface for the installation of solar panels is 12,597 m², which represents the basis for sizing the photovoltaic plant within the port perimeter.

Table 16 - Surfaces identified on EMAP's land.

		Extension (m²)	Factor	Surface (m²)
Buildings	EMAP Building 1	2620	0,8	2096
	EMAP Building 2	1700	0,8	1360
	EMAP Building 3	600	0,8	480
	EMAP Building 4	1000	0,8	800
	EMAP Building 5	1400	0,8	1120
Parks	Park 1	1240	0,9	1116
	Park 2	5400	0,9	4860
	Park 3	850	0,9	765
Total		**14810**		**12597**

Source: Fundación Valenciaport.

To size the most suitable photovoltaic installation for the available space at the Port of Itaqui, different commercial models of high-efficiency solar panels currently available in the Brazilian market were analyzed. Specifically, three representative modules of the 550 Wp monocrystalline PERC technology were compared: Tensite EM550-PH, Jinko Solar Tiger Pro 550W, and Canadian Solar HiKu6 CS6W-550MS. The technical characteristics of these pieces of equipment are available in [3], [4], and [5].

All selected models use "half-cut" cells, which improve performance under partial shading conditions, reduce resistance losses, and increase system reliability. In addition, they present efficiencies higher than 21%, which makes them especially suitable for limited spaces, such as rooftops and parking areas.

The dimensions and weights of the three models are similar, which facilitates assembly standardization. For a usable surface area of 12,597 m², assuming a typical installation density of 0.53 kWp/m², the maximum installable photovoltaic power would be approximately 6.7 MWp. This translates into the need for approximately 12,138 modules of 550 Wp, regardless of the model, since all have the same unit power.

The final choice of the module will depend on additional factors such as local availability, commercial conditions, warranties, and compatibility with mounting systems and inverters. In any case, all analyzed models are technically suitable for the port environment, compliant with international quality standards, and widely applied in large-scale industrial installations.

Thus, considering an average annual solar irradiance in the Port of Itaqui of 4,366 kWh/m²/day and an overall photovoltaic system efficiency estimated between 15% and 18%, the expected annual production for the available usable surface is in the range between 3,011,168 kWh/year and 3,613,402 kWh/year.

This value exceeds EMAP's annual consumption (2,601,926.13 kWh in 2022), so the energy surplus would be available to meet alternative consumptions, whether from the terminals or to provide OPS services, when these become a reality at the Port of Itaqui.

To ensure the optimal performance, safety, and durability of the photovoltaic system designed for the Port of Itaqui, it is recommended to follow a series of technical best practices, aligned with national and international standards. First, a detailed shading and obstacles study must be carried out, especially on rooftops with equipment, guardrails, or auxiliary structures, in order to optimize the distribution of modules and minimize losses from partial shading.

The recommended orientation for São Luís is towards true north, with an inclination close to the local latitude (~2.5°), although coplanar Configurations on flat roofs may also be viable if energy density is a priority.

In addition, the entire installation must include projects approved by an electrical engineer registered with CREA and comply with the access procedures of the local utility (Equatorial Maranhão), in accordance with ANEEL Normative Resolution No. 1,059/2023 on distributed micro- and mini-generation.

In the port environment, it is also recommended to coordinate with operational safety authorities (ANVISA, Receita Federal, Brazilian Navy) if there is interference in sensitive or protected areas.

Finally, it is advisable to integrate a real-time remote monitoring system to ensure performance tracking, early fault detection, and efficient planning of preventive maintenance activities.

2.4. Expanded Approach: Areas Outside the Port Polygon

After analyzing the available surface within the Itaqui Port area, it was estimated that it is possible to install a photovoltaic system of approximately 6.7 MWp over a total of 12,597 m² of usable area, distributed between building rooftops and parking areas. However, this capacity represents only a fraction of the technical potential of injection that the existing electrical infrastructure allows — in particular, the substation equipped with a Schneider Electric SM6 medium-voltage modular cell, configured to operate at 13.8 kV with a rated current of 630 A.

For this reason, this study proposes, as an initial stage, the maximization of photovoltaic generation up to the limit of the internal distribution network capacity of the Port of Itaqui.

The strategy consists of combining the already identified internal surfaces with new complementary external areas that make it possible to reach this capacity without the need to modify the existing medium-voltage infrastructure. This design approach not only maximizes the use of the assets already available, but also optimizes the energy and economic return of the system, by distributing the fixed infrastructure costs over a larger volume of renewable generation — without implying changes in the port's electrical network that would require higher-order investments.

Figure 64 - EMAP medium-voltage panel [6].

Source: Fundación Valenciaport.

The maximum power injection capacity through this cell was calculated based on its three-phase apparent power, using the following expression:

$$S = \sqrt{3} * V * I_n = \sqrt{3} * 13.800 * 630 = 15{,}05\ MVA$$

Considering a typical power factor of 0.95 in modern photovoltaic systems, the effective active power that can be evacuated without overloading the cell is:

$$P = S * Cos(\varphi) = 15{,}05 * 0{,}95 = 14.3\ MW$$

This value (14.25 MW of active power, considering a power factor of 0.95) is adopted as the upper design limit for the total photovoltaic installation of the Port of Itaqui, assuming that all units are connected to the medium-voltage grid.

Subtracting the power already allocated to internal installations, **7.6 MWp** remain available for expansion. To meet this amount, an estimated useful surface area of approximately **14,340 m²** would be required, considering a typical installation density of **0.53 kWp/m²**, as adopted in the internal units.

The selected external areas must meet a series of technical, operational, and legal requirements, among which the following stand out:

1. **Public ownership or availability of use**: priority will be given to land under EMAP management or belonging to the Government of the State of Maranhão, located in adjacent areas to the port, such as former logistics yards, disused railway areas, or areas near the passenger terminal.

2. **Proximity to the port's electrical infrastructure**: in order to minimize energy losses and reduce connection costs, it is recommended that the external plant be located at a maximum distance of 1.5 to 2 km from the SM6 substation.

3. **Topographical and irradiation conditions**: the land must present low slope, absence of shading, viable access for construction works and installation machinery, as well as low susceptibility to flooding, which is common in coastal areas surrounding the port.

4. **Electrical connection feasibility**: it will be necessary to design a medium-voltage connection — either overhead or underground, depending on technical feasibility — up to the available cell in the existing substation, with adequate dimensioning of cables, protections, and switchgear, in accordance with **NBR 14039 (medium-voltage electrical installations)**.

In this way, the maximization of the Port of Itaqui's photovoltaic infrastructure respects both the technical limits of power evacuation from the grid and the physical and legal constraints of the port area.

Table 17 - Superfícies necessárias para a geração fotovoltaica.

		Extension (m²)	Factor	Surface (m²)
Buildings	EMAP Building 1	2620	0,8	2096
	EMAP Building 2	1700	0,8	1360
	EMAP Building 3	600	0,8	480
	EMAP Building 4	1000	0,8	800
	EMAP Building 5	1400	0,8	1120
Parks	Park 1	1240	0,9	1116
	Park 2	5400	0,9	4860
	Park 3	850	0,9	765
Total		**14810**		**12597**
Areas outside the polygon.		15933	0,9	14340
Total		**30743**		**26937**

Source: Fundación Valenciaport.

The following table presents a summary of the technical characteristics of the planned installations.

Table 18 - Technical characteristics of the planned facilities.

Parameter	Internal installation	External installation
Effective available surface (m²)	12.597	14.340
Maximum installed capacity (kWp)	6.676,4	7.600,2
Number of modules (550 W)	12.138	13.818
Estimated minimum annual production (kWh)	3.011.168	3.427.812
Estimated maximum annual production (kWh)	3.613.402	4.113.375

Source: Fundación Valenciaport.

The maximum estimated production is **7,726,777 kWh per year.**

2.5. Economic Considerations

This section presents an economic-financial assessment of the photovoltaic system designed for the Port of Itaqui, considering a total planned capacity distributed across three construction modalities: installations on building rooftops, carport-type structures in parking areas, and an external ground-mounted solar plant on land adjacent to the port.

The analysis is based on updated data from the Brazilian market and, in particular, incorporates the electricity tariff applicable to industrial consumers — a more realistic reference for estimating the project's economic benefits within the port's operational context.

Table 19 - Components of the electricity cost estimable for the Port of Itaqui

Component	Estimated percentage	Value in R$/kWh	Reference
Energy Tariff (ET)	40 % – 50 %	R$ 0,284 – 0,355	[7]
TUSD – Distribution/Transmission	30 % – 35 %	R$ 0,213 – 0,249	[8]
Taxes and charges	15 % – 25 %	R$ 0,107 – 0,178	[9], [10]

Source: Fundación Valenciaport.

The analysis is based on a reference price of BRL 0.711/kWh, representative of the actual cost paid by high-voltage industrial consumers in Maranhão, including generation, distribution, and regulated components.

2.6. Initial Investment

The initial investment constitutes one of the critical factors for determining the economic feasibility of a photovoltaic system. In this case, a breakdown was carried out considering the substantial differences in installation costs among the three proposed typologies. This methodology not only improves the calculations but also makes possible a phased implementation.

The first category corresponds to the installation on the rooftops of administrative and logistics buildings within the port premises. This modality makes use of already existing spaces, minimizing physical and urban impacts, and allows direct integration with local electricity consumption. An effective area of 7,320 m² is estimated, allowing the installation of approximately 3,883 kWp.

The cost per installed kWp on industrial rooftops is generally lower than in other modalities, but in this case, specific technical aspects (waterproofing, access, support structure) were considered, assuming a price range between BRL 4,600 and BRL 5,800/kWp, which results in a total investment between BRL 17.8 million and BRL 22.5 million.

The second modality considers the installation of panels in parking areas, through metallic carport-type structures. In addition to generating energy, this solution provides shade and thermal comfort to vehicles and people, improving the operation on-site.

The identified surface is 7,490 m², with potential for 3,970 kWp. As these structures require reinforced foundations and greater height, the cost per kWp is estimated between BRL 4,800 and BRL 6,000, resulting in an investment of BRL 19.1 million to BRL 23.8 million.

Finally, the largest component will be a ground-mounted plant installed on land, in external areas to the port, with an estimated capacity of 7,600 kWp, distributed over 14,340 m² of usable area. This installation is considered necessary to reach the maximum injection capacity limit allowed by the existing medium-voltage substation.

This modality involves additional costs for land preparation (leveling, drainage, access) and for the construction of a medium-voltage line to connect the plant to the internal substation. Therefore, the estimated cost per kWp is higher, between BRL 5,000 and BRL 6,500, resulting in a projected investment between BRL 38.0 million and BRL 49.4 million.

In total, the estimated investment for the system ranges between BRL 74.9 million and BRL 95.7 million, depending on the technical solutions adopted and the commercial conditions at the time of contracting.

Table 20 - Cost by type of installation.

Type of installation	Power (kWp)	Cost per kWp (BRL)	Estimated Investment (BRL)
Rooftops (roofs)	3.883	4.600 – 5.800	17.846.000 – 22.521.400
Parking lots (carports)	3.970	4.800 – 6.000	19.056.000 – 23.820.000
Ground-mounted (external) [11]	7.600	5.000 – 6.500	38.000.000 – 49.400.000
TOTAL	**14.276**		**74.902.000 – 95.741.400**

Source: Fundación Valenciaport.

2.7. Estimated Annual Savings

The main economic advantage of a photovoltaic installation lies in the savings generated by avoiding the purchase of electricity from the grid. In this case, the average price considered is BRL 0.711/kWh, a value representative of the actual cost paid by industrial consumers, as explained earlier.

Based on this data, the estimated annual savings from self-production of electricity range between BRL 4,578,032 and BRL 5,491,633, depending on the volume of energy generated. These savings directly impact the port's energy bill, reducing fixed operating costs and freeing up resources for other investments or logistical improvements.

In addition, it helps mitigate exposure to the volatility of electricity tariffs — a relevant risk in industrial environments and in critical infrastructures such as ports.

It is also important to consider advantages that, although not directly quantifiable, add value to the project. Among them are the energy independence provided by an in-house installation, which strengthens the operational resilience of the infrastructure, as well as the social benefits associated with greater availability of energy for alternative uses.

2.8. Payback Period of the Investment (ROI)

The long-term profitability analysis is based on the calculation of the Return on Investment (ROI), which indicates how many years are required to recover the invested amount through the savings generated. Based on the values presented earlier, the payback period of the complete system ranges between 13.6 years in the most favorable scenario (lower investment and higher production) and 20.9 years in the most conservative scenario (higher investment and lower production).

These results indicate that the system is economically viable even without tax incentives and that it can be fully amortized within its estimated useful life of 25 years. From the payback year onward, the system begins to generate net benefits for the port authority.

2.9. Maintenance Costs

The specific environmental conditions of the Port of Itaqui require a more intensive approach regarding system maintenance. The constant presence of suspended dust, typical of bulk cargo logistics operations, combined with the salinity of the coastal environment, can accelerate soiling on the modules and compromise conversion efficiency if regular cleaning protocols are not in place.

For this reason, the study considers an annual maintenance cost equivalent to 2% of the initial investment, a value slightly above the sector's average references, which generally range between 1% and 1.5%.

2.10. Annual Generation Profiles with Hourly Granularity

The objective of this section is to obtain the hourly generation profile of a photovoltaic plant installed at the Port of Itaqui, in order to assess the temporal distribution of energy production, its seasonal behavior, and provide inputs for economic studies, self-consumption modeling, and impact analysis on the electrical grid.

For this purpose, the Photovoltaic Geographical Information System (PVGIS) [12], developed by the Joint Research Centre (JRC) of the European Commission, was used. This tool provides hourly estimates of energy production for photovoltaic systems, based on satellite climatological databases and validated physical models for various regions of the world. It is a publicly accessible and free online application.

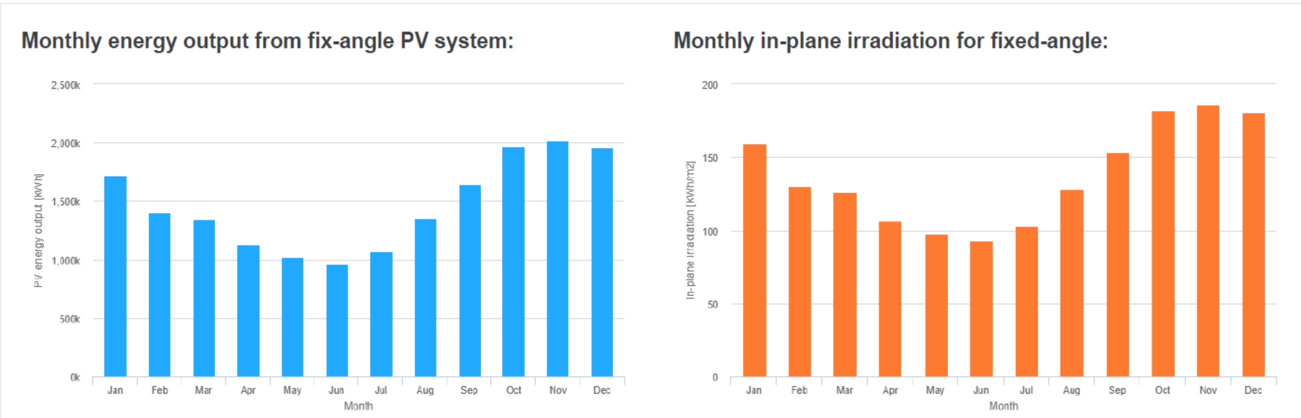
PVGIS allows estimating hourly production for a specific geographic location, considering variables such as solar radiation, module tilt and orientation, system losses, and ambient temperature.

Table 21 - Input parameters in PVGIS.

Parameter	Value used
Location	Port of Itaqui, São Luís, Maranhão (Brazil)
Coordinates	Latitude -2.5692°, Longitude -44.3658°
Installed nominal power	14.3 MWp (for analysis purposes, scaled to 1 kWp)
System tilt	15°
Orientation (azimuth)	0° (orientation to the north — ideal for Brazil)
System losses	14% (considering temperature, dirt, cabling, etc.)
Selected period	Typical Meteorological Year (TMY)
Desired output	Hourly profile (8,760 annual data points)

Source: Fundación Valenciaport.

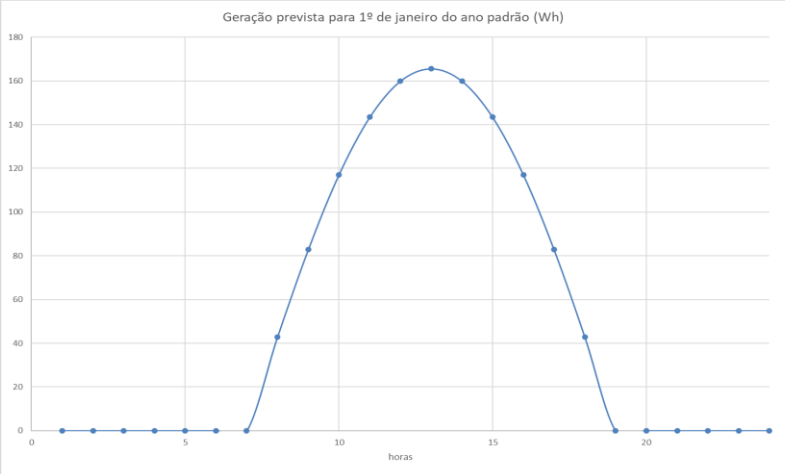
Figure 65 - Monthly solar production and irradiation calculated by the PVGIS software.



Source: Fundación Valenciaport.

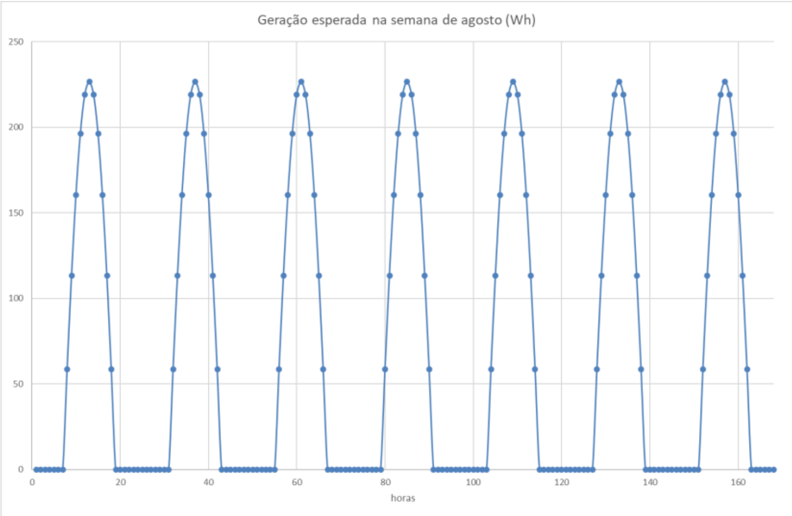
The following presents the normalized generation profiles, that is, in terms of Wh per kWp, as a reference for the first day of the year, the first week of August, and finally, the complete generation profile throughout the year.

Figure 66 - Hourly profile of daily generation (January).



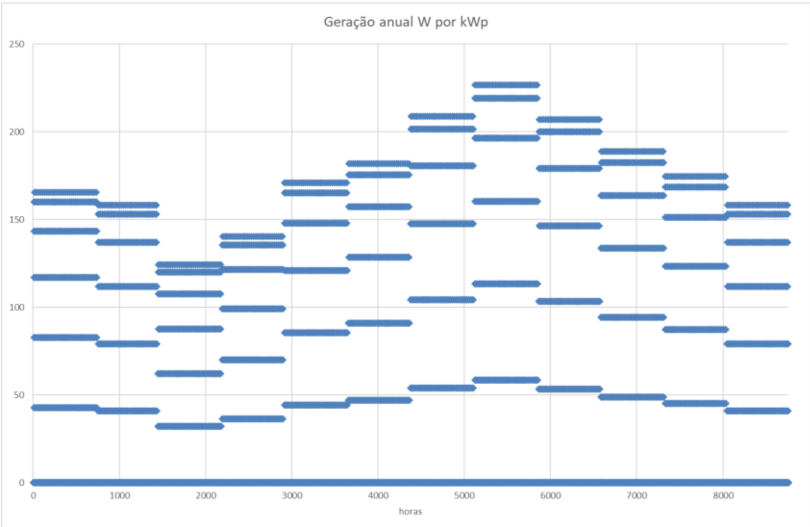
Source: Fundación Valenciaport.

Figure 67 - Hourly profile of weekly generation (August).



Source: Fundación Valenciaport.

Figure 68 - Annual hourly generation – reference year.



Source: Fundación Valenciaport.

The hourly analysis of photovoltaic generation corresponding to the Port of Itaqui makes it possible to conclude that the designed system presents a well-distributed production throughout the year, with moderate seasonality and a daily pattern typical of humid tropical regions — characterized by gradual sunrises, generation peaks between 11 a.m. and 2 p.m., and a smooth decline at the end of the afternoon.

Monthly variability follows the oscillations of solar radiation, with August and September being the most productive months, while March and April present the lowest generation volumes, which is consistent with the regional cycles of cloudiness and rainfall.

Since generation is null during the nighttime period and 100% concentrated in solar hours, in order to maximize self-consumption or manage surpluses, it is recommended to study complementary measures such as:

- energy storage systems,
- load profile adjustment, or
- demand management strategies.

In an integrated way, the hourly profile obtained represents an essential tool for electrical sizing, economic evaluation, and effective integration of the photovoltaic system into the port's energy operation.

3. Subtask 2: Storage Needs

3.1. Assessment of Energy Storage Needs

During 2022, EMAP recorded a total energy consumption of 2.6 GWh, according to data provided by the port authority. This value corresponds to the set of operational and administrative facilities within the premises served by EMAP.

This consumption volume makes it possible to establish an initial approximation of the energy magnitude of the complex, which can be considered moderate in industrial terms, opening the way for a strategy of partial or even total coverage through renewable generation sources.

The photovoltaic system proposed for installation at the port, with a total capacity of 14.3 MWp, was modeled with site-specific climatic data using PVGIS software. Based on this model, an annual production between 6,438,848 and 7,726,618 kWh was estimated, depending on the effective system efficiency (estimated range between 15% and 18%). The direct comparison between the estimated production and the recorded consumption allows some key conclusions to be drawn:

- The designed plant would generate between 2.47 and 2.97 times the port's current consumption.

• This implies a significant energy surplus, which will require careful evaluation of surplus management scenarios.

• Under a direct self-consumption scheme, the installation could cover 100% of the current demand managed by EMAP, even in the months of lower solar irradiance.

This result highlights EMAP's enormous potential for energy self-sufficiency, with the possibility of contributing to the port's complementary supply, reinforcing the technical and environmental feasibility of the photovoltaic project — provided that a flexible grid architecture is adopted and the potential evolution of future energy demand is considered, such as operational growth, equipment electrification, refrigeration system implementation, and fleet electrification.

The photovoltaic plant sizing proposed in this study, with an installed capacity of 14.3 MWp, will allow the generation of an annual amount of energy significantly higher than the current needs of the port facility. Compared to the recorded consumption in 2022 of 2.6 GWh, the solar installation will be capable of generating between 6.4 and 7.7 GWh/year, depending on operating conditions and actual system performance.

This means that, even in a conservative scenario, generation will be more than double the current consumption, which requires a careful analysis of how to manage the energy surpluses that are not directly consumed by the port's internal loads.

In the first scenario, a hybrid model based on instant self-consumption is considered, with the possibility of injecting surpluses into the public grid. This strategy is in line with several Brazilian distributed generation regulations, being feasible through a technical-commercial agreement with the local distributor, Equatorial Maranhão.

In this model, all production is connected to the port's internal grid; the energy is consumed in real time and the surplus is exported via substation or another enabled point, according to the evacuation project. This solution requires technical compatibility, bidirectional metering systems, and specific protections to avoid uncontrolled curtailment or the formation of electrical islands. Although technically feasible and operationally simple, its economic efficiency will depend on the compensation model and the grid usage costs.

The second alternative consists of local storage of surpluses through industrial batteries. In this case, the energy not consumed during the day is stored for later use, such as during the night or demand peaks. This strategy increases the self-consumption index, reinforces energy self-sufficiency, and reduces dependence on the external grid but presents greater technical and financial requirements.

Precise sizing of the storage capacity would be necessary based on the hourly generation and consumption profile, as well as adequate physical space, safe operating protocols, and proper maintenance. The life-cycle costs of the batteries, their replacement, and eventual disposal should also be considered. Despite the high initial investment, the additional benefits include greater resilience, peak-shaving, and grid stability.

In addition, this scenario allows surpluses to be viewed not as a problem but as a strategic opportunity to transform the port's energy model. Instead of only managing surplus energy, it is proposed to expand the electricity consumption base by electrifying new loads to directly absorb this energy, without the need for export or storage. This strategy may include:

• implementation of charging infrastructure for internal vehicles,

• replacement of thermal consumption with efficient electrical technologies such as heat pumps.

This approach increases the local use of renewable energy, contributes to decarbonization objectives, reduces the carbon footprint of operations, and improves the port's environmental competitiveness.

The implementation of the measures analyzed in this decarbonization study, such as the electrification of the consumption of berthed ships (cold ironing / OPS), would significantly increase the base demand of the Port. These surpluses of electricity generation could be directly integrated, without the need for intermediate storage, and would enable the expansion of the installed renewable generation. However, this would require a more robust internal distribution infrastructure, which goes beyond the scope of this study.

3.2. Technical Study on Storage Potential (Scenarios)

With the objective of rigorously and realistically assessing the techno-economic feasibility of harnessing photovoltaic solar energy at the Port of Itaqui, the present study was structured into two differentiated analysis cases.

This division responds to the need to compare the performance, impact, and profitability of different renewable generation implementation strategies, taking into account both the physical limitations of the port environment and the current tariff and technological scenario.

Based on the generation profiles and considering the reference demand (uniformly distributed as an initial assumption), the economic optimization of battery sizing will be carried out, considering the following assumptions:

• The projected generation in this case allows covering a substantial part of the port's current electricity consumption through direct self-consumption, significantly reducing the electricity bill, with an avoided energy cost estimated at BRL 0.711 per kWh, according to the industrial tariffs in force in the State of Maranhão.

• However, due to the limitation of the available surface, this solution does not allow the full exploitation of the photovoltaic potential of the enclave, nor the complete coverage of port demand in certain periods. Additionally, the hourly generation curve does not always coincide with the consumption curve, which highlights the need to consider complementary electrical storage options to improve the self-sufficiency index.

• Given the current cost of stationary battery storage, estimated at BRL 2,000 per kWh installed [13], the optimal battery capacity was analyzed in this case, allowing the shifting of solar energy from hours of maximum generation to hours of higher demand, without incurring in unjustified oversizing.

• The balance between the investment cost in storage and the savings generated by the reduction of grid electricity consumption is crucial to determine the final feasibility of this scenario.
• The objective of the optimization is the maximization of the Net Present Value (NPV) of the investment, considering an internal discount rate of 4%.

To carry out the optimization, a battery optimization tool developed by Fundación Valenciaport was used.

Case Study 1: Photovoltaic installation on EMAP's buildings and parking areas

In this first scenario, only the installation of photovoltaic systems on the rooftops of administrative buildings and in the parking areas previously identified as technically viable within the port facility is considered. This option represents a strategy for utilizing already urbanized areas, with minimal impact on the soil, lower licensing complexity, and maximum architectural integration.

The optimization results are presented in the following table:

Figure 69 - Technical-economic parameters of storage capacity optimization (Case study 1).

DEMAND (2022)	INSTALLATION		
1000	Storage Power	307,2795715	kW
	Storage Capacity	2230,082314	kWh
	Solar Installation	6,6	MW
	Wind Installation	0	Aero
RENEWABLE GENERATION	Solar Production	3205,88	MWh
	Maximum Solar Generation	1,50	MW
	Wind Production	0,00	MWh
	Maximum Wind Generation	0,00	MW
DEMAND	Total Demand	2592,88	MWh
	Annual Average Demand	0,30	MWh/h
	Annual Maximum Demand	0,30	MWh/h
	Annual Minimum DemandL	0,30	MWh/h
STORAGE	Energy Spilled without Storage	2030,34	MWh
	Energy Spilled with Storage	1094,23	MWh
	Hours of Imbalance	3642	h
	Stored Energy	936,11	MWh
	Renewable Percentage with Storage	29,20%	%
	Energy Purchased from the Grid without Storage	622,03	MWh
	Energy Purchased from the Grid with Storage	1417,33	MWh
	Number of Cycles	364	Ciclos
	Average Battery Charge Percentage	38,17%	%
	Average Battery Power Utilization	83,65%	%
ECONOMICS	Investment in Storage (Estimated)	614.559,14	R$
	Investment in Solar Generation (Estimated)	-	R$
	Investment in Wind Generation (Estimated)	-	R$
	Total Investment (Estimated)	614.559,14	R$
	Electricity Purchase Price	0,711	R$/kWh
	Annual Savings with Electricity Purchase	565.458,04	R$
	OPEX	21.249,89	R$
	Cash Flow	565.458,04	R$
	Discount Rate	4%	
	NPV	3971812,08	R$

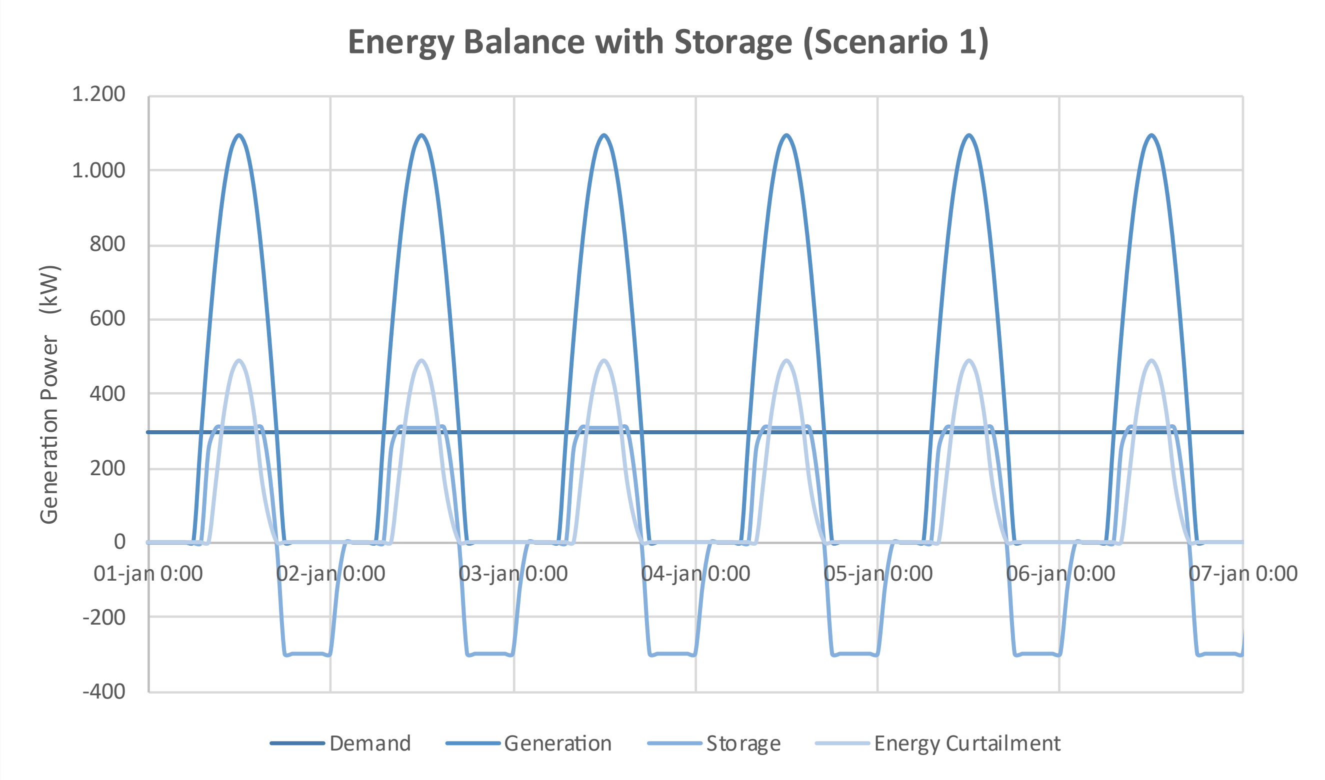
Source: Fundación Valenciaport.

For the first case study, an optimized value of 307 kW of required storage power and a total capacity of 2,230 kWh is obtained, which represents an investment of BRL 614,559 for the acquisition of the battery system. With this Configuration, an annual saving of BRL 565,458 in electricity purchases from the grid is generated.

In addition, there is a significant reduction in renewable energy curtailment (energy generated but not utilized due to grid limitations), which decreases from 2,030 MWh (63% of generation) to 1,094 MWh (34%). The maintenance costs of the storage installation are estimated at BRL 21,249 per year [14].

The following chart presents the energy balance for the first week of the base year considered.

Figure 70 - Energy balance with storage (Scenario 1).



Source: Fundación Valenciaport.

Case Study 2: Photovoltaic installation considering the complete installation

In the second scenario, the scope of the photovoltaic installation is expanded with the inclusion of an additional ground-mounted plant, located in areas outside the immediate facility but still within the port management area or under the jurisdiction of the State Government, such as adjacent yards or logistics expansion zones.

This alternative allows achieving a significantly higher installed capacity, which not only ensures full coverage of the port's current consumption but also enables new vectors of energy consumption, such as:

- Production of green hydrogen.
- Electrification of port equipment.
- Supply of energy to third parties.

This greater generation capacity inevitably produces a higher volume of daily solar surpluses, making the need for electrical storage more relevant. However, it also opens the possibility of employing part of this additional energy in flexible uses, such as hydrogen production, nighttime charging, or refrigeration systems, which reduces the pressure on the battery system.

Thus, this case allows not only the assessment of a larger-scale energy utilization strategy but also progress toward a model of integral energy self-sufficiency and distributed generation with added value.

Figure 71 - Technical-economic parameters of the optimization of storage capacity (Case study 2).

DEMAND (2022)	INSTALLATION		
1000	Storage Power	568,1136626	kW
	Storage Capacity	6650,266962	kWh
	Solar Installation	14,3	MW
	Wind Installation	0	Aero
RENEWAB LE GENERATI ON	Solar Production	6946,08	MWh
	Maximum Solar Generation	3,24	MW
	Wind Production	0,00	MWh
	Maximum Wind Generation	0,00	MW
DEMAND	Total Demand	2592,88	MWh
	Annual Average Demand	0,30	MWh/h
	Annual Maximum Demand	0,30	MWh/h
	Annual Minimum DemandL	0,30	MWh/h
STORAGE	Energy Spilled without Storage	5757,68	MWh
	Energy Spilled with Storage	4102,07	MWh
	Hours of Imbalance	4004	h
	Stored Energy	1655,61	MWh
	Renewable Percentage with Storage	23,84%	%
	Energy Purchased from the Grid without Storage	2,08	MWh
	Energy Purchased from the Grid with Storage	1404,47	MWh
	Number of Cycles	1	Ciclos
	Average Battery Charge Percentage	73,50%	%
	Average Battery Power Utilization	72,78%	%
ECONOMICS	Investment in Storage (Estimated)	1.136.227,33	R$
	Investment in Solar Generation (Estimated)	-	R$
	Investment in Wind Generation (Estimated)	-	R$
	Total Investment (Estimated)	1.136.227,33	R$
	Electricity Purchase Price	0,711	R$/kWh
	Annual Savings with Electricity Purchase	997.104,45	R$
	OPEX	46.041,43	R$
	Cash Flow	997.104,45	R$
	Discount Rate	4%	
	NPV	6951182,97	R$

Source: Fundación Valenciaport.

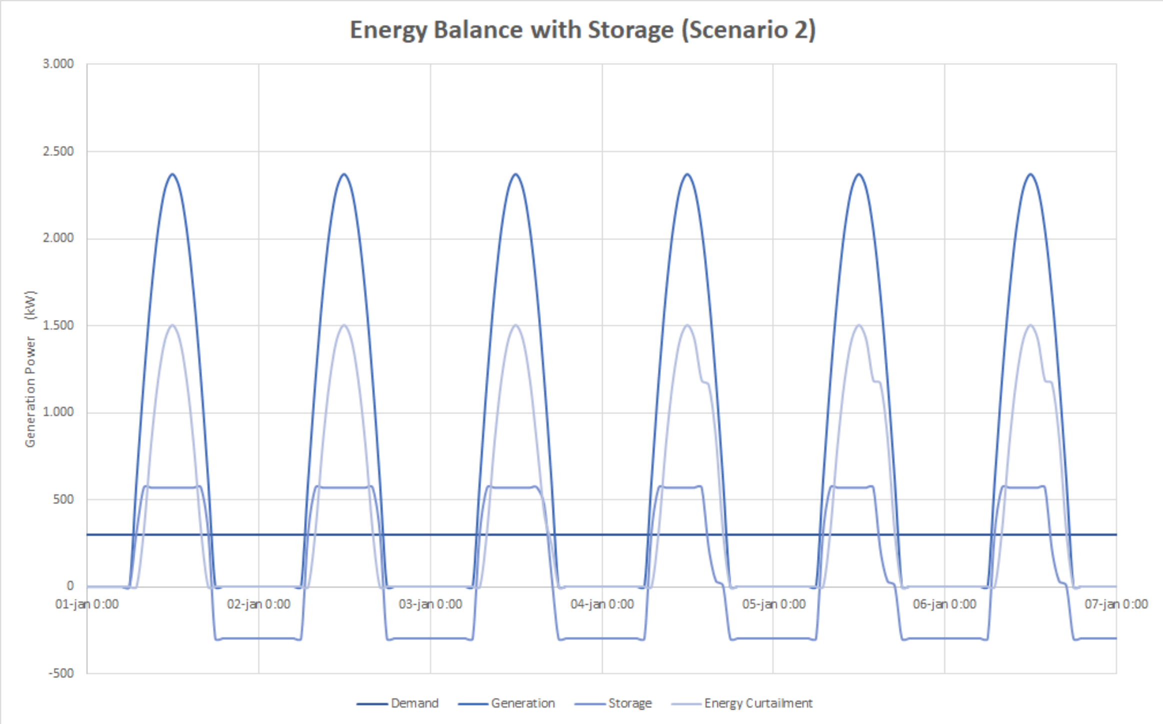
For the second case study, an optimization value of 568 kW of required storage power and a capacity of 6,650 kWh is obtained, which implies an investment of BRL 1,136,227 for the acquisition of the batteries. As a result, an annual saving of BRL 996,755 in electricity purchases is generated.

The renewable energy curtailments (due to the grid's inability to absorb) are reduced from 5,757 MWh (equivalent to 82% of generation) to 4,105 MWh (59%). The maintenance costs of the installation are estimated at BRL 46,041, proportional to the scale of the proposed solution.

This result shows that, even with optimized storage, a significant portion of the renewable energy generated cannot be utilized without the adoption of new system flexibility measures.

The following chart presents the projected energy balance for the first week of the base year considered:

Figure 72 - Energy balance with storage (Scenario 2).



Source: Fundación Valenciaport.

In comparative terms, the first case presents better relative efficiency in energy utilization, with lower investment and a higher proportion of self-consumption.

On the other hand, the second case, although less efficient from the standpoint of relative energy use, makes it possible to achieve higher absolute volumes of energy utilized and greater total savings, thanks to the larger scale of the installed solar generation.

Both scenarios demonstrate the technical and economic feasibility of combining solar generation and electrical storage in the port environment. However, they also highlight the need to develop complementary strategies — such as the use of green hydrogen, the electrification of equipment, or the implementation of microgrids — to take advantage of surplus renewable energy that cannot be absorbed by the grid or efficiently stored.

4. Subtask 3: Local Hydrogen Production

4.1. Assessment of the Hydrogen Generation Potential at the Port

The Port of Itaqui, thanks to its identified solar potential and the projected energy infrastructure, presents favorable technical conditions for the implementation of a local green hydrogen production facility. The proposed photovoltaic plant, with an installed capacity of 14.3 MWp and an estimated production between 6.4 and 7.7 GWh per year, provides a sufficient renewable energy base to partially or fully supply an electrolysis plant dedicated to hydrogen generation.

In this context, the sizing of an electrolysis unit with a maximum production capacity of 450 kg of hydrogen per day is proposed, which corresponds to an approximate annual production of 150,000 kg, considering continuous operation during the 365 days of the year.

This amount of hydrogen could be allocated to the refueling of port mobile equipment, internal logistics fleets, auxiliary systems, or external vehicles linked to port operations. This would allow the supply of approximately 10 port logistics machines already identified in the decarbonization plan.

This moderate-scale plan was chosen taking into account the maturity level of the technology, as well as the degree of implementation of these solutions in the port environment, which is still quite limited.

4.2. Proposed Capacity for the Electrolysis Plant

Based on the decarbonization strategy of the Port of Itaqui and the renewable potential identified in this study, the starting point considered was the sizing of an electrolysis plant capable of producing a maximum of 450 kilograms of hydrogen per day. This capacity is aligned with a scenario of progressive development of port and logistics demand, while at the same time ensuring a sufficiently representative scale to demonstrate technical and economic feasibility.

To achieve this daily production rate, it is first necessary to establish the relationship between the energy consumption of the electrolyzer and the efficiency of the process. Current commercial systems present energy consumption ranging between 50 and 55 kWh per kilogram of hydrogen produced, depending on the technology used, the purity of the feed water, and the output pressure. Assuming an average value of 52.5 kWh/kg H_2, the production of 450 kg per day will require an electrical consumption of 23,625 kWh per day.

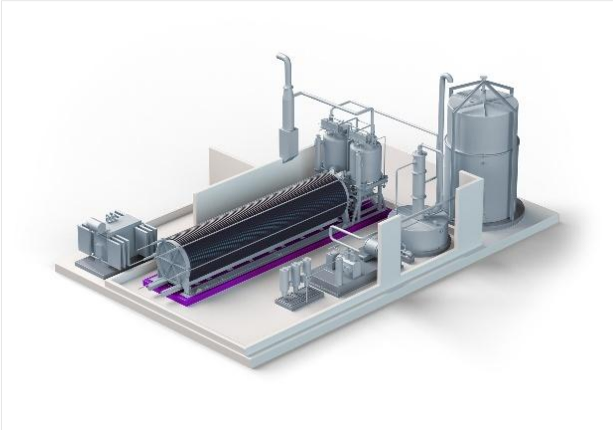
This daily energy demand is equivalent, in terms of nominal power, to 984 kW of continuous load over 24 hours. However, since renewable energy — in this case, solar photovoltaic — is not continuously available throughout the day, and considering the need for operational flexibility (due to maintenance, irradiance variability, or disconnections), the installation of an electrolyzer with a nominal power of 1 MW is proposed.

The electrolyzer may operate adjusted to the port's solar generation curve or maintain a more stable operation through the use of complementary grid electricity. This flexibility is critical to ensuring continuous hydrogen supply without the need to oversize the storage system.

Regarding electrolysis technology, two main alternatives currently consolidated in the market are considered:

Alkaline Electrolysis (AWE): a mature and widely available technology, with relatively low investment costs. Its main limitation lies in the lower response capacity to variations in electrical load, which may hinder direct integration with intermittent renewable sources such as solar photovoltaic.

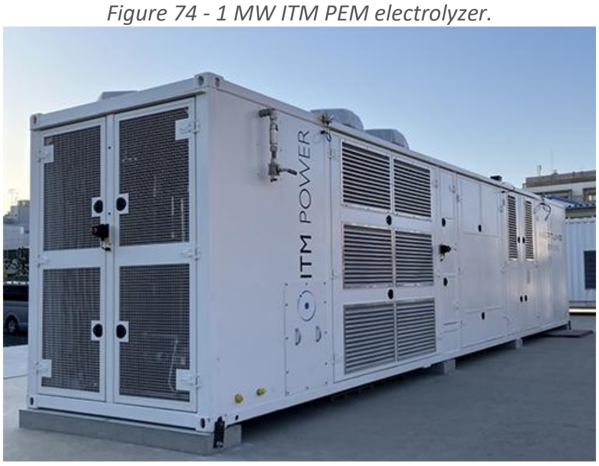
Figure 73 - Atmospheric Alkaline Electrolyzer | Nel Hydrogen.



Source: Nel Hydrogen.

PEM Electrolysis (PEM): latest technology, suitable for environments with variable power generation. It offers faster start-up times, higher energy density, and ease of operation at high pressures, although with a slightly higher acquisition cost than the alkaline option.

Figure 74 - 1 MW ITM PEM electrolyzer.



Source: ITM Power.

Considering that the plant will be partially connected to photovoltaic generation, with fluctuating production profiles, and prioritizing operational flexibility, the adoption of PEM technology is recommended for this first pilot installation at the Port of Itaqui. This choice allows maximizing the use of the available solar energy, reducing the risk of production loss due to the instability of the energy source, and facilitating future modular expansions of the system.

In the case of a daily production of 450 kg of hydrogen, a water requirement of approximately 5,000 to 6,750 liters per day is therefore estimated, which is equivalent to between 5 and 6.75 m³/day. The supply of this resource must be ensured from the Port of Itaqui's water supply network.

4.3. Proposed Technologies for Hydrogen Storage

As a storage and refueling system directly connected to the production described in the previous section, the implementation of a Hydrogen Refuelling Station (HRS), specifically adapted to the port environment, is proposed, following the operational model tested in the European H2PORTS project, currently in operation at the Port of Valencia.

The solution implemented in H2PORTS demonstrated technical and operational feasibility in a complex logistics environment, successfully serving heavy port equipment, such as a Reach Stacker and a tractor unit equipped with a fuel cell. The proposal for the Port of Itaqui consists of replicating this solution as a technological basis, adjusting its storage capacity to the projected energy demand in this study.

Specifically, it is proposed to triple the hydrogen storage capacity at low pressure, increasing from the 150 kg used in Valencia to 450 kg in Itaqui, with the aim of supporting a more intensive and continuous daily operation.

Figure 75 - Hydrogen refueling station of the H2Ports project located at the Port of Valencia..

Source: Fundación Valenciaport.

The proposed HRS will be composed of the following main subsystems:

• **Low-pressure storage unit (30–40 bar):** system composed of cylinder racks designed to contain up to 450 kg of hydrogen. This capacity would cover approximately a full day of operation, coinciding with the production rate of the designed electrolysis plant. Low-pressure storage allows greater safety in complex operational environments and reduces the technical requirements of transfer equipment.

• **Compression and refueling system:** compressor module that raises the hydrogen pressure from the primary storage to the levels required for refueling (350 or 700 bar, depending on the type of vehicle or equipment). This unit will be equipped with an automated control system, cooling, and flow management, as well as one or more dispensers with standardized connection.

• **Control, safety, and SCADA system:** integration of sensors, shut-off valves, leak detectors, ventilation and extinguishing systems, as well as a real-time remote monitoring system (SCADA) for the safe operation of the system.

• **Modular technical container (plug & play):** all systems will be integrated into a compact and transportable structure, allowing its installation in different areas of the port facility without the need for intensive civil works. The station can be relocated, scaled, or easily replicated in other areas of the port.

From a functional standpoint, this HRS will be able to serve the refueling of heavy logistics equipment, port service fleets, or even regional or long-distance transport trucks operating in the port's vicinity. The daily storage capacity of 450 kg coincides with the maximum hydrogen volume produced by the planned electrolysis plant, which allows closing a complete cycle of local generation, storage, and consumption, with no surpluses and no need for external evacuation.

4.4. Economic Sizing

The implementation of a complete infrastructure for the production, storage, and supply of green hydrogen at the Port of Itaqui requires not only a solid technological base but also rigorous and detailed economic planning. This section presents the overall economic sizing of the proposed system, considering the different components that make up the hydrogen value chain: from water electrolysis with renewable energy to intermediate storage and final dispensing for port or logistics applications.

The model adopted was developed based on criteria of modularity, scalability, and replicability, taking as a direct reference the European H2PORTS project, adapted to the operational, climatic, and regulatory conditions of the Brazilian context. As a baseline, an electrolysis plant with a nominal capacity of 1 MW is considered, with the capacity to produce up to 450 kg of hydrogen per day, in addition to a storage system in low-pressure tanks with equivalent capacity to ensure continuous daily operation. The Hydrogen Refuelling Station (HRS) was also sized to serve port equipment and heavy vehicles.

The costs presented here include all the elements necessary for a "turnkey" solution: equipment acquisition, water treatment, compression systems, safety, civil works, integration, and installation. This approach provides a clear view of the investment effort required for the implementation of the system, as well as assisting in future planning for expansion, operation, and maintenance.

The proposed economic estimate is not only a technical analysis tool but also an essential strategic input for evaluating financial feasibility, securing public or private funding, and decision-making in the context of the port's energy transition.

Table 22 - Estimated costs by functional block for green hydrogen system.

Functional block	Component	Technical description	Estimated cost (R$)
Generation	1 MW PEM electrolyzer	Complete system, includes stack, inverters, control and integration. Production: ~450 kg/day.	R$ 11.000.000
	Water treatment system	Reverse osmosis, for production of ~8 m³/day of ultrapure water.	R$ 700.000
	Plant balance and infrastructure	Civil works, electrical systems, cooling, controls and general integration.	R$ 2.500.000
Subtotal – Generation			**R$ 14.200.000**
Storage	3 low-pressure tanks (150 kg each)	Horizontal cylindrical tanks, in certified steel. Total capacity: 450 kg @ 30–40 bar.	R$ 1.600.000
	Instrumentation and safety system	Valves, pressure sensors, temperature control and purge, integrated into SCADA.	Incluído em outros blocos
Subtotal – Storage			**R$ 1.600.000**
Dispensing	High-pressure compressor (350–700 bar)	Multi-stage compressor, cooled, for supplying dispenser for vehicles or equipment.	R$ 2.000.000
	Dispenser (1 charging point)	Standardized dispenser with hose, coupling and internal cooling.	R$ 600.000
	Technical container + integration	Plug & play system in container skid with air conditioning, safety and SCADA.	R$ 1.600.000
	Installation and commissioning	Transport, licenses, assembly, documentation and training.	R$ 600.000
Subtotal – Dispensing			**R$ 4.800.000**
TOTAL		Generation, storage and refueling system of 450 kg/day of hydrogen	**R$ 20.600.000**

Source: Fundación Valenciaport.

4.5. LCOH Calculation – Levelized Cost of Hydrogen at the Port of Itaqui

The Levelized Cost of Hydrogen (LCOH) represents the average cost per kilogram of hydrogen produced over the entire lifetime of a plant, considering both the initial investment and the costs of operation, maintenance, water, and electricity. It is an essential indicator for evaluating the economic competitiveness of renewable hydrogen projects and comparing them with other production technologies or conventional energy vectors.

For the case of the Port of Itaqui, an installation was designed with the capacity to produce up to 450 kg of hydrogen per day, which represents an annual production of 164,250 kg. Over an estimated lifetime of 15 years, the plant would generate a total of 2,463,750 kg of hydrogen. The system is based on electrolysis powered by electricity, with a specific consumption of 52.5 kWh per kg of hydrogen, resulting in an annual electricity demand of approximately 8,621,000 kWh.

For the economic calculation, the most demanding investment scenario was considered, with a total implementation cost of BRL 20,600,000, including the electrolysis system, water treatment, low-pressure storage tanks, and the complete refueling station. To the capital costs are added the annual operating costs, mainly electricity, estimated at BRL 6,125,000/year based on the current industrial tariff in the state of Maranhão (BRL 0.711/kWh). Additionally, annual costs between BRL 750,000 and BRL 1,000,000 were considered for operation and maintenance, including ultrapure water, inspections, component replacement, and technical supervision.

Projecting these expenses over the 15-year lifetime, there would be approximately BRL 91,880,000 in electricity costs and up to BRL 15,000,000 in operation and maintenance, resulting in a total accumulated cost of BRL 127,480,000 when adding the initial investment of BRL 20,600,000. Dividing this value by the total estimated production of 2,463,750 kg of hydrogen yields an LCOH of approximately BRL 51.74 per kg of hydrogen.

Although this value is still higher than that of gray or blue hydrogen, it falls within the range considered reasonable for pioneering medium-scale projects partially connected to the electricity grid. The energy component represents more than 70% of the total cost, which reinforces the strategic importance of using the solar plant designed for the Port of Itaqui as the primary energy source for the electrolyzer. Integration with renewable generation will allow the reduction of hydrogen costs in the medium term, increase its competitiveness, and position the port as a low-carbon logistics hub in northern Brazil.

4.6. Integration with the Port’s Renewable Generation

One of the fundamental pillars of the proposed hydrogen production system for the Port of Itaqui is its direct integration with the 14.3 MWp photovoltaic solar plant assessed in this study. This installation, conceived specifically for use in a port environment, has an estimated annual electricity generation potential between 6.4 and 7.7 GWh, enough energy to power a 1 MW electrolysis plant and enable the daily production of up to 450 kg of green hydrogen.

Photovoltaic solar generation presents limited and variable hourly availability, concentrated between 8 a.m. and 5 p.m., with production peaks at midday. This generation curve, typical of tropical regions such as Maranhão, reasonably coincides with the operating profile of electrolysis, especially if configured to operate during solar hours, taking advantage of the months with higher irradiance. For this reason, the PEM (Proton Exchange Membrane) technology was selected, as it stands out for its ability to operate with good efficiency at partial loads and respond quickly to variations in renewable generation. This technology allows frequent starts and stops without compromising stack durability, making it ideal for coupling with intermittent sources such as solar.

During periods of higher photovoltaic generation, the plant will be able to directly meet a large part of the electrolyzer’s demand, reducing grid consumption and, consequently, the final cost of the hydrogen produced. In periods with lower solar generation (due to weather, excess demand, or outside solar hours), the system can use the electrical grid as support, ensuring continuity of operation without the need to oversize storage.

To efficiently manage this dynamic balance between generation, consumption, and storage, the implementation of an Energy Management System (EMS) is recommended, capable of controlling in real time solar production, electrolyzer operation, hydrogen tank charge state, and consumption forecasts. This tool will allow maximizing the use of renewable energy, optimizing the overall efficiency of the system, and ensuring operational safety and stability.

The comparative study shows that the integration between green hydrogen production and the photovoltaic plant significantly improves solar energy utilization:

• Scenario 1 (only distributed generation – rooftops and parking lots): Energy utilization increases from 73.6% to 88.5% with the inclusion of the electrolyzer, representing a 14.9% improvement in system efficiency.

• Scenario 2 (with inclusion of ground-mounted solar plant): Utilization increases from 25.2% to 46.7%, a gain of 21.5%, thanks to the hydrogen system's ability to absorb renewable generation surpluses.

These results prove that hydrogen acts as a strategic vector to valorize renewable energy not consumed in real time, contributing to a more efficient, flexible, and sustainable energy model.

The functional and energy integration between the photovoltaic plant and the hydrogen production system enables the closing of a local, emission-free production cycle, adapted to the port operational environment and with high strategic value. This synergy positions the Port of Itaqui as a national and Latin American benchmark in the energy transition of the port sector, with a replicable, scalable model aligned with national and international decarbonization objectives.

5. Conclusion

The present study demonstrated the technical, energy, and strategic feasibility of an integrated proposal for local renewable generation, based on photovoltaic solar energy, combined with the production of green hydrogen as a complementary vector of decarbonization. Through a detailed analysis of the existing infrastructure, local climatic conditions, and the consumption profile of the port area, a robust, scalable energy model was defined, adapted to the operational characteristics of an expanding maritime logistics environment.

The characterization of the port's solar potential evidenced the availability of sufficient areas for the installation of photovoltaic systems distributed on building rooftops, parking lots, and adjacent external lands. This installed capacity makes it possible to achieve a volume of renewable generation greater than EMAP's current electricity consumption, paving the way not only for energy self-sufficiency but also for the development of new electrical applications or the supply of alternative energy vectors.

Regarding energy storage, the study identified the opportunity to incorporate battery solutions as an essential component of the designed photovoltaic plant. This solution becomes especially relevant given the hourly variability of solar generation, which, although abundant, is intermittent. The implementation of storage systems would maximize the use of renewable energy generated during hours of higher radiation, enabling its use during periods of lower generation or higher demand. In addition, storage would contribute to the operational stability of the port's internal electrical system, reduce dependence on the grid in critical situations, and reinforce the facility's energy security.

The proposed hydrogen production plant was conceived as a proportional, realistic, and technically feasible solution, compatible with the current state of technology, planned to operate in an integrated manner with local solar generation and in line with the port's energy needs. Its implementation enables not only the reduction of the environmental impact of certain logistical processes but also positions the Port of Itaqui as a demonstrator hub of clean technologies, capable of attracting investments, innovation projects, and sustainable trade flows.

As a whole, the project proposes a clear route toward a low-carbon port model, supported by mature, economically justifiable, and environmentally responsible technologies. The Port of Itaqui has the natural resources, technical infrastructure, and strategic context necessary to lead this transformation — consolidating itself as a national and international benchmark in the energy transition applied to the maritime-port sector.

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