

Article

Optimization of Port Layout to Determine Greenhouse Gas Emission Gaps

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Abstract: Ports are of great strategic importance for a country. Nowadays, compliance with environmental requirements is required, forcing the migration towards clean energies. Therefore, it is necessary for emerging ports, as those in developed countries, to incorporate in their policies the use of electric power in the machinery that moves containers in the terminals. To learn how the problem is addressed in other countries, an extensive bibliographic review is presented. Then, the energy policies and criteria of a group of ports in an emerging country and a European port are studied. Subsequently, in order to determine the gaps between the ports investigated, the layout of the cargo yard of each of the terminals is optimized; the emissions of Carbon Dioxide (CO₂) and other Greenhouse Gases (GHG) gases are calculated; and finally, the decrease in emissions when switching from diesel to electricity is estimated. The strategic and operational gaps related to energy management between the emerging and developed countries are discussed. It is concluded that research is needed to investigate how these initiatives impact the city and improve other sustainable aspects.

Keywords: CO₂ emissions; optimization; port terminal



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1. Introduction

The globalization has increased exports and imports in the country, which have generated more container traffic in port terminals [1]. The implementation of strategic sustainable actions is a relevant factor for business models, especially for the implementation and development of good practices related to automation in port enclosures to optimize the functioning of their operations and improve the quality of service [2,3].

On the other hand, ports are considered logistic centers in which economic, human, infrastructural and technological resources are required to carry out their activities [4]. In terminals, it is necessary to optimize the planning of the design of the facilities in order to have an efficient layout that minimizes the costs of cargo movements, energy consumption of equipment, etc. [5,6].

Containers loaded with perishable and non-perishable products are transported daily in the ports during import and export activities. These land and maritime operations generate pollution due to the emission of Greenhouse Gases (GHG) such as Carbon Dioxide (CO₂) from different sources—namely, (1) main and/or auxiliary ships engines and boilers; (2) trucks arriving at the port for loading and unloading of goods; and (3) the use of fuels by the equipment operating in the port [7–9].

Currently, it is a priority for port authorities to include in their planning actions that reduce energy consumption and GHG emissions generated by climate change [9,10]. To improve energy management, research has optimized the planning of port operations with mathematical models that have an objective function related to energy consumption in ship loading and unloading yards [11,12].

Although Chile is considered efficient in its logistics management, it is just beginning the energy transition, as noted in the use of fossil-fuel-based material handling equipment at terminals [13]. Significant gaps exist between developed and developing countries, as investing in cleaner energy requires high investments and further technological development [7,14].

In green ports, the need to reduce emissions in order to achieve energy efficiency has been studied; thus, the use of fossil fuels has been reduced and the use of electrical energy has been increased [11,15]. Technology advances have generated a positive relationship between operational efficiency and energy efficiency, in which fifth-generation ports manage energy with significant cost savings by electrifying equipment and its components (batteries, distributors and converters) [16–18].

The energy consumption and CO₂ emissions of the Port of Valencia in Spain have been investigated, where it was identified that the main equipment responsible for emissions correspond to the terminal tractors and the gantry cranes with tires, Rubber Tyred Gantry (RTG); the authors proposed a solution to change the equipment for others that use liquefied natural gas [10].

Due to the strategic importance of this environmental issue for a country's public policies, a detailed study is needed on the energy consumption of terminals that are major energy consumers and, therefore, CO₂ emitters [10,15].

Unlike the traditional semi-automated systems of Latin American countries in which containers are located in parallel, in developed countries the layout is optimized by locating the blocks perpendicularly depending on their dimensions (length, width and height) [19]. Examples of block distribution in green ports include the Maasvlakte II terminals in Rotterdam, Long Beach in the US and the ACT Yangshan IV in China [6].

Motivation

In Latin American countries, the generation of more strategic policies and business objectives that increase levels of sustainability, investment in technology and operational efficiency are required in port areas, in order to reduce energy consumption in container yards and reduce costs [13,20]. Therefore, the motivation of this study is to determine which are the main sources that generate greenhouse gas pollution in fifth-generation ports, in order to create a method able to optimize the energy management of port operators and their terminals in three ports in Chile.

Chilean ports in recent years are beginning to implement aspects of sustainability as those of green ports to reduce fuel consumption, and emissions are being handled to obtain the European EcoPorts certification [7]. Chilean ports can be classified as part of Industry 3.0 but with some characteristics of Industry 4.0 [21]. They are automated and most of the cargo in port facilities is moved using fossil fuels (diesel, gasoline, liquefied natural gas and liquefied petroleum gas) [20]. According to the results of the Energy Consumption and Emissions Survey carried out in the State Port Companies for the operation of the year 2020, the largest amount of CO₂ emissions are generated in the terminals by the use of both fuels and the handling of the load by the equipment (cranes, stackers, trucks, etc.), and the fact that only a third of the energy consumption of the four terminals that have a greater movement of cargo is by electricity [22].

Due to the importance of reducing CO₂ emissions and using cleaner technologies in publicly owned ports conceded to private companies [23], this research aims to identify the current port situation and show the need to carry out more investigation in this field to improve port sustainability.

In addition, in order to establish the gaps that are present in the terminals with more cargo transfer such as the small Chilean Port of Arica and a large semi-automated European port, a case study was included in which the CO₂ emission parameters for diesel and electricity shown in the Section 4.1 below will be used.

Finally, the current investigation aims to assess the relevance of saving on energy consumption by optimizing the movement of cargo in container yards when moving from

a diesel matrix to an electric matrix in Chilean ports with more cargo transfer, which are the medium-sized operators located in the Valparaíso Region: Port of Valparaíso and Port of San Antonio [24].

2. Energy Management in Ports

2.1. Location Ports

Figure 1 shows the locations of the ports of Valencia in Spain, and of Valparaíso, of San Antonio and Arica in Chile.

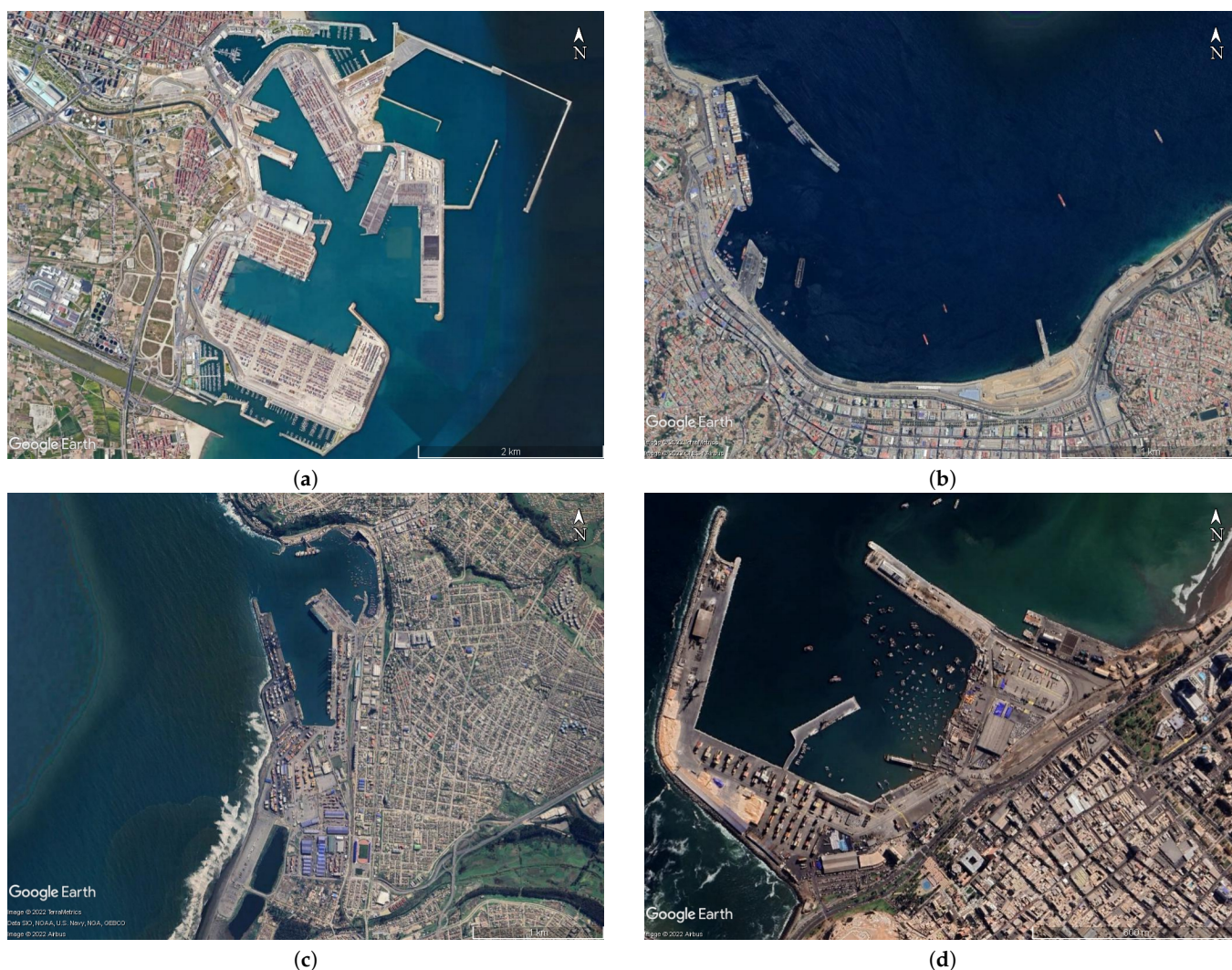


Figure 1. Location port in Google Earth: (a) Port of Valencia, <https://shorturl.at/hilrY>, accessed on 20 September 2022; (b) Port of Valparaíso <https://shorturl.at/dyENV>, accessed on 20 September 2022; (c) Port of San Antonio <https://shorturl.at/ASW37>, accessed on 20 September 2022; (d) Port of Arica, <https://shorturl.at/hkqz4>, accessed on 20 September 2022.

2.2. Literature Review

The literature is reviewed in the WOS and SCOPUS databases on topics related to the improvements that maritime ports have made to their layouts to reduce the greenhouse effect.

To determine the effects of greenhouse gases on port facilities, as shown in Table 1, keywords are used to search the repositories of the WOS and Scopus databases. Table 2 summarizes the information obtained in Table 1.

Table 1. Search summary.

Database	Script	Results
WoS ¹	TS = (Layout AND (Maritime OR SeaPort) AND (Optimization OR GHG OR CO2 OR “Carbon dioxide”))	28
SCOPUS	TITLE-ABS-KEY (layout AND (Maritime OR Seaport) AND (Optimization OR GHG OR CO2 OR “Carbon dioxide”))	45

¹ Accessed on 29 September 2022, <https://www.webofscience.com/wos/woscc/summary/592a0b72-715d-4854-8432-036930f3b7e0-528ad3de/relevance/1>.

Table 2. Summary of optimization applications in ports.

Author	Methodology/Method	Description	Study Case
[25] ^{1,2}	Optimization, simulation and queuing theory	Literature review of the evolution of layout designs with container stacking systems in ports, moving from traditional to next-generation automated systems. The problems that are generated in strategic, tactical and operational decision-making are identified.	Ports of Hamburg, Hong Kong, Singapore, Rotterdam, Long Beach and Venice
[26] ¹	Bi-objective optimization, non-linear model that is solved with epsilon method	Analyzes intermodal transport and proposes a design to optimize the transport networks of the layout in container terminals. It seeks to meet the high demand for containers with low greenhouse gas emissions, reducing costs and travel times. Optimal Pareto solutions are obtained.	Port of Montreal in Canada
[27] ^{1,2}	Bi-objective optimization, integer linear programming model that is solved with the epsilon method and heuristics	Minimizes the total rotation time and delay of departure of ships to reduce operational costs and fuel consumption of maritime transport. In addition, it minimizes the maintenance cost and energy consumption of dock cranes, as they represent a bottleneck in port terminals. A Pareto solution is obtained that dominates the strategies used for maintenance.	Port terminal in China
[28] ^{1,2}	Discrete event simulation model, with a mixed integer optimization routine	Proposal of a methodology to evaluate the potential benefits of new berthing policies and shipping contracts. It follows the logic of a planner and solves the traditional problem of allocation of berths in a terminal and the use of fuel by ships.	Port terminal
[29] ¹	Integrated discrete event simulation	Design of stacking configurations in the yards and in container terminals in seaports. The dimensions of the containers and the performance of the cranes and trucks are identified, and the optimal value of the average delivery of the ships is calculated.	Generic Container Terminals
[30] ¹	Linear Programming	Combines the problems of tactical berth assignment and dock crane specific assignments, with the aim of minimizing container transshipment distances within the terminal yard and reducing costs.	Terminal
[31] ¹	Stochastic route model for street vendors	Problem of uncertain waiting times at port terminals and inefficient transit caused by severe congestion. The optimal route for a boat is determined.	Port of Houston
[32] ¹	Markov Chain	Analysis of the distribution of the number of container relocations that do not generate added value in empty container yards, by using a crane, stacker and top elevator. Container relocation decreases operating costs.	Terminal
[33] ²	Workflow optimization	Research focused on maritime infrastructure construction, proposing a workflow to evaluate energy and CO ₂ emission for maritime infrastructure projects.	Maritime infrastructure projects
[34] ²	Integration of optimization methods and machine learning techniques	It presents the problem of container relocation in port terminals, with the objective of finding the optimal movement sequence to minimize the total number of container relocation operations. Using algorithms based on machine learning and optimization methods, to solve the problem, using the upper bound method called MLUB that incorporates branch pruners.	Port terminals

¹ WoS. ² Scopus.

Table 2 shows that almost all research has case studies on fifth-generation ports and that there is a lack of publications related to ports in developing countries.

2.3. Strategic Gaps between Chilean and Spanish Ports

In order to study the strategic gaps in the sustainable aspects in the ports of Valparaíso, San Antonio, Arica and Valencia, the environmental and energy policies were reviewed based on the documentation available on their corresponding port websites.

Based on the strategic actions defined by each company on their website, the following Table 3 was created, which shows the key strategic criteria to assess port sustainability. In parallel, with the information of the repositories of each port and the evaluation of two experts in port issues, the degree of compliance with environmental and energy policies was evaluated with the Likert scale [35,36], wherein 1 is non-compliance, 2 is low compliance, 3 refers to medium, high (4) and very high (5) compliance. It is noted that those responses greater than 1 were justified in order to identify the relevant aspects that have been executed.

From Table 3, it can be noted that Chilean ports have a low compliance level when compared with the Port of Valencia. This is observed in the results of the application of the Likert scale, where the Port of Valencia has approximately double the scores of each Chilean port.

This is explained due to the fact that the ports of Valparaíso, San Antonio and Arica are beginning to define actions to improve environmental and energy policies, which is observed in the existing instruments and collaboration agreements between the State, trade associations and port companies, related to clean production (NAMA, CPA), territorial dialogues, subsidies to implement best practices in clean production, technical advice and technology transfer [37].

It should be noted that the agreements are voluntary and that the Chilean ports have reduced the fuel burning, the consumption of electricity and the waste that is sent to landfills [38].

On the other hand, the Port of Valencia is a large, fifth-generation port. It has the Ecoport seal and defines as objectives for the year 2030 to have zero emissions and to be fully electrified. It is also developing the Wave Energy Converter project to generate green energy [39].

Table 3. Environmental and energy policies of ports.

Criteria	Valparaíso ¹	San Antonio ²	Arica ³	Valencia ⁴
Protects the environment	3: ISO 14000 Standard	3: Agreement for clean production in waste management (CPA)	3: CPA	4: Ecoport, Iso 14001 and Iso 14064 Standards
Reduces environmental footprint	1	1	1	4
Efficiency in the use of natural and energy resources	2: Identifies opportunities	2: Encourages practices	3: Manages and optimizes	4: In the strategic and operations plan
Reduction in greenhouse gas emissions	1	1	1	4: Incorporation of clean energy
Cultural change	2: In operations, to make them more environmentally friendly	2: Publishes environmental strategies on the website	2: Publishes sustainability strategies on the website	3: Makes knowledge explicit
Eco-efficiency	2: Acquires new eco-efficient mobile cranes ⁵	1	1	3: Transition from fossil fuel to electricity

Table 3. Cont.

Criteria	Valparaíso ¹	San Antonio ²	Arica ³	Valencia ⁴
Environmental and energy-related legal requirements	1	1	1	3: Not mandatory
Minimize emissions, consumption and waste generated by operations	3: From the design stage in port projects, it is considered to minimize risks of negative impacts on the environment ⁶	1	1	5: Develops and implements projects
Uses clean technologies	1	1	1	3: It has active projects to incorporate hydrogen technologies
Considers the UN Sustainable Development Goals	5	5	5	5
Total Sum	21	18	19	38

¹ Valparaíso, (accessed on 8 August 2022) <https://www.puertovalparaiso.cl/sostenibilidad>. ² San Antonio, (accessed on 8 August 2022) <https://www.puertosanantonio.com/sustentabilidad>. ³ Arica, (accessed on 8 August 2022) <http://puertoarica.cl/politica-de-sostenibilidad>. ⁴ Valencia, (accessed on 8 August 2022) <https://www.valenciaport.com/medio-ambiente/>. ⁵ Portal Portuario, (accessed on 9 August 2022) <https://portalportuario.cl/ee-uu-seaport-manatee-y-logistec-usa-dan-la-bienvenida-a-dos-nuevas-gruas-moviles-portuarias-ecoeficientes/>. ⁶ Reporte de Sostenibilidad, Valparaíso, (accessed on 9 August 2022) https://www.puertovalparaiso.cl/epv/site/docs/20220330/20220330171415/reporte_sostenibilidad_2016.pdf.

3. Materials and Methods

The methodology begins with a literature review to explain the context and identify the differences in the methods used to study different port cases worldwide. Then, the criteria of the sustainable strategic policies defined by the three Chilean ports and the Spanish port are evaluated using the Likert scale in order to assess the gaps that exist between the ports of a developing country and a developed country.

On the basis of [5,40], the optimization equations and their restrictions are proposed to determine the greenhouse gas emissions in the port terminals studied. With the method obtained in this section and discussed in Section 4, the parameters and GHG emissions in the ports of Valparaíso, San Antonio, Arica and Valencia are calculated. Finally, a conceptual evaluation of the strategies and sustainable operational aspects is carried out.

The development of the optimization method is shown below:

It is considered as the path of a 20 foot container in the Terminal Port to the following transport flows:

- In the loading process, the flow is divided into two sections: (1) the truck transports it to the yard where it is stored for an interval of time; (2) transport from the loading yard to the ship by a crane.
- In the unloading process, the flow is divided into two sections: (1) from the ship, it is transferred to the yard by a crane; (2) transport from the yard to the truck.

The flows are considered to be continuous. As shown in Figure 2, the dimensions of a 20-foot container are defined as X, Y and Z. The 20 feet correspond to the longest dimension of the container, which is the X in Figure 2. The other dimensions of the container are 8 feet on each side, corresponding to the Y and Z axes in Figure 2.

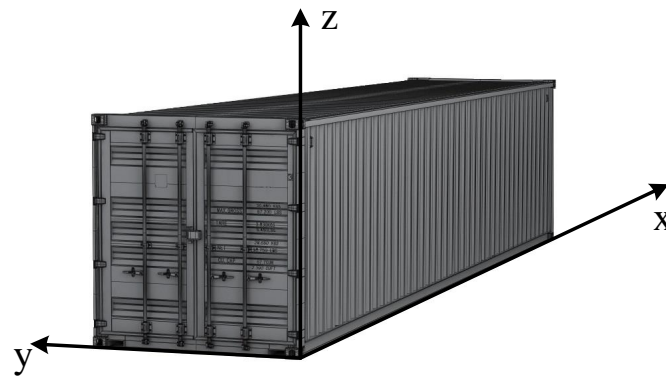


Figure 2. Dimensions of a 20-foot container: $x = 6.096$ m, $y = 2.4384$ m, $z = 2.4384$ m.

The movement of the container is defined in the dimensions X, Y and Z (see Figures 2 and 3):

$$T_x = \frac{N(a + v)}{2} \tag{1}$$

$$T_y = \frac{M(l + u)}{2} \tag{2}$$

$$T_z = \frac{H}{2} \tag{3}$$

With the results of (1), (2) and (3), the total movement of a container is calculated:

$$T = T_x + T_y + T_z \tag{4}$$

with the following:

- N : number of containers at dimension x ;
- a : container width;
- v : space between containers at dimension x ;
- M : number of containers at dimension y ;
- l : container length;
- u : space between containers at dimension y ;
- H : height of containers at dimension z in meters;
- T : the average distance traveled by a container.

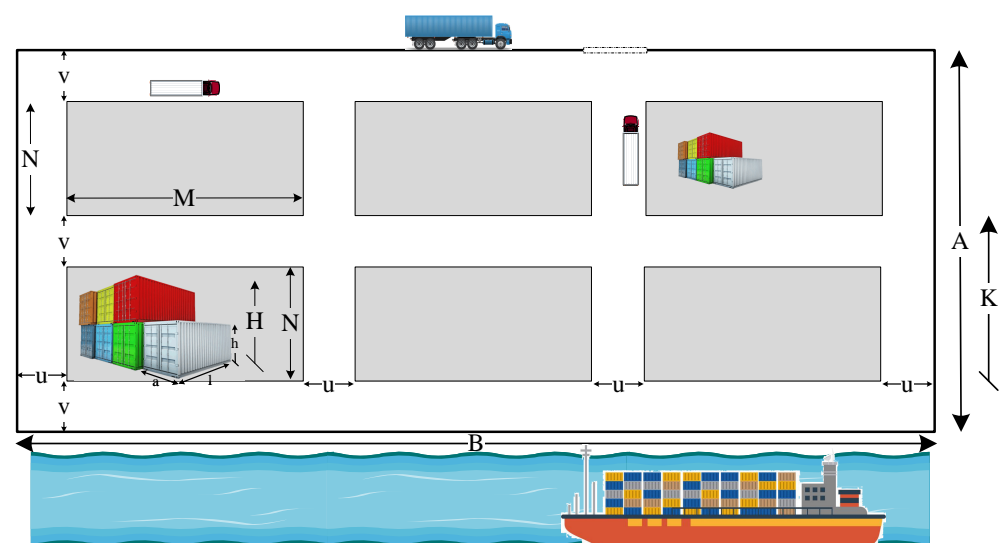


Figure 3. Layout of the container yard.

We consider the assumptions that parameters A (length of the yard), B (width of the yard) and K (height of the yard) are known (Figure 3).

Then, an optimization model is proposed that seeks to determine the number of containers that should be stored in the loading yard. It is worth mentioning that the formulas proposed are based on research related to the design of industrial type rectangular warehouses in Chile [5] and in other industries [40].

The objective function is to minimize the total distance that a container travels in the cargo yard, whether it comes from a ship or a truck.

$$\min: T \quad (5)$$

subject to

$$A = N(a + \frac{1}{c}v) \quad (6)$$

$$B = M(l + \frac{1}{s}u) \quad (7)$$

$$K = H + S \quad (8)$$

$$V = N(a + \frac{1}{c}v) * M(l + \frac{1}{s}u) * H \quad (9)$$

wherein,

$$N \geq 0, M \geq 0, H \geq 0, S \geq 0$$

$\lambda_1, \lambda_2, \lambda_3, \lambda_4$: restrictions associated to Equations (5)–(8);

K: height of the yard measured in meters;

S: height restriction adjustment in meters;

c: constant that indicates between how many containers an aisle of v width is created in direction y ;

s: constant that indicates between how many containers an aisle of u width is created in direction x ;

V: ideal volume of the loading yard.

The objective function shown in expression 10 describes the Total Carbon Dioxide (TCO₂) emissions in tons generated by the average travel of the containers that are mobilized in the loading and unloading yard in a year. By minimizing it, the optimized ideal values of M, N and H are obtained, which are used in the calculations of the emissions in Section 4.

$$\min : \text{TCO}_2 = \text{CO}_2 d \left[\frac{N(a + \frac{1}{c}v)}{2} + \frac{M(l + \frac{1}{s}u)}{2} + \frac{H}{2} \right] \quad (10)$$

d: cargo moved at the terminal in one year, in Twenty-foot Equivalent Unit (TEU).

Forming the Lagrangian of the objective function TCO₂ under the constraints (5)–(8) yields

$$L = \text{TCO}_2 + \lambda_1 [A - N(a + \frac{1}{c}v)] + \lambda_2 [B - M(l + \frac{1}{s}u)] + \lambda_3 [K - (H + S)] + \lambda_4 [V - N(a + \frac{1}{c}v) * M(l + \frac{1}{s}u) * H]$$

By calculating the partial derivatives with respect to each variable, the following is obtained:

$$\frac{\partial L}{\partial N} = \frac{\text{CO}_2 d (a + \frac{1}{c}v)}{2} - \lambda_1 - \lambda_4 (a + \frac{1}{c}v) * M * (l + \frac{1}{s}u) H = 0 \quad (11)$$

$$\frac{\partial L}{\partial M} = \frac{\text{CO}_2 d (l + \frac{1}{s}u)}{2} - \lambda_2 - \lambda_4 N * (a + \frac{1}{c}v) * (l + \frac{1}{s}u) * H = 0 \quad (12)$$

$$\frac{\partial L}{\partial H} = \frac{\text{CO}_2 d}{2} - \lambda_3 - \lambda_4 N * (a + \frac{1}{c}v) * M * (l + \frac{1}{s}u) = 0 \quad (13)$$

$$\frac{\partial L}{\partial \lambda_1} = A - N * (a + \frac{1}{c}v) = 0 \quad (14)$$

$$\frac{\partial L}{\partial \lambda_2} = B - M * (l + \frac{1}{s}u) = 0 \quad (15)$$

$$\frac{\partial L}{\partial \lambda_3} = K - (H + S) = 0 \quad (16)$$

$$\frac{\partial L}{\partial \lambda_4} = V - N * (a + \frac{1}{c}v) * M * (l + \frac{1}{s}u) = 0 \quad (17)$$

$$N \geq 0, M \geq 0, H \geq 0, S \geq 0; \text{unrestricted } \lambda_1, \lambda_2, \lambda_3, \lambda_4$$

and the following results are achieved:

from Equation (14),

$$\Rightarrow N = \frac{A}{a + \frac{1}{c}v} \quad (18)$$

from Equation (15),

$$\Rightarrow M = \frac{B}{l + \frac{1}{s}u} \quad (19)$$

from Equation (16),

$$\Rightarrow H = \frac{V}{N(a + \frac{1}{c}v) * M(l + \frac{1}{s}u)} \quad (20)$$

The values λ_i are not relevant since the values of N, M and H do not depend on them and are only calculated to check for global coherence. For simplicity, $\lambda_4 = 1$ is set, obtaining the expressions as shown below:

from Equation (11),

$$\lambda_1 = \frac{1}{2} \text{CO}_2 d * (a + v) - (a + \frac{1}{c}v) * M * (l + \frac{1}{s}u)H] \quad (21)$$

from Equation (12),

$$\lambda_2 = \frac{1}{2} \text{CO}_2 d * (l + u) - (a + \frac{1}{c}v) * N * (l + \frac{1}{s}u)H \quad (22)$$

from Equation (13),

$$\lambda_3 = \frac{1}{2} \text{CO}_2 d - N * (a + \frac{1}{c}v) * M * (l + \frac{1}{s}u) \quad (23)$$

4. Estimation of GHG Emissions for Port Terminals

4.1. Calculation of CO₂ Emission

In the present work, Tables 4–6 show the emission of CO₂ in the terminals of the ports of Valparaíso, San Antonio, Arica and Valencia. For the calculations, the parameters mentioned in Table 7 were used, which are based on the method of energy efficiency in ports [41], the technical report of the Port of Valencia [42], the ISO 668:2020 standard [43] and the information prepared by McKinsey [44], in which it is shown that at a global level for 2021 the relationship between consumption of electricity and fossil fuel were 36% and 64%, respectively.

The year 2021 is considered as representative since the previous periods were the years of pandemic, in which there were lower CO₂ emissions. It should be noted that during COVID there were logistic problems at a global level that had not been seen before; in this new scenario, the movement of cargo in the terminals decreased, logistic times increased and, therefore, less equipment was used to move containers in the ports [45–47].

The following Tables 4–6 show the CO₂ estimation of the port sites based on the information obtained from the document of the Inter-American Commission of the Port of Valencia [41], the optimized Formulas (5)–(10) and (18)–(20), the results of Table 7 and the data of the cargo transferred during the year 2021 in the loading and unloading yards of containers of the three Chilean ports that are analyzed in this research [42,48,49].

It is considered that the height of a crane is standard and the height of the yard is N = K = 10 (m), and it is assumed that cranes and other equipment pass from diesel to electricity for the calculation of the decrease in CO₂ emission.

Table 4. Emission of CO₂ in the Port of Valparaiso in 2021.

Concept	Valpo. Sites 1, 2 and 3	Valpo. Sites 4 and 5	Valpo. Site 6	Valpo. Site 7	Valpo. Site 8
Transferred cargo (t)	7,254,930	147,660	296,751	16,810	1,078,111
d: equivalent containers (TEU)	536,865	10,927	21,960	1244	79,780
A: terminal length (m)	740	266	245	120	240
B: terminal width (m)	100	133	97	97	97
K: crane height (m)	10	10	10	10	10
M: Number of containers	15	20	15	15	15
N: Number of containers	238	86	79	39	77
TCO ₂ electricity t-year	661	6	11	0.39	39
TCO ₂ diesel t-year	7963	75	132	4	473
TCO ₂ total t-year	8624	82	143	5	513
TCO ₂ 100% electricity t-year	1836	17	30	1	108
Emission reduction using electricity TCO ₂ -year	6788	64	112	4	403

Table 5. Emission of CO₂ in the Port of Arica and Port of San Antonio in 2021.

Concept	Arica	South Seawall Sites 1, 2 and 3	Breakwater Sites 4, 5, 6 and 7	North Terminal, Site 8
Transferred cargo (t)	2,969,153	14,819,221	2,106,204	2,482,914
d: equivalent containers (TEU)	170,178	1,096,622	155,058	183,736
A: terminal length (m)	400	253	341	186
B: terminal width (m)	100	200	300	100
K: crane height (m)	10	10	10	10
M: Number of containers	15	30.32	45.48	15.16
N: Number of containers	129	81.48	109.82	59.90
TCO ₂ electricity t-year	125	707	140	77
TCO ₂ diesel t-year	1504	8514	1686	931
TCO ₂ total t-year	1629	9220	1826	1008
TCO ₂ total t-year 100% electricity	344	1679	391	215
Emission reduction using electricity TCO ₂ -year	1282	7257	1437	794

Table 6. Emission of CO₂ in the Port of Valencia in 2021.

Concept	1	2	3	4	5	6	7	8	9
Transferred cargo (t)	4,149,362	2,074,681	518,670	518,670	1,037,340	4,149,362	10,373,405	757,918	1,842,309
d: equivalent containers (TEU)	307,053	153,526	38,382	38,382	76,763	307,053	767,632	56,086	136,331
A: terminal length (m)	1230	430	281	347	182	770	2310	595	837
B: terminal width (m)	400	400	180	180	200	437	627	200	200
K: crane height (m)	10	10	10	10	10	10	10	10	10
M: Number of containers	61	61	27	27	30	66	95	30	30
N: Number of containers	396	138	90	112	59	248	744	192	270
TCO ₂ electricity t-year	717	177	25	29	41	523	3239	64	205
TCO ₂ diesel t-year	8642	2134	303	348	493	6301	39,035	773	2466
TCO ₂ total t-year	9360	2311	328	376	534	6824	42,274	837	2671
TCO ₂ total t-year 100% electricity	1992	492	70	80	114	1452	8999	178	568
Emission reduction using electricity TCO ₂ -year	7367	1819	258	296	420	5371	33,276	659	2102

¹ Levante Pier. ² Llovera Pier. ³ Turia Breakwater North Pier. ⁴ Turia Breakwater South Pier. ⁵ Turia Breakwater Testero Pier. ⁶ MSC Valencia Terminal SAU. ⁷ CSP Iberian Valencia Terminal. ⁸ TEMAGRA (Bulks). ⁹ Tepsa + Galp + Teva (Liquid Bulks).

Table 7. Parameters of CO₂ emissions by 2021.

Concept	Units	Value	Ref.
Container width	m	2.4384	[43]
Container length	m	6.096	[43]
Container height	m	2.4384	[43]
(1) Average electricity consumption per container and m transported	KWh/TEU-m	0.01492	[41,42]
(2) Emission of CO ₂ by use of electricity	kg CO ₂ e/KWh	0.385	[41,42]
(3) = (1) * (2) Emission of CO ₂ per m and container	kg CO ₂ /TEU-m	0.0057442	[41,42]
(4) Average consumption of fossil fuels per container and m transported	L/TEU-m	0.01442	[41,42]
(5) Emission of CO ₂ by use of fossil fuels	kg CO ₂ e/L	2.7	[41,42]
(6) = (4) * (5) Emission of CO ₂ per m and container TEU	kg CO ₂ /TEU-m	0.038934	[41,42]

It is observed in Tables 4–6 that the ports of San Antonio and Valparaíso together moved approximately 25 million tonnes in 2021, an amount very similar to the cargo transferred by the Port of Valencia in the same period. These results show that it is possible to compare the gaps between the two Chilean medium-sized ports of the Valparaíso region and the second largest port in Spain [7,50].

4.2. Calculation of Emission of GHG

With the results obtained in Tables 4–6, it is possible to obtain the levels of emissions of the main GHG, which correspond to CO₂, Methane (CH₄), Nitrous Oxide (N₂O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulfur Hexafluoride (SF₆) [51] in the Ports of Valparaíso, San Antonio and Valencia.

For the estimates shown in Tables 8–10, the percentages of greenhouse gas emissions CO₂, CH₄, N₂O and other gases (HFCs + PFCs + SF₆) that were registered in Spain during the year 2021 were used, which were 75.5%, 15.08%, 7.27% and 2.13%, respectively [52].

Table 8. Emission of GHG in the Port of Valparaíso in 2021.

Concept	Terminal 1, Sites 1, 2 and 3	Terminal 1, Sites 4 and 5	Terminal 2, Site 6	Terminal 2, Site 7	Terminal 2, Site 8
Total emission GHG = CO ₂ + CH ₄ + N ₂ O + other gases (HFCs + PFCs + SF ₆)	11,422	109	189	7	679
Emission of Methane (CH ₄) 15.08% (t)	1724	16.4	28.6	1	103
Emission of Nitrous Oxide (N ₂ O) 7.27% (t)	831	7.9	13.8	0.5	49
Emission of other gases (HFCs+PFCs+SF ₆) 2.13%	244	2.3	4	0.1	14.5

Table 9. Emission of GHG in the Port of San Antonio in 2021.

Concept	South Seawall Sites 1, 2 and 3	Breakwater Sites 4, 5, 6 and 7	North Terminal, Site 8
Total emission of GHG = CO ₂ + CH ₄ + N ₂ O + other gases (HFCs + PFCs + SF ₆)	12,212	2418	1335
Emission of CH ₄ 15.08% (t)	1843	365	201
Emission of N ₂ O 7.27% (t)	888	176	14.7
Emission of other gases (HFCs+PFCs+SF ₆) 2.13%	261	52	29

Table 10. Emission of GHG in the Port of Valencia in 2021.

Concept	1	2	3	4	5	6	7	8	9
Total Emission GHG	12,397	3061	434	499	707	9038	55,992	1109	3538
Emission of CH ₄ 15% (t)	1871	462	66	75	107	1364	8449	167	534
Emission of N ₂ O 7.27% (t)	902	223	32	36	51	658	4074	81	257
Emission of other gases (HFCs + PFCs + SF ₆) 2.13%	265	65	9	11	15	193	1195	24	76

¹ Levante Pier. ² Llovera Pier. ³ Turia Breakwater North Pier. ⁴ Turia Breakwater South Pier. ⁵ Turia Breakwater Testero Pier. ⁶ MSC Valencia Terminal SAU. ⁷ CSP Iberian Valencia Terminal. ⁸ Temagra (Bulks). ⁹ Tepsa + Galp + Teva (Liquid Bulks).

5. Discussion

5.1. Global Energy Strategies

Due to the concern about climate change and dependence on fossil fuels, the sustainable use of energy has become a priority of the national strategy, involving the State, companies and people. It requires political will, innovation and large investments in technological development projects to comply with the international commitments that require the supply to be sustainable over time [53,54].

There has been a worldwide tendency to increase the use of different types of energy during 1990–2019; in the period of the pandemic, the consumption pattern of people and companies changed due to the decrease in commercial, industrial and transport activity in the domestic sphere [55,56]. In addition, it can be noted that there is a propensity for the need of using cleaner fuels by 2050 and that total consumption tends to stabilize.

Figure 4 is created with Chilean port data from the energy consumption and emissions survey [22]. It is based on the representation of global energy consumption from [44], since it is similar to that of Chilean port operators at the country level. It is observed that in the long term, the consumption of oil decreases and the use of electricity increases. This situation is not only due to environmental care but to macroeconomic conditions and international relations between producers and consumers of crude oil. For example, currently, less oil is consumed due to an increase in inflation, the possibility for a recession for next year and the restrictions on supply capacity, among other factors.

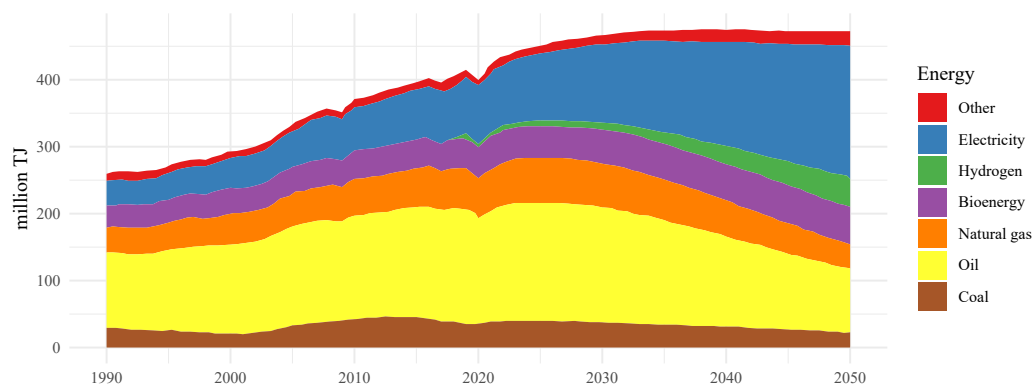


Figure 4. Final energy consumption per fuel based on [22,44].

In relation to the port industry, energy efficiency is a priority in the decision-making of the Port Authority, which is why in business policies sustainable and eco-efficient aspects that seek new business opportunities are increasingly being included, so as to integrate clean technologies that are more responsible with the environment and that reduce greenhouse gas emissions [57,58].

As shown in Table 3 and Ref. [7], in the Chilean ports of Valparaíso, San Antonio and Arica, some sustainable aspects that seek to reduce emissions of CO₂ and increase energy efficiency have been included in business policies and strategic definitions.

5.2. Energy Management in Port Terminals

The analysis of the results of Tables 4–6 allows to verify that the amount of cargo transferred (Ton-year) and the CO₂ emissions are much lower in the Port of Arica (small size) than in the medium-sized ports that are located in the Valparaíso Region (Port of Valparaíso and Port of San Antonio). In addition, as the sum of the cargo transferred in the two medium-sized Chilean ports is similar to the movement of cargo in the Port of Valencia (large-sized port), in the present work the gaps existing between the two public terminal ports of the Valparaíso Region and the Spanish terminal were compared.

In the tables of Section 4.1, it is observed that in 2021 the ports of the Valparaíso Region moved 10% more cargo and containers than the Spanish port but they emitted approximately a third of the CO₂ as that of the Port of Valencia. Then, if in the terminals the

use of diesel was stopped and 100% electricity was used, Chilean ports would still pollute less than the Spanish port.

In relation to the emissions of GHG gases, as shown in Tables 8–10, the percentages of emissions that occurred in Spain during the year 2021 [52] were used to compare the ports of the Valparaíso Region with the Port of Valencia. The results obtained in Section 4.2 show that the ports of Valparaíso and San Antonio together emit an amount equivalent to 33% of the GHG of the Port of Valencia; this proportion is maintained if CH₄, N₂O, CO₂ and the other gases are analyzed.

On the other hand, to analyze the energy consumption, the efficiency in its use and the associated costs, the Ministry of Transport and Telecommunications of Chile carried out a survey during the year 2020 in 11 public ports, in which the emissions of CO₂ were measured with indicators as produced by the cargo handling equipment; the refrigerated platforms (storage in warehouses or collection centers); and the connections of refrigerated containers, transport, offices, and ships and tugboats [59]. In the results, it was appreciated that the ports studied have different degrees of maturity in the management of energy consumption, mainly due to operators being of different sizes and having different levels of technological and infrastructural development [11,22]. In addition, it was obtained that the emissions of CO₂ from electric generators and diesel cargo handling machinery were higher in Chilean ports than in the Port of Barcelona despite the fact that they consume the same amount of energy [22,60].

If the results obtained in Section 4 and those delivered in the survey carried out by the State of Chile [22] are compared, it can be seen that different conclusions are obtained. Among the possible reasons, this could be due to the fact that the present study used the two public ports that have the highest cargo movement and the highest technological development; instead, the survey included the ports of the Valparaíso Region and nine public ports, the latter being terminals that move less cargo and have less infrastructure and equipment. On the other hand, the present study compared two Chilean ports, with the Port of Valencia that moves more cargo than the Port of Barcelona; for example, in 2020, the Port of Valencia had 36% more traffic than the Port of Barcelona.

It is worth mentioning that it is important to investigate more in this topic in order to improve energy management to reduce the emission of CO₂ in port terminals. In the fifth-generation ports, with the purpose of reducing GHG, gantry cranes equipped with tires RTG are used as the main storage equipment in the cargo yard; as a variant, gantry cranes on electric rails (Rail Mounted Gantry (RMG)) [61–64] are used. Other solutions proposed for RTG in automated and electrified ports are conductive bars, cable reels and the use of hybrid systems (battery-diesel) [65,66]. Among the advantages, the cost of operation and maintenance are lower due to lower fuel consumption, as well as the reduction in emissions and noise levels [65]. The economic profitability of electrifying the RTGs of a terminal is conditioned by the number of load transfers made by each crane [66].

6. Conclusions

Since there is a lack of research to calculate for Chilean ports how much greenhouse gas emissions would be reduced if 100% electricity were used, a conceptual evaluation was carried out in this work.

A bibliographic review was performed to determine which are the methods or methodologies that are currently used to measure greenhouse gas emissions in port terminals. It was determined that most of the ports that are committed to comply with sustainability correspond to smart ports that are geographically located in developed countries having a high Gross Domestic Production (GDP) per capita. As these ports possess public funds, they can make large investments in infrastructure and machinery [62]. These countries have regulatory frameworks that promote the incorporation of sustainability into port protocols and business models [67,68].

In the case of the ports of Valparaíso, San Antonio and Arica, it is difficult to implement sustainable practices that promote the use of clean energy in developing countries as they

are companies that can be classified as Industry 3.0 [23]. On the other hand, as they are public ports contracted to private companies, they are not autonomous and investments depend on the approval of the annual State budget [7]. The annual public allocation for port investment is very low, for example, for the year 2022 an amount of less than 0.02% was allocated for the three ports under study [69].

On the other hand, from the analysis of port policies related to energy and environmental management shown in Table 3, it is possible to observe the gaps between the strategic actions that are developed in Chilean ports and in the Port of Valencia. In the analyzed Chilean ports, energy efficiency criterion is becoming incorporated, as observed in the policies, since ports are in a diagnostic stage in which the identification of sustainable opportunities is sought. It is worth mentioning that among those strategies, only the ISO 14000 quality standard, clean production agreements in waste management and partial compliance with the objectives of the United Nations are included. In relation to the Spanish Port, as it is a large and highly developed port, its strategic and operational efforts are directed to improve energy management; currently, large investment projects are being developed to ensure that the terminals are 100% electrified [39].

In Section 4, the emissions of CO₂ and other greenhouse gases in the ports of Valparaíso and San Antonio and in the Port of Valencia were calculated, and it was determined that Chilean ports emit a third of the greenhouse gases in the terminals when compared with the Port of Valencia. This is explained since the Spanish port is larger, which is why logistics are more complex as there is a greater number of equipment and workers, and the distance traveled by cargo movement is greater, thus requiring more logistic coordination and transport management. As Chilean ports are smaller, they move cargo in less time and distance and, therefore, they have fewer logistical difficulties; despite this, they have higher greenhouse gas emissions as they use fossil fuel equipment.

Further research is needed to investigate how public policies and the strategies of port managers impact decision-making and the allocation of resources, such as to reduce the amount of greenhouse gas emissions. A more detailed study is required to determine the technical and economic feasibility of migration, in which it is known which equipment can be optimized and which can be replaced.

It should be noted that these projects require large investments, which is why these transformations have been generated in smart ports and not in the terminals of developing countries [70,71]. The electrical power installation has many cables; so, the layout of the terminals has to be redesigned and the layout of the energization system of the equipment has to be evaluated, especially if it is mobile. On the other hand, it is possible to automate the movement of cargo with a computerized logistics process that optimizes times and identifies the traceability of the containers in real time in order to be clear about their location and generate optimal routes. This saves electricity by reducing storage transfer times [72].

Finally, a possible topic to study would be to analyze if a reduction in gas emissions replaced by the use of electricity in port terminals would improve the port–city relationship, since the negative externalities that are generated for the inhabitants of the port city could be reduced. On the other hand, it is necessary to analyze new variables that improve the degree of sustainability in the terminals.

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Abbreviations

The following abbreviations are used in this manuscript:

CH ₄	Methane
CO ₂	Carbon Dioxide
GDP	Gross Domestic Production
GHG	Greenhouse Gases
HDI	Human Development Index
HFCs	Hydrofluorocarbons
N ₂ O	Nitrous Oxide
PFCs	Perfluorocarbons
RMG	Rail Mounted Gantry
RTG	Rubber Tyred Gantry
SF ₆	Sulfur Hexafluoride
TCO ₂	Total Carbon Dioxide
TEU	Twenty-foot Equivalent Unit

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