Problem Design and Analysis of Onshore Power Supply to Berthed Ships at the Port of Mombasa

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***Abstract* – International shipping is a major contributor to greenhouse gas emissions leading to environmental degradation in seas and ports. The Port of Mombasa which is frequented by vessels plans to supply ships at berth with onshore power, a technology promoted by the International Maritime Organization (IMO). This paper discusses the provision of onshore power supply (OPS) to container ships to replace the onboard auxiliary diesel generator sets thereby reducing emissions at the port. By estimating the amounts of the major pollutants from vessels, the study designed an OPS system consisting of supply from both the public electricity grid at 5 MVA and 2 MVA solar PV source to supply the ships' energy demand. The emissions from the vessels resulted in CO_2 equivalents of 103,000 TCO_2e emitted by the container vessels. The financial appraisal for the project indicated viability with a 6-year payback period, a positive NPV and an IRR of 16.9%.**

***Index Terms* – auxiliary diesel generators, onshore power, pollutants, shipping, and vessels.**

I. INTRODUCTION

Shipping provides a low-cost form of transport across continents through the sea for raw materials, product parts, finished goods, foods, and fuel to various destinations worldwide. According to the United Nations Conference on Trade and Development (UNCTAD), the global volume of maritime trade in 2019 was estimated at 11.08 billion tons [1]. These high volumes show how important the shipping industry is to global trade. Cargo ships currently transport 90% of global consumer goods. The efficiency and benefits however have come at an enormous cost to the environment [2]. International shipping is a major contributor to greenhouse gas emissions. About 0.5 million ships operate worldwide emitting about one billion tonnes of CO_2 yearly which accounts for 2% to 3% of the global emissions total [2].

The IMO is a specialized United Nations (UN) agency charged with setting safety and environmental standards for the global shipping industry. IMO introduced stringent environmental requirements to monitor the maritime transport sector. These requirements also regulate the energy efficiency of the vessels; encourage the use of alternative fuels, and tackles GHG emissions from shipping [1]. The main exhaust gases from ships are CO_2, SO_2, NO_x, CH_4, CO and PM_{10}. The most significant and abundant GHG ship emission is CO_2 and causes long-lasting global warming [3]. These gases, apart from causing environmental degradation, also impact human health negatively by causing diseases and even leading to deaths. Implementing onshore power supply, also called cold ironing in ports leads to reduction of GHG gases hence improved air quality leading to a reduction in the respiratory diseases and general wellness of people around ports [1]. By the year 2017, there were only 28 ports globally with OPS facilities installed according to World Ports Climate Initiative (WPCI) [4]. As global maritime trade increases, the number of vessels has increased. Bigger ships have also been built leading to a greater power demand during their berthing and hence more pollution [5].

The Kenya Ports Authority (KPA) is mandated by a 1978 Act of Parliament to manage and operate the Port of Mombasa, other seaports and inland container deports in Kenya. In 2017, KPA adopted a Green Port Policy (GPP) at the Mombasa port to enhance energy efficiency and environmental conservation and requires all ships calling at the port to adopt cold ironing during hoteling [6]. The port currently has 21 berths and is carrying out continuous infrastructural expansion. In the financial year 2019/2020, the port of Mombasa received 1661 vessels with container traffic of 1,384,000 twenty tonne equivalent units (TEUs) handled with an overall throughput of 33,636,000 MT [7] [8].

This paper presents the problem design of an onshore power system for the Port of Mombasa supplied by the national grid and solar energy and discusses the technical and operational aspects. It discusses and analyzes the emissions reductions and carries out a cost appraisal for implementing the project. The paper is organized in sections from Section I to VI. The sections are Introduction, Literature Review, Proposed Methodology, Problem Design, Results and Discussion, and Conclusion in that order. A list of references is also given.

II. LITERATURE REVIEW

A: Types of Marine Vessels

The vessels in the shipping industry are mainly classified based on the purpose, size, and type of cargo. These classifications include container vessels, bulk cargo vessels, product tanker ships, Roll-on Roll-off (Ro-Ro) ships, passenger vessels, specialty vessels and other vessels.

B: Onboard Power Systems Configuration

Over time, the power system of a marine vessel has evolved and differs depending on the type of ship, frequency, voltage level, system analysis, power generation amongst other parameters [9]. The whole power system of a vessel includes generation, distribution, and demand as discussed below:

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Conventional Propulsion Vessels: The propeller shaft is coupled to the prime mover via a mechanical system with gears. The Main Engine (ME) is used to propel the vessel at sea and while maneuvering while the Auxiliary Engine (AE) supply power during hoteling as illustrated in Figure 1 [9].

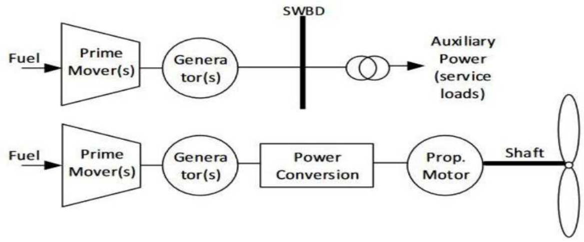

Fig. 1. Conventional Propulsion Vessels [9]

Diesel-Electric Propulsion Vessels: The electric propulsion allows for faster response for maneuvering and at the quay by means of a power electronics device. Several engines are coupled to their own electric generator and the whole package is connected in parallel to the main switchboard which feeds the on-board electrical-driven equipment and the drive coupled to the propeller [9]. There is no distinction between ME and AE as illustrated in Figure 2. Cruise ships and big vessels which operate with high voltage use this system.

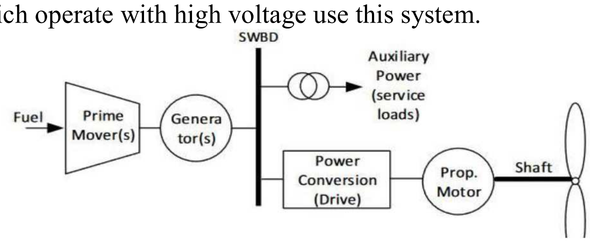

Fig. 2. Diesel-Electric Propulsion Vessels [9]

C: International Regulations

Due to the complexity of the shipping industry, IMO has provided international regulations to oversee these operations. Prevention of Marine Pollution Convention (MARPOL) is concerned with preventing marine pollution from ships and has stringent requirements with severe penalties for non-compliance. International Safety Management (ISM) Code gives an international standard on pollution prevention during operating and managing ships [10]. There are three tiers (I, II and III) of the MARPOL Annex VI NO_X emission standards. The IMO under MARPOL Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) also adopted mandatory measures to reduce emissions of GHG gases in 2018 [11]. The EEDI promotes the use of equipment and engines that are more efficient and less polluting to the environment while the SEEMP ensures cost-effective energy efficiency improvement for vessels during its operation [11].

D: Onshore Power Supply System

Connecting vessels to an OPS source eliminates the need to run the onboard auxiliary diesel generator sets thereby reducing the emission of greenhouse gas pollutants and eliminating noise and vibrations during hoteling. Figure 3 illustrates the connection of a vessel to the OPS system and shows the various components of an OPS system including the substation, frequency converter, transformers, power cables, switchgear, connection boxes and the onboard installation.

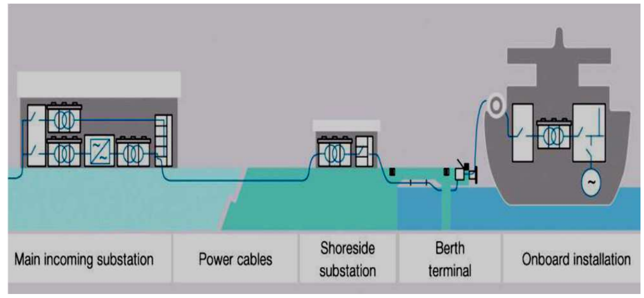

Fig. 3. OPS System Configuration [12]

Renewable energy power source like Solar PV ensures maximum benefits of utilizing clean energy. Components used in the solar PV supply include the solar PV modules, DC to AC inverters, step-up transformers, a connection interface for tying into the grid supply as well as the Supervisory Control and Data Acquisition (SCADA) system for real time monitoring, data and reporting.

E: Challenges of OPS System Implementation

The implementation of the OPS system presents both technical and operational challenges for the high and low voltage onshore connections. The power requirement for cold ironing varies with every vessel. Onboard voltage and frequency requirements differ from the onshore supply utility, frequency of calls per vessel per berth, compatibility of installed components also differ [13]. International standards for implementation of OPS system have been developed by the IEC, IEEE in conjunction with ISO to regulate the global shipping industry and address these implementation challenges. These standards include IEC/ISO/IEEE 80005-1:2019 for High-Voltage Shore Connection (HVSC) systems, IEC/ISO/IEEE 80005-2:2016 for communication, monitoring and control of HVSC and Low-Voltage Shore Connection (LVSC) systems and *IEC/ISO/IEEE 80005-3:2016* for LVSC systems [9]. There also exist other complementary standards.

F: Research Gap

Little study has been done for the shipping industry in Africa as a continent with most studies involving European and Asian ports. Additionally, most of the studies that have been done do not include a renewable energy source and hence the need to include Solar PV supply as part of this study. There is need to also estimate emissions from the energy of the national grid since some countries may have more non-renewable energy than renewable energy generation from the grid. The cumulative effect of this is a reduction of GHG gases at the port area while transferring the emission to the power generation site which may result to a very minimal overall reduction.

III. METHODOLOGY

To come up with a working methodology, this study reviewed methodologies from previous studies of similar nature.

A: Review of Previous Methods

In [9], Juan collected data from the port on the number of vessels calling and time spent at berth. He used technical surveys and interviews to get information on the on-board power systems, fuel consumption and emissions of container

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and tanker vessels visiting the port from port managers and engineers. The researcher used average data to carry out estimations on energy savings, fuel savings and emission reduction, and used calculations for the various technical aspects for the design [9]. In [14], Wang et al. used the activity-based approach recommended by IMO in 2014 to estimate the global port emissions and used data from Automatic Identification System (AIS) to calculate emissions from container ships [14]. He used the quantitative approach to sum all emissions from each vessel category to get the total emissions from all the ships calling at the port for a given duration [14]. He then used life cycle analysis to estimate the global port emissions reduction at the port [14].

B: Proposed Method

The data was collected primarily from KPA operations department from records, surveys and interviews with marine engineers and captains. More data was collected from online sources including Lloyd's register, Starcrest data and AIS data from shipping websites. This data included the vessels name, IMO number, date of visit including arrival and departure times, TEUs, gross tonnage (GT), length overall (LOA), Main Engine (ME) and Auxiliary Engine (AE) capacities, and dwell time at berth. Secondary data about the vessel including the Country of origin, year of build (YOB), deadweight tonnage (DWT), load factor and emission factor were obtained from online sources. The data was averaged to determine the actual load to be used for the calculations and the design while also comparing with existing standards. Based on the dwell time of the ships, the annual energy demand was determined in kilowatt-hours (kWh). The amount and cost of annual fuel burned by the vessels was calculated and the annual vessel emissions when the vessel is using auxiliary power calculated using Equation 1 to generate the annual cost of pollution [15].

$$E = EF * P * LF * t \qquad [1]$$

Where E is the amount of emissions for a taken period, EF emission factor for the AE in g/kWh, LF the AE load factor (%), P the AE nominal power (kW), and t time (hours).

This study used AutoCAD Autodesk software to design components of the OPS system and Microsoft Excel for graphical presentation, comparison, and cost estimation. A cost-benefit analysis for the project was done using financial project appraisal tools.

IV. PROBLEM DESIGN

The problem design of the OPS system was done with a supply from both the grid and solar PV source to meet the calculated load demand by the vessel during hoteling. Designs of all the components required for the installation including the transformers, frequency converters, solar PV modules, inverters, circuit breakers and switchboards and the cables and ducts were designed using AutoCAD software to produce an electrical layout drawing.

V. RESULTS AND DISCUSSION

The data of the container vessels that visited the port in the month of December 2021 was collected from the operations department at KPA. Additional information about the ships was retrieved from online AIS data. It was established that the container vessels visiting the port averaged 33,671 GT and 40,664 DWT. The largest container vessel during the duration of the data collection was the Ever Uranus with a carrying capacity of 5652 TEU and a length of 285m by 40m beam. The shortest vessel to visit the port was 148m long while the longest was 294 m. 123 vessels visited the port in that month as recorded in Table I.

Table I: Summary of Vessels that Visited the Port

Item	*Vessel Type*	*No.*	*LOA Range*
1	Container Vessels	33	148-294
2	General Cargo Ships	16	35 - 150
3	Bulk Carriers	27	140 - 230
4	Product Tankers	15	32 – 250
5	RORO/Vehicle Carrier	19	70 - 240
6	Other Vessels	13	22 - 230
	Total Vessels	123	

The data collected included a register for 33 container vessels giving their details including the vessels name, IMO identification number, date of call (both arrival and departure), the dwell time at the port, the flag country, year of build, gross tonnage, DWT and the length overall and the beam. The chart in Figure 4 shows that container vessels presented the highest category of vessels that visited the port within that month at 27%. The average dwell time for the container vessels was 71.3 hours which was the longest for the ship types.

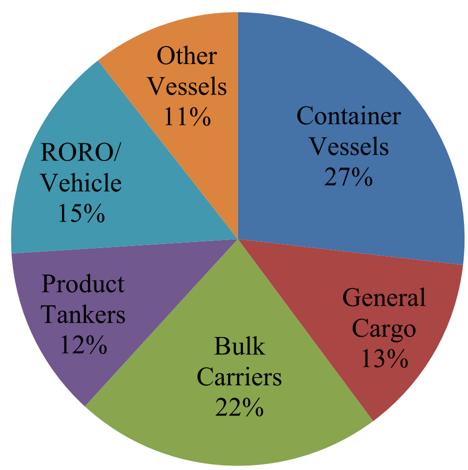

Fig. 4. Vessels Call in December

A: Key Parameters of the Vessels

The vessel data collected was then averaged for several vessels and presented in Table II. The ratio of the AE to ME capacity was calculated for each vessel type and it was observed that the cruise ships, tugboats and pilot boats only possess one main engine hence have a unity ratio. The average power demand for an OPS facility for a container vessel was calculated as 1,469.88 kW after adopting a LF of 0.18 while the vessel is hoteling. The vessel with the highest demand was the cruise ship with an OPS load of 24.6 MW with a load factor of 0.64. The table shows the challenge of variation in power demand that must be considered while implementing cold ironing. This study designed for only the container ships to address this variation in power required.

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The graph of Figure 5 gives a comparison of key parameters of the vessels tabulated in Table II. The line graph shows the gross tonnage while the columns compare the main engine to the auxiliary engine power and the OPS power in kW. From the graph, the higher the GT of a vessel, the higher the power required except for the bulk carriers. To calculate the OPS load during hoteling, load factor from Starcrest database was used. For a container vessel with 13,501 kW AE rating at a

Table II: Average Parameters for Vessels

Vessel Type	*GT*	*DWT*	*ME (kW)*	*AE (kW)*	*LF*	*Load (kW)*
Container	39,562	49,854	36,465	8,166	0.18	1,469.8
Tanker	75,128	71,148	17,201	7,473	0.26	1,942.9
RORO	45,505	17,131	19,155	4,380	0.26	1,138.8
Cruise	104,322	9,303	38,500	38,500	0.64	24,640
Ferry	8,127	936	32,800	1,640	0.22	360.8
Bulk	82,531	158,021	16,367	2,089	0.1	208.9
Tugboat	757	632	3,410	3,410	0.22	750.2
P. Boat	75	10	360	360	0.22	79.2

load factor of 15%;

$$P_{ops} = P\ (kW) \times LF = 13{,}501 \times 0.15 = 2{,}025\ kW.$$

The OPS system would supply three adjacent berths namely berth 20, 21 and 22. An approximate total load was calculated by; $P_{tot} = 1{,}084 + 1{,}305 + 2{,}025 = 4{,}414$ kW. The average load for the container vessels surveyed in Table II was given as 1,469.88 kW. Hence the supply for three berths using this average load is 4,409.64 kW which is almost equal to the calculated load using Starcrest data. For this design, a maximum load of 5 MVA was considered to carter for any three large vessels berthing simultaneously along the three berths. From the survey the bulk carriers and some of the container vessels mostly use low voltage of 450 V. Some of the tankers and the container vessels are supplied at 6.6 kV while the cruise ships use high voltage of 11 kV. Additionally, it was noted that a few vessels operate at 50 Hz while most operate at 60 Hz frequency cutting across the types. The design was to supply the three berths with power at 6.6 kV with a frequency of both 50 Hz and 60 Hz.

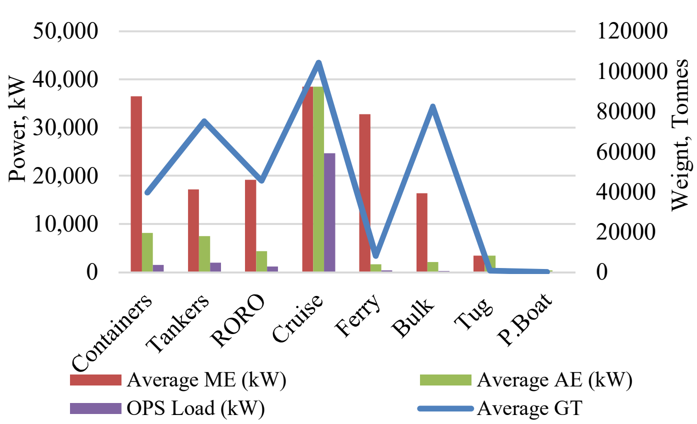

Fig. 5. Vessel Average Parameters

B: Components Specification and Design of the OPS System

The calculated load and supply voltage were used in sizing and specifying all the components used in the design as given in Table III. A grid tied system was designed with power supply from the grid and Solar PV source using AutoCAD software to produce an electrical layout drawing as illustrated in Figure 6.

Table III: OPS Main Components Specifications

Component	*Electrical Properties*	*Qty*
Frequency Converter	5 MVA, Input - 6.6 kV; 50 Hz, Output - 6.6 kV; 60 Hz as ACS880 SFC ABB	1
Grid and Solar PV Transformer	5 MVA, Input – 11 kV; 50 Hz and 2 MVA, Input – 660 V; 50 Hz Output - 6.6 kV; 50 Hz as ABB	1
Solar Modules	365 Wp, Vmax - 36.87 V, I max 9.90 A as Jinko panel JKM365M-66HB	4240
Switchgear	Double BusBar 6.6 kV; 50/60 Hz 11 kV and 6.6 kV switchgear as ABB	Lot
Inverter	2000 kVA; 3200 kWp max, VDC Max 1500 V; Output – 1750 A, 660 V, 50/60 Hz as ABB PVS980-58	1
Junction Box	Junction Box complete with Plug as Cavotec X5	6
HV Cabling	2 set of 4x120 mm2 XLPE armored copper cable UG	1200

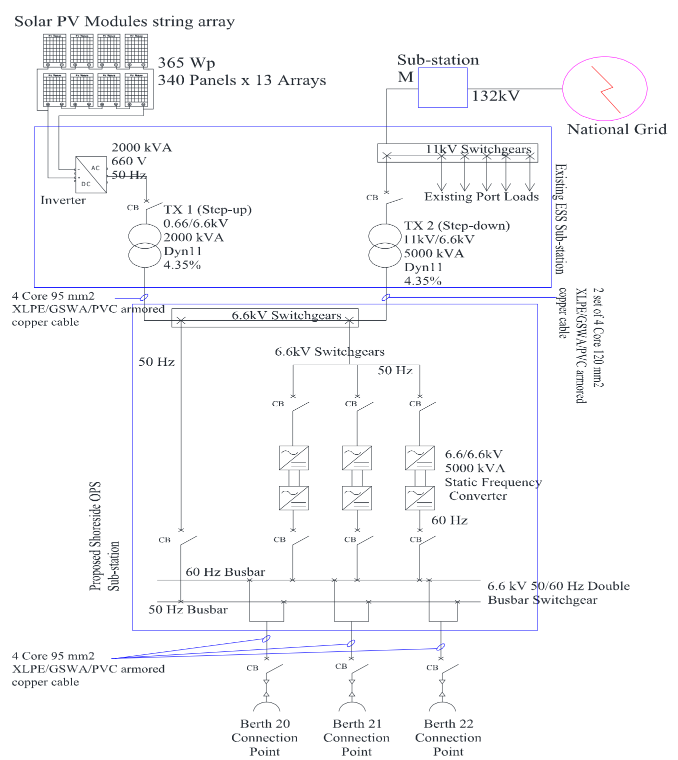

Fig. 6. OPS system problem design

C: Cost of OPS Project Implementation

The total cost of implementing the OPS system for the three container berths using a grid-tied system was estimated at Kenya Shillings 516,203,016 (an equivalent of USD 4,534,062.50 at the prevailing exchange rates). Notably, the solar component composed of 43% of the total cost.

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D: Annual Cost of Fuel Used when Hoteling

Total energy spent at the three berths by vessels when running on their AE engine was estimated as 146.4 GWh annually. Using a specific fuel consumption of 200 g/kWh for an engine using HFO fuel, the total annual fuel was calculated as 5,270.4 tons. Using an average cost of HFO of USD 575 per ton, the total annual cost of fuel was calculated as USD 3,030,480.

E: Total Emissions from the Vessels

From the survey done on the vessel types, it was noted that most of the vessels AE engines run on HFO fuel. Emission factors in g/kWh for HFO fuel is given as 13.7, 722, 0.8 and 12.3 for NO_x, CO_2, PM and SO_2 respectively. To calculate the amount of NO_x emitted by a container vessel with an AE power of 8,166 kW staying at the port for 71.3 hours, using Equation 1, the total emissions was E = 13.7 g/kWh x 8,166 kW x 0.18 x 71.3 h = 1,435.8 kg. This gives 361.8 tons for 3 vessels for duration of one year. Similarly, the amounts of the other pollutants were also estimated and recorded in Table IV. The EU Emissions Trading System prices were then used to arrive at the total cost of emissions from the three container berths.

Table IV: Annual Cost of Emissions for Three Berths

Pollutant	*Amount (tons)*	*Cost Per Ton (USD)*	*Emissions Cost (USD)*
NOx (t)	361.8	417.60	151,087.7
CO_2 (t)	19,076.4	7.20	137,350.1
$PM_{2.5/10}$ (t)	21.1	17107.20	360,961.9
SO_2 (t)	324.8	619.20	201,116.2
Total Cost of Emissions Annually (USD)			850,515.90

To better understand the environmental impacts caused by the running of the onboard engines at berth, CO_2 equivalents of each power source emissions were calculated based on the fuel consumption and technology type and tabulated in Table V. Notably, the emissions from the vessels' HFO fuel used were ten times higher than the grid and solar PV OPS source.

Table V: Emissions in CO_2 Equivalents for the Power Sources

Energy Source	**CO_2 Equivalent (tonnes)**
HFO at GWP20	*103,000*
Electricity Grid	*10, 674.1*
Solar PV	*12.57*

F: Cost of Energy from the OPS System

The annual cost of electricity was calculated as USD 1,965,977.86. Part of the power was supplied from Solar PV.

Table VI: Summary of Project Costs

	CAPEX (USD)	OPEX (USD)
OPS Installation Costs	4,534,062.50	
Cost of Annual Fuel		3,030,480
Emissions Annually		850,515.90
Cost of Electricity		(1,965,977.8)
Estimated Maintenance		(439,174)
Estimated Cost of Retrofit		(702,678)
Totals	4,534,062.50	773,166.1

G: Cold Ironing Cost Appraisal

The payback period for the project was 5.86 years hence it will take about 6 years to benefit from the project. The Net Present Value was a positive value of USD 1,567,092.88 hence beneficial to the organization and the Internal Rate of Return gave a 16.8% rate showing viability of the project. Table VI gives a summary of project costs.

VI. CONCLUSION

The Port of Mombasa is a major gateway frequented by ships loaded with cargo to various countries in Africa. These ships, through their auxiliary engines emit pollutants during their stay at the port while loading and unloading. The study showed that the vessels spend 71.3 hours on average at dock. During their stay, for three container berths, the main pollutants emitted were 361.8 tons of NO_x, 19,076.4 tons of CO_2, 21.1 tons of PM and 324.8 tons of SO_2. This resulted in CO_2 equivalents of 103,000 TCO_2e emitted by the container vessels when running on HFO fuel. The design of the OPS system provided for supply from both the public electricity grid at 5 MVA and a 2 MVA solar PV source to supply the ships' energy demand. The results indicate a ten times reduction of GHG emissions from the port and its environs by supplying the vessels from an OPS system. The power from renewable energy source, solar PV, has great environmental benefits though still more expensive. This study estimated the annual savings from emissions as USD 850,515.90 which is much higher when all berths are considered.

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