Assessment of onshore power supply for ship's emissions reduction in Alexandria Port utilizing national grad/ renewable energy

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المستخلص

تُعد مشكلة تلوث الهواء الناتجة عن الشحن البحري قضية هامة، خاصة في المدن الساحلية. من بين الحلول المقترحة، نظام تزويد الطاقة من الشاطئ (OPS)، حيث تقوم السفن بفصل محركاتها الاحتياطية والتواصل مع شبكة الكهرباء في الميناء. رغم الدراسات المتعددة في موانئ أوروبا والولايات المتحدة، تركز هذه الدراسة على تطبيق نظام OPS في ميناء الإسكندرية بما يتماشى مع رؤية مصر ٢٠٣٠ في مواجهة تغير المناخ.

تركز الدراسة على تحليل البيانات المجمعة من السفن لتقديم تحليل اقتصادي وتقييم الانبعاثات الناتجة عن استخدام النظام. كما تستعرض استخدام الطاقة الشمسية كمصدر للكهرباء لتحسين الفعالية البيئية للنظام. تشير النتائج إلى أن الاعتماد على الشبكة الوطنية يقلل الانبعاثات بنسبة تصل إلى ٢٧,٥٪، بينما يمكن للطاقة الشمسية تقليل الانبعاثات بنسبة تصل إلى ١٠٠%.

تنفيذ نظام OPS المعتمد على الطاقة الشمسية في ميناء الإسكندرية لا يساهم فقط في تحسين جودة الهواء، بل يعزز أيضًا الأهداف البيئية والاجتماعية والاقتصادية للبلاد، ويسهم في تحسين جودة الحياة والتنمية المستدامة.

ABSTRACT

Air pollution from shipping is a critical issue, especially in dense ports. One of the proposed technologies to reduce ship emissions in ports is the Onshore Power Supply (OPS) system, where ships turn off their auxiliary electric generator engines and connect into the port grid. Several studies were conducted in European and USA ports. This study tackles the application of the OPS in the port of Alexandria, in line with Egypt's Vision 2030 concerning the issue of climate change. The study focuses on analyzing the ships data collected from Alexandria port along one month. The present investigation aiming to conduct a comprehensive socio-economic and cost effectiveness analyses of OPS. To enhance the environmental potential of OPS, deploying four solar energy scenarios as the OPS electricity source is proposed.

The results revealed that relying on the national grid decreases emissions by 27.5%, and it is predicted to reach 100% if the electricity is generated from solar energy. Also, the economic analysis shows good profitability with a payback period of almost two years. Therefore, the implementation of the solar-powered OPS system in Alexandria port not only contributes to improving the air quality in the area, but also enhancing the country's environmental, social and

economic goals. Improving port infrastructure and using clean energy technologies can significantly enhance the quality of life in port cities and promote sustainable development.

Keywords: Onshore Power Supply, Renewable Energy, Solar Energy, Alexandria Port, Ship Emissions, Sustainable Development.

1- Introduction

Maritime transport facilitates global trade efficiently but relies heavily on fossil fuels, contributing approximately 2.89% of global CO_2 emissions in 2018—a figure projected to rise by 50% by 2050 without intervention (IMO, 2021). Notably, 70% of emissions occur within 400 km of land, heavily affecting ports (Corbett et al., 2007), where ship emissions can contribute up to 54% of total port emissions (Merk, 2014). Such emissions pose health risks, while noise pollution from auxiliary generators exacerbates cardiovascular and hearing issues (Badino et al., 2012).

The IMO has adopted measures such as the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) since 2013, alongside sulfur and nitrogen emissions limits and noise regulations (IMO, 2020). Onshore Power Supply (OPS) systems offer a viable solution by enabling ships to connect to port grids, eliminating emissions, noise, and vibration from auxiliary engines during berthing (Zis, 2019). When integrated with renewable energy sources (RES) like solar or wind, OPS amplifies environmental benefits (Yarova et al., 2017). However, OPS requires substantial investment, necessitating cost-benefit analyses and prioritization for high-traffic, densely populated ports (Zis, 2019).

In Egypt, Alexandria Port serves as a key Mediterranean hub. While Damietta Port pioneered OPS in 2019, Alexandria Port also has shore power-ready berths (Mohamed & Salah-Eldine, 2020). Limited research explores OPS adoption in Egyptian ports, particularly with RES integration. This study investigates OPS implementation in Alexandria Port, emphasizing solar energy as a power source, aligning with Egypt's Vision 2030 to enhance socio-economic and environmental sustainability.

2- Literature Review

The implementation of (OPS), or shore-side electricity (SSE), is a key solution to reducing emissions from ships at berth. By connecting to shore power, ships can shut down diesel engines, eliminating emissions of CO_2, SOx, and NOx during docked operations (Dai, et al., 2020). This aligns with regulations from the EU Commission and IMO, aiming to lower shipping emissions in sensitive coastal areas (Kumar, et al., 2019). OPS significantly improves air quality and reduces noise pollution, benefiting port cities and nearby residential areas (Martínez-López, et al., 2021). Ports in California, Europe, and China have adopted OPS to comply with strict environmental laws, achieving substantial CO_2 reductions, such as 99.5% in Oslo and 85% in France (Dai et al., 2019; Kotricla, et al., 2017). These benefits are especially critical in high-traffic ports like Shanghai, where air pollution poses severe health risks (Radwan et al., 2019).Infrastructure for OPS includes shore power sources, transformers, and communication systems, ensuring safe and efficient electricity transfer to ships. While complex to implement, OPS aligns with global environmental goals, such as the IMO's MARPOL Annex VI and the EU Green Deal, which require ports to meet 90% of ships' energy needs via shore power by 2025 (Wu and Wang, 2020).By reducing fuel consumption, emissions, and noise pollution, OPS supports sustainability and compliance with international regulations. As more ports adopt this technology, it plays a pivotal role in transitioning the maritime industry toward greener practices (Winkel et al., 2016).The ship's electrical power load is shifted to an on-shore power supply source of electrical power without disruption to onboard services, as shown in Figure (1).

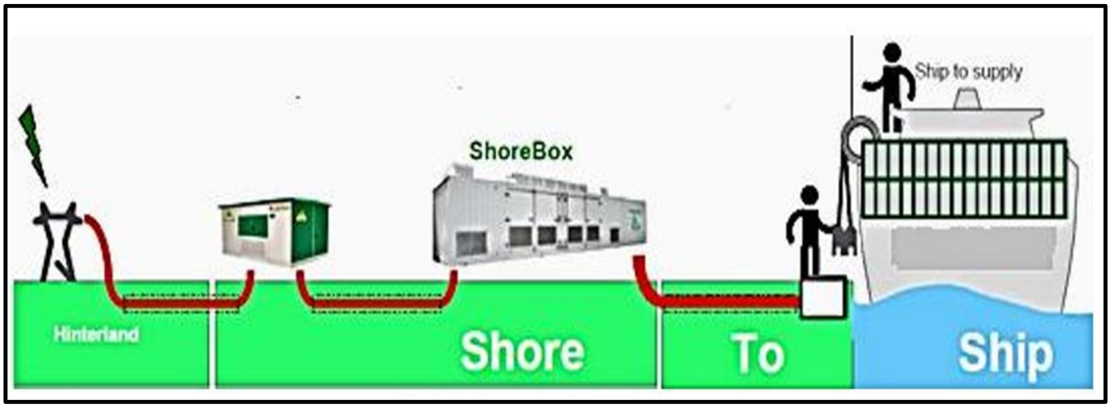

Figure (1) OPS configuration [Baltic Ports Organization (2015)]

<u>3- Case Study: Alexandria Port</u>

The Port of Alexandria is Egypt's largest and most important port, handling about 60% of the country's foreign trade. Located on the Mediterranean coast at the western edge of the Nile Delta, it connects Egypt with Europe, Asia, and Africa. The port has two main areas: the shallow Eastern Port and the deeper Western Port, which handles most cargo and passenger traffic. Covering 8.4 km² (6.8 km² water, 1.6 km² land), it has 55 berths with a maximum draft of 16 meters, accommodating various vessel types (Alexandria Port.2024). Its strategic location makes it a key player in Egypt's global maritime trade, especially with Europe.

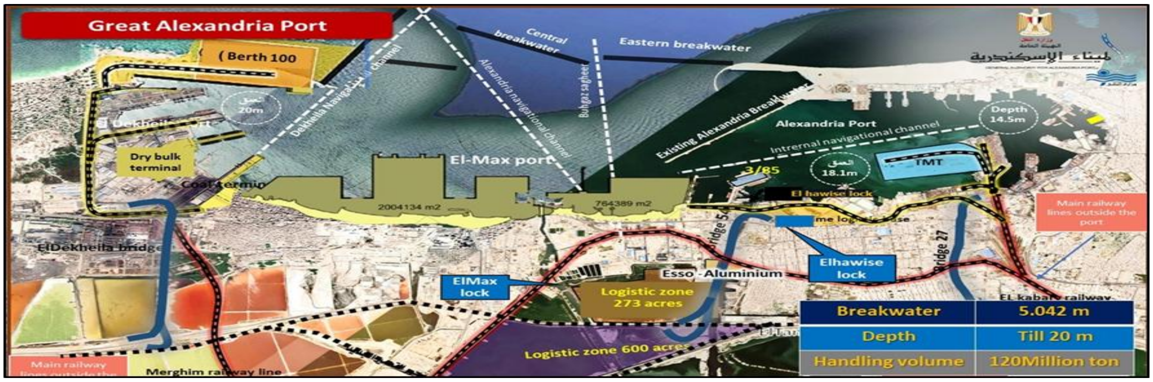

Figure (2) Map of Alexandria Port (Alexandria Port, 2024).

The port serves a wide range of commercial, industrial, and logistical functions, with basins designed for different types of vessels. The port has multiple quays, storage facilities, grain silos, and a logistics zone, all connected to Egypt's road and rail networks for efficient cargo movement. The port located near the Suez Canal, and handles 60-70% of Egypt's foreign trade, making it a cornerstone of the national economy. Figure (2) present Alexandria port map showing its layout, highlighting key areas such as basins for different vessels, quays for loading and unloading, storage zones, and its access to major transportation routes, underlining its crucial role in global and domestic trade.

4- Methodology

The research adopts an analytical and comparative approach to establish an environmental framework for applying green port operating principles. The methodology involves three main axes: data collection from Alexandria Port's operating systems and ship activities, analyzing energy consumption scenarios during various operational states, and using software to calculate emissions and carbon footprints from ship generators.

The study focuses on ocean-going vessels due to limited data availability, with ships classified by function and cargo type. Data provided by the Alexandria Port Authority includes ship specifications, arrival, and departure times. The research compares the environmental and economic impacts of traditional ship generators versus an OPS system in the port.

4.1 Ship emissions inventory

4.1.1 EPA method

EPA methodology for estimating total emissions from auxiliary engines onboard ships during specific operations is detailed by EPA (2017). Equation (1) is utilized to calculate the emissions (E_i) of specific pollutants from auxiliary engines during the hoteling phase.

$$Ei = Pj * LFj * Cj * Tj * EFi \qquad (1)$$

Where, P_j represents the total auxiliary engine power demand in port, LF_j is the hoteling load factor, C_j denotes the number of ship port calls, and T_j is the hoteling time.

The emission factors (EF_i) for Marine Diesel Oil (MDO) with 0.5% sulfur content used in auxiliary engines are provided in Table (1) (EPA 2017),

Table (1) Emissions factors of MDO (g/kWh) [EPA 2017].

Fuel Type	CO_2	So_x	NO_x		PM_{10}	$PM_{2.5}$
			Tier 0	Tier 2		
MDO (0.5%S)	690	2.1	13.9	9.7	0.38	0.35

In this study, NOx emissions are calculated based on Tier 0 and Tier II standards, depending on the ship's age and rated engine speed. Tier 0 standards apply to ships built before 2000, while Tier

II standards apply to ships built after 2000. Even if a ship's construction date allows it to operate under Tier I standards, it is assumed to comply with Tier II standards, as per Chapter 5 of the Emissions Inventory Methodology (Faried 2024). Tier III standards, applicable only in NOx emission control areas, are excluded from the study.

4.1.2 IMO method

The International Maritime Organization (IMO) has set regulations to calculate greenhouse gas (GHG) emissions from ships, including exhaust emissions in ports. The methodology uses various equations to estimate CO_2 and other pollutants based on available data accuracy. IMO guidelines help coastal states and local authorities create policies to reduce GHG emissions from ships in their ports (IMO, 2023). To estimate emissions from ship auxiliary engines (Ei), the auxiliary engine Fuel Consumption (FC_i) is first calculated (equation 2), followed by emission calculation using equation (3).

$FCi = SFCbase * WAE$ g/kWh (2)

Ei = $FCi * EFf$ g/kWh (3)

Where, WAE represents the auxiliary engines' power output, and the Baseline Specific Fuel Consumption (SFC$base$) is the lowest specific fuel consumption observed in their loading curve. The (SFC$base$) of an auxiliary engine can be determined based on its year of construction, as shown in Table (2), (IMO, 2020).

WAE is the Weighted Average Efficiency and it consider as a factor that accounts for the vessel's performance under various operational conditions, such as speeds, loads, and other parameters

Table (2) SFC_{base} (g/kWh) based on engine age and fuel type (IMO, 2020)

Engine Type	Fuel Type	Before 1983	1984- 2000	2001+
Auxiliary Engines	MDO	210	190	185

4.2 Ship Information Application

The database used in this study includes data on over 300,000 commercial ships, covering ship specifications, equipment, and communication systems. It provides information on each ship's power generation capacity in kilowatts. Additionally, port data such as berthing days, working hours, and generator load factor were used to calculate the ship's total energy consumption in Gigawatt-hours (GWh) per port call. Emission factors for auxiliary engines during various ship operations depend on the fuel type used. Data from Alexandria port in October 2019 was used to estimate energy consumption during berthing. Equation (4) was used to calculate CO2 emissions generated by ships in the port (Yahya, 2022; Joseph, Patil, and Gupta, 2009).

$E = P \times LF \times EF \times T$ (4)

Where.

E: emissions in units of pollutant

P: maximum power output of the auxiliary engine in kW presented from ship data.
LF: load factor for auxiliary engines, as a fraction of maximum, installed power capacity (40% of ship total Aux. Engine Capacity).
EF: emission factor (pollutant specific) in mass emitted per work output (in kWh) of the auxiliary engine in maneuvering and berthing modes, g/kWh,
T: maneuverings and berthing time in hours.

4.3 Ship emission in the study period

Emission calculations for ships at Alexandria port during the study period (1/10/2019 to 31/10/2019) showed significant variation based on ship type and number. Bulk carriers were the largest contributors, accounting for 52.19% of total emissions. Container ships followed with 20.13%, while other ship types, such as general cargo vessels (11.85%) and oil tankers (6.49%), contributed lower percentages. Figure (3) illustrates the emission percentages of various ship types during the study period.

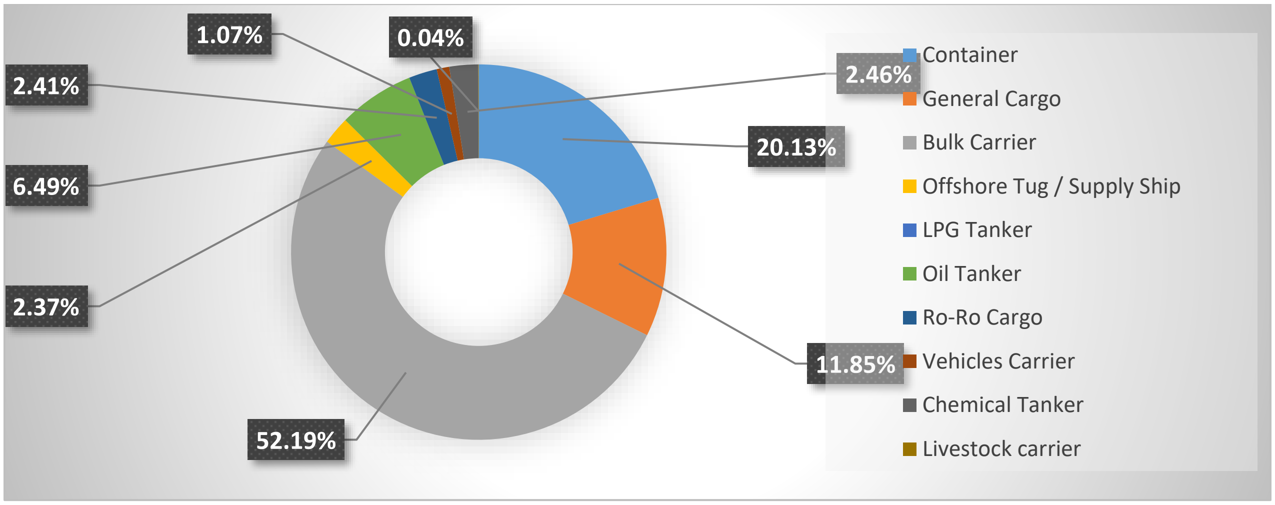

Figure (3) Percentage Breakdown of CO_2 Emissions by Ship Type

4.4 Assessment of solar energy resource

Solar technology is widely used due to its reliability, flexibility, and longevity. Alexandria, Egypt, located within a high solar irradiation region (1980.9 kWh/m² direct normal irradiation), is ideal for solar energy generation as seen in figure (4). Utilizing renewable sources like solar energy addresses climate change, fossil fuel depletion, and energy security concerns, aligning with the Paris Agreement's goals for reducing greenhouse gas emissions. Rooftop spaces, like warehouse roofs in port areas, can be effectively used for solar energy generation. Photovoltaic (PV) technology is growing due to decreasing costs and increasing efficiency. Marine solar energy is a promising new option, offering higher power production (5-10% more) and minimizing land use compared to land-based projects.

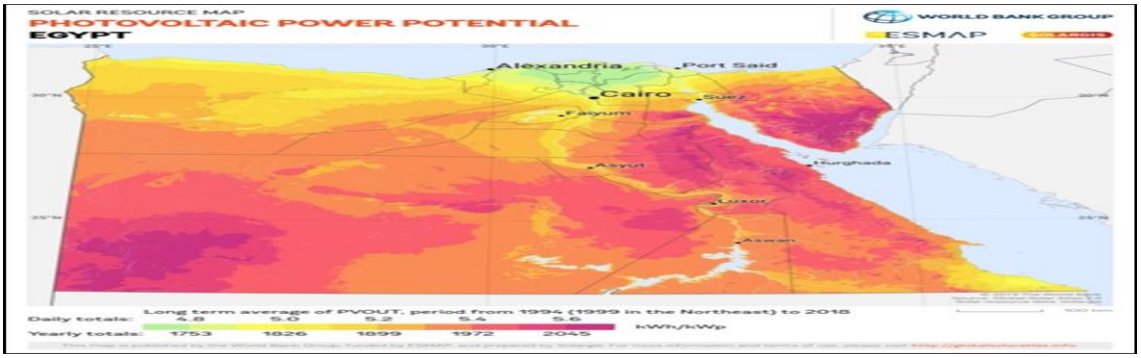

Figure (4) Map of average annual solar irradiation in Egypt (SolarGIS, 2018)

Egypt's geographical location between latitudes 22° and 31° north places it in the subtropical region, making it one of the most sun-exposed countries year-round. Solar radiation in Egypt ranges from 5-6 kWh per square meter per day, particularly in desert areas. The heat map shows temperature variations, with moderate coastal temperatures and higher temperatures in the desert during summer. This location offers a great opportunity to harness solar energy for electricity generation, supporting renewable energy projects and contributing to reduced emissions and environmental sustainability.

4.4.1 Proposal of OPS system in Alexandria port

In order to improve the environmental performance of the proposed OPS system at Alexandria Port, the OPS should provide berthed ships with electricity from a clean source such as solar energy. Therefore, a sensitivity analysis of the available unused open area and deck areas of buildings and warehouse ceilings located within the port is carried out to assess the potential for installing a photovoltaic system. Table (3) presents the five scenarios proposed for selected areas to install the PV system, which covers the four scenarios regarding the available area inside Alexandria Port as follows;

Table (3) Impact of Energy Scenarios on Solar Generation and Emissions Reduction

Scenario	Main power source	Total Solar Energy Generated (kW)	Energy Savings Achieved (%)	Remaining Energy After Solar (kW)	Calculated Emission Reduction by percentage
First scenario	Natural gas	0	0%	47083	27.5%
Second Scenario	25% of solar and natural gas use	11306.75	24%	35776.25	44.93%
Third Scenario	50% solar and natural gas use	22613.5	48%	24469.5	62.34%
Fourth scenario	75% solar and natural gas use	33920.25	72	13162.75	89.3%

Fifth scenario	100% solar and natural gas use	45227	96%	1866.5	97.12%

Figure (5) presents the impact of five energy scenarios on solar energy generation and emissions reduction. In the first scenario, which relies entirely on natural gas, no solar energy is generated, resulting in no energy savings but a 27.5% reduction in emissions. In the second scenario, 25% of solar energy is combined with natural gas, generating 11,306.75 kW of solar power, resulting in a 24% energy savings and a 44.93% emissions reduction. With a 50% solar share in the third scenario, solar energy generation increases to 22,613.5 kW, achieving a 48% energy saving and a 62.34% emissions reduction. In the fourth scenario, where 75% solar and 25% natural gas are used, 33,920.25 kW of solar power is generated, resulting in a 72% energy savings and an 89.3% reduction in emissions. Finally, in the fifth scenario, which relies entirely on solar energy, 45,227 kW of solar energy is generated, achieving a 96% energy saving and a 97.12% emissions reduction. These results demonstrate the significant benefits of transitioning to solar energy, not only in terms of energy savings but also in reducing harmful emissions, thus enhancing the role of renewable energy in achieving environmental sustainability.

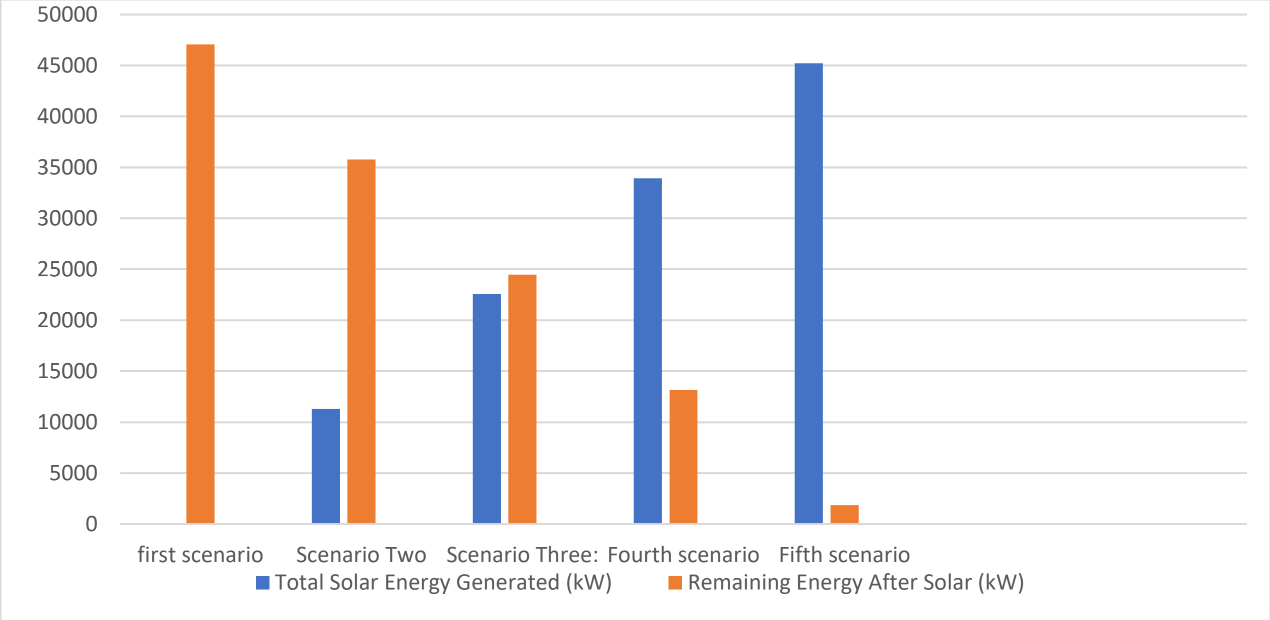

Figure (5) The Impact of Increasing Solar Energy Utilization on Reducing Energy Consumption and Emissions

5- Results and Discussion

5.1. Statistical Analysis

Table (4) represents the percentage of container ships, general cargo ships, and other types that entered the Port of Alexandria, with classification and detailing of all information such as the period, the number of ships for each type, and the amount of energy consumption.

Table (4) Results of data of ships entering the port

Ship type	Number of ships	Period	Total co2 ton	Percentage of pollution	amount of energy consumed per type kWh
Container	108	01/10/2019 to 31/10/2019	8540.388	% 20.13	229635
General Cargo	90		5026.734	% 11.852	49478
Bulk Carrier	62		22136.404	% 52.19	82977
Offshore Tug / Supply Ship	22		1008.416	% 2.37	36364
LPG Tanker	8		410.222	%0 .967	4487
Oil Tanker	27		2752.814	% 6.490	32912
Ro-Ro Cargo	16		1022.586	% 2.411	43621
Vehicles Carrier	9		454.552	% 1.07	26787
Chemical Tanker	13		1043.114	% 2.459	14445
Livestock carrier	1		15.8976	% 0.037	600

Analysis of vessel data for Alexandria Port from 1 to 31 October 2019 reveals significant differences in emissions and energy consumption among ship types. Bulk carriers (62 ships) were the largest contributors, producing 52.19% of CO2 emissions (22,136 tonnes) and consuming 82,977 kWh. Container ships (108 ships), while contributing only 20.13% of emissions (8,540 tonnes), had the highest energy consumption at 229,635 kWh, reflecting their greater energy demands.

General cargo ships and oil tankers had moderate impacts, contributing 11.85% and 6.49% of emissions, respectively, with energy consumption of 49,478 kWh and 32,912 kWh. Smaller vessels like LPG carriers and livestock carriers had minimal emissions and energy usage.

These results, specific to October 2019, emphasize that impacts vary by ship type and time period, highlighting the need for tailored strategies to enhance efficiency and reduce environmental effects. Figure (6) depicts the average electricity consumption for each ship category during the study.

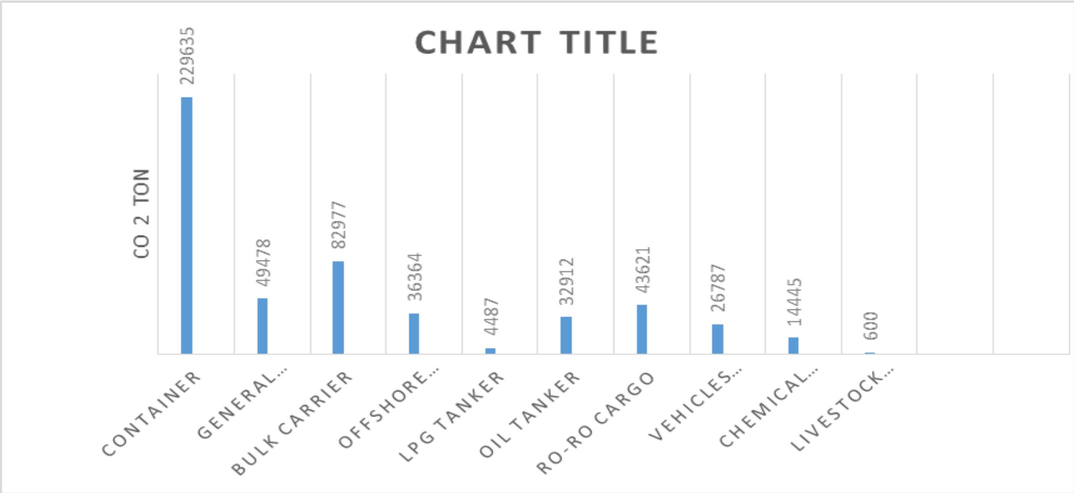

Figure (6) CO_2 Emission Rate by Ship Type

5.2. Socio-Economic Analysis

The analysis examines the cost of CO2 emissions from ships in ports, comparing damages with and without an (OPS) system. At $50 per ton (Ferried, 2024), emissions during the study period using onboard diesel generators cost $2,115,556.38. Implementing OPS, powered by the national grid, reduces emissions damage costs by 27.5%, saving $581,677.90 and lowering costs to $1,533,878.48.

OPS enhances air quality, reducing health risks like respiratory and cardiovascular diseases, and aligns with sustainability goals. Integrating renewable energy, such as solar power, into OPS cuts long-term operating costs despite high initial investment. This transition boosts energy efficiency, reduces fossil fuel dependence, and ensures sustainable port operations.

5.3. Assessment of Solar Energy Resource

To enhance the environmental performance of the proposed solar power plant project, it is essential to integrate renewable energy sources into the national grid. This approach allows the solar power plant to provide clean electricity to moored vessels, significantly reducing emissions. A sensitivity analysis was conducted to explore available spaces within the port for solar panel installation, leading to several scenarios:

1. **First Proposal**: By utilizing vacant yards and rooftops of port buildings at 25% capacity, solar panels can meet approximately 24% of the electrical energy needs of moored vessels, with the remainder supplied by the national grid.
2. **Second Proposal**: By incorporating some rooftops of warehouses and administrative offices at 50% capacity, solar panels can provide 48% of the required electricity.
3. **Third Proposal**: Using both vacant yards and rooftops of warehouses and offices at 75% capacity, solar installations can cover 72% of the energy needs.
4. **Fourth Proposal**: Maximizing the use of all available spaces can enable solar power to cover up to 96% of electricity needs.

The total energy consumption is approximately 47,083 kilowatt-hours, while the generated solar energy can reach around 45,227 kilowatt-hours with full installation. This high coverage rate is particularly beneficial during the summer months but may decrease in winter due to increased electricity demand, highlighting the necessity for an energy storage system to manage peak demand.

5.4. Cost-Effectiveness Analysis

A Net Present Value (NPV) analysis was conducted to assess the feasibility of Onshore Power Supply (OPS) systems, where positive NPVs indicate viability. OPS becomes profitable when savings in electricity and external costs exceed total private costs. The analysis considered the transition from the national grid to solar energy at Alexandria Port, which has a peak daily electricity consumption of 47.8 MW, costing approximately $4,971.20 at a fossil fuel rate of $104/MW.

Integrating solar energy for 25%, 50%, 75%, and 100% of the port's electricity needs results in cost reductions of 18.66%, 37.5%, 56.32%, and 75.05%, respectively. These findings demonstrate significant financial savings and reduced environmental impact with higher solar energy integration.

Table (5) illustrates the cost reductions based on different levels of solar energy integration.

Solar Energy Integration (%)	Cost Reduction (%)
25%	18.66%
50%	37.5%
75%	56.32%
100%	75.05%

5.5. Challenges Facing OPS Application in Egypt

The main challenges for implementing Onshore Power Supply (OPS) in Egypt, particularly at Alexandria Port, are:

- Lack of Strong Regulations: The absence of clear legislation hinders OPS adoption, unlike the US with strong regulations driving success.
- Insufficient Compatible Vessels: Ports hesitate to invest in OPS without enough compatible vessels, making it a high-risk investment.
- Limited Applicability: OPS is most effective for frequent transport services involving container ships, cruise ships, bulk carriers, and chemical tankers.

To effectively implement OPS at Alexandria Port, the following solutions should considered:

- Establish Regulations and Collaboration: Strong regulations and cooperation among stakeholders are essential.
- Financial Incentives: Provide financial support, tax reductions, and port fee adjustments to encourage OPS integration.
- Port Concessions: Offer preferential docking and concessions for OPS-equipped vessels.
- Incentivize Early Adoption: Implement programs to reward early OPS adopters.
- Awareness Campaign: Promote OPS benefits, focusing on reduced emissions, fuel savings, and regulatory compliance.

6- Conclusion and Recommendations

Ships are a major contributor to global marine pollution, both in ports and coastal areas. Therefore, it's crucial to properly implement the (OPS) system to reduce emissions from ships. The study at Alexandria Port showed that emissions from auxiliary ship engines amounted to 42,311.13 tons in one month. Using the national grid for OPS reduced emissions by 27.5%, amounting to 30,677.57 tons. This reduction could be higher if solar energy were used.Using solar energy for OPS would significantly reduce emissions, especially if 100% of the port area is covered with solar panels. Additionally, the cost of damage from emissions is reduced by 27.5% compared to auxiliary engine emissions, and this would increase with clean energy sources. A Net Present Value (NPV) analysis showed that the most profitable scenario is using 100% of the available area with solar energy.

This study's methodology can serve as a foundation for similar research in other Egyptian coastal areas. To implement OPS at Alexandria Port, the following professional recommendations are proposed based on the analysis:

- Enhancing Regulatory Frameworks and Environmental Laws
- Encouraging Vessel Modification for OPS Compatibility:
- Investing in Port Infrastructure:
- Improving the Port's Energy Mix:
- Coordinating with Stakeholders and Offering Financial Incentives:
- Conducting Economic Feasibility Studies:
- Promoting Innovation and Sustainable Development:
- Raising Environmental and Health Awareness:

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