A solar energy based shore side power system for a ferry service across the Suez Canal

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Abstract

For more sustainable shipping operation in coastal areas and port cities, shore side power (SSP) systems are attracting widespread interest as a solution to reduce ships auxiliary engines' emissions, noise, and vibration. The potential of these systems can be further improved by integrating renewable energy into the electricity grid. However, the majority of prior research has focused on investigating SSP systems for large ports in large shipping hub countries. Therefore, in this study, SSP technology is investigated for an inland waterway in Egypt on the Suez Canal utilizing real ferries operational data. Green electricity from solar sunshade structures is generated for the SSP system utilizing the Egyptian excellent solar energy potential. For this study, the ferry diesel generator, battery, and solar systems are modelled in MATLAB/Simulink environment to investigate the proposed SSP system. Results indicate that the proposed SSP system could eliminate annually 1420 tonnes of emissions as well reduce the grid CO_2 emissions by 1204 tonnes through the green electricity supplied to the grid. Moreover, the cash flow and net present value analyses have shown good profitability with a payback period between 7.4 to 12 years.

Keywords: Shore Side Power, Solar energy, Photovoltaic systems, MATLAB, Simulink, Egypt

1. Introduction

Sustainable development of maritime transportation has generated considerable research interest recently in order to preserve the available resources and the surrounding environment while achieving the targeted economic growth (Roh et al., 2016; Gupta et al., 2005). This is due to the fact that shipping handles more than 80% of the world trade while ships fuel consumption is dominated by conventional fossil fuels (Hansson et al., 2019). As a result, the total shipping greenhouse gas (GHG) emissions has increased by 9.6% between 2012 and 2018. These emissions are projected to increase by from 90% to 130% of 2008 emissions by 2050 as investigated by the International Maritime Organization (IMO) (Faber et al., 2020). In addition to air pollution,

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Abbreviations & Nomenclature

AC	Alternating Current	A	Fitting factor of the PV module performance curve
CII	Carbon Intensity Indicator	a, b	Constants
CF	Cash Flow	A_{PV}	Photovoltaic system area
CO	Carbon Monoxide	E_{PV}	Photovoltaic electrical potential energy
CO_2	Carbon Dioxide	F_d	Fuel consumption of diesel generator
DC	Direct Current	H	Solar irradiation
DCF	Discounted Cash Flow	I, i	Current
ECA	Emission Control Area	I_{pv}	Photo-generated current
EEDI	Energy Efficiency Design Index	I_{sat}	Diode reverse saturation current
EEXI	Energy Efficiency Existing Ship Index	K	Boltzmann's constant
GHG	Greenhouse Gas	Ns	Number of photovoltaic modules connected in series
IMO	International Maritime Organization	P_d	Power output of diesel generator
NPV	Net Present Value	P_d^{rated}	Rated power of diesel generator
NOx	Nitrogen Oxides	PR	Performance ratio
O& M	Operations and Maintenance	Q	Battery capacity
PBP	Payback Period	q	Electron charge
PM	Particulate Matter	r	Photovoltaic panel efficiency
PV	Photovoltaic	R_S	Series resistance
SCA	Suez Canal Authority	R_{sh}	Shunt resistance
SEEMP	Ship Energy Efficiency Management Plan	T	Temperature
SOC	State Of Charge	t	time
SOx	Sulphur Oxides	V	Voltage
SSP	Shore Side Power		
VOC	Volatile Organic Compounds		
WHO	World Health Organization		

negative environmental impacts of shipping include water, oil, and noise pollution which endanger the marine ecosystems especially of coastal and port cities.

Coastal areas and ports play a crucial part in the development of the local as well as the world socio-economic growth due to their role with transportation, trade, commerce, tourism, politics, etc. However, these operations and activities contribute significantly to the deterioration of the surrounding areas marine environment (Eyring et al., 2010). For example, ship emissions were the major source of urban pollution in several port cities due to ships and port activities (Winkel et al., 2016). It was also found that port and coastal cities suffer from the emissions released from ships at sea, as 70% of these emissions occur within 400km of shore and can readily travel hundreds of kilometers towards land (Winkel et al., 2016; Eyring et al., 2010). The main ship emissions include carbon monoxide (CO) and dioxide (CO_2), nitrogen oxides (NOx), sulphur oxides (SOx), particulate matter (PM), and volatile organic compounds (VOC). These emissions contribute to climate change and are responsible for thousands of deaths and millions of childhood asthma, cardiovascular, cancers, and pulmonary cases (Di Natale et al., 2022; Kotrikla et al., 2017). These negative environmental impacts also include the noise pollution which causes disturbances to humans by auditory and non-auditory problems as well as the marine mammals by influencing their communications (Casazza et al., 2018; Badino et al., 2012). Therefore, several technologies, solutions, and measures have been suggested and adopted to improve ships environmental performance.

In order to reduce the negative environmental impacts of shipping, the IMO has taken many mandatory regulatory, technical and operational measures; for new ships this includes the Energy Efficiency Design Index (EEDI) whilst for all ships require a Ship Energy Efficiency Management Plan (SEEMP) measure (Rehmatulla et al., 2017; Bazari and Longva, 2011). Also, ships are now required to meet a specific Energy Efficiency Existing Ship Index (EEXI) and to calculate their operational Carbon Intensity Indicator (CII) annually with an aim of reducing the carbon intensity by 40% of all ships by 2030 compared to 2008 (De Oliveira et al., 2022). In addition to carbon emissions, limitations on nitrogen and sulphur emissions have been made with the introduction of Emission Control Areas (ECA), Tier III NOx standard, and the 0.50% global sulphur limit in fuel (Ni et al., 2020). Moreover, a code on noise has been adopted by the IMO in 2012 to reduce the negative impacts of noise on humans and the marine life (Badino et al., 2012).

One of the promising approaches to reduce both the GHG emissions and noise by ships at port and coastal areas is using shore side power (SSP) systems (Qi et al., 2020; Winkel et al., 2016; Seddiek, 2016). SSP systems, which are also known as shore side electricity, onshore power supply, or cold ironing systems, allow ships to satisfy their electricity requirements from the shore network instead of their generators while berthing. As a result, ships can shut off their auxiliary engines during their stay at port which can effectively reduce the negative environmental impacts of air emission and noise to a larger extent (Qi et al., 2020; Yun et al., 2018). Although SSP systems receives power from the national grid which mostly relies on large power plants using fossil fuels, these land-based power plants are more efficient in terms of electricity generation and more environmentally friendly than the diesel generators onboard ships. Moreover, large power plants are normally located outside the heavy populated areas which relocates and reduces the impacts of air emissions and noise away from port and coastal areas (Stolz et al., 2021; Hall, 2010). Furthermore, the use of SSP systems promotes the transition towards the electrification of ships which has been proposed as a feasible solution to achieve the decarbonization and energy efficiency of the shipping sector (Barreiro et al., 2022; Perčić et al., 2022).

The environmental potentials of SSP systems can be further improved by deploying renewable energy and increasing its share in the energy mix used for electricity production which is also targeted by the Egyptian government (Wang et al., 2019b). In 2016, a long-term strategy, *Egypt's Vision 2030*, has been developed in Egypt which incorporates three main dimensions; economic, environmental, and social dimensions for the sustainable development (El-Megharbel, 2015). The second pillar of this strategy is about the efficient use of energy and increasing the renewable energy utilization ratio to 30% of the fuel mix for electricity production by 2030 (El-Megharbel, 2015). However, with the current growing national demand of energy in Egypt, the renewable energy share is declining despite the increasing deployment of renewable energy sources (Bank, 2021; Mondal et al., 2019). Therefore, to move toward a more sustainable and low-carbon energy system, additional efforts are needed to satisfy renewable energy targets.

With a total solar irradiance between 2000 to 3200 $kWh/m^2/year$, Egypt is considered one of the most feasible regions for solar energy applications. Egypt has a solar energy potential of 74 billion $MWh/year$ distributed throughout the country as shown in Figure 1 (Moharram et al., 2022; IRENA, 2018). For direct electricity generation from solar energy, Photovoltaic (PV) systems are the most commonly used technology (Sahu et al., 2016). This is because PV systems have the advantages of reliability, flexibility, sustainability, modularity, environment-friendly, and quiet operation with long lifetime which can be used for stationary, transportation and portable applications (Alami et al., 2022; Sahu et al., 2016). Moreover, it was found that the climatic conditions in Egypt of humidity, air temperature, sunshine hours and solar radiation are compatible with the safe operating conditions of PV modules (Salah et al., 2022; El-Shimy, 2009). Furthermore, several studies and techniques have been conducted and proposed in order to improve the performance and operational efficiency of PV systems under the Egyptian climate conditions (Elminshawy et al., 2022, 2021, 2019; Moharram et al., 2013).

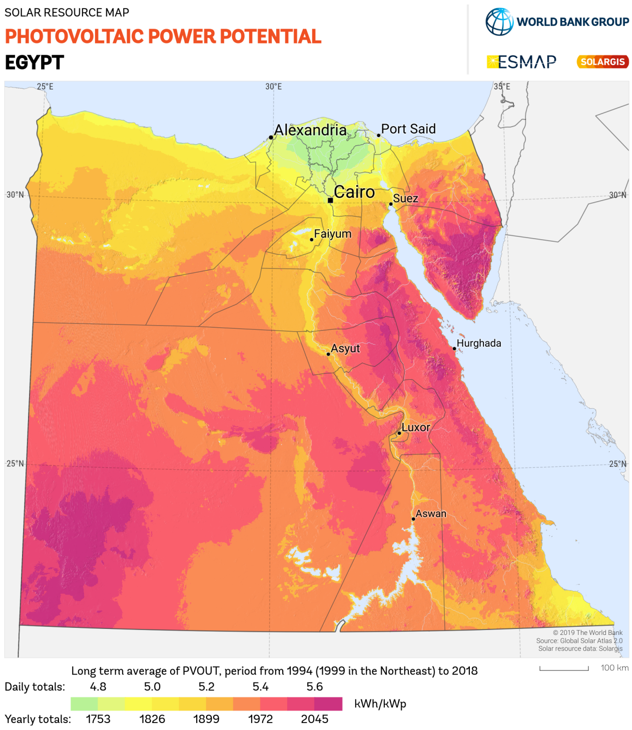


Figure 1: Solar photovoltaic power potential distribution in Egypt (Global Solar Atlas, 2022)

Recently, there has been numerous studies and applications of PV systems in the maritime field. In these applications, solar energy can be utilized for the main propulsion system of ships such as the 'MS Tûranor PlanetSolar' or for the ship auxiliary power system such as the 'Auriga Leader' or the 'Emerald Ace' (Pan et al., 2021). These applications can be small-sized where it can purely solar-powered such as the "Sun21" or large where the solar energy is hybridized with diesel generator, wind energy, etc. (Karatuğ and Durmuşoğlu, 2020; Wang et al., 2019a). In addition to ships, solar energy maritime applications include offshore and floating platforms for power generation, water desalination, or hydrogen production (Bassam et al., 2023; Amin et al., 2020; Temiz and Javani, 2020; Sahu et al., 2016). Moreover, solar energy can be utilized onshore to supply the power demands of ports or ships through SSP systems (Wang et al., 2019b; Kotrikla et al., 2017).

Towards the decarbonization and electrification of ports, the synergy between SSP and ports' microgrid systems incorporating renewable energy sources has been investigated in several studies (Bakar et al., 2023; Alzahrani et al., 2021). Large ports of the United States which includes ports of San Diego, Los Angeles, and Long Beach have integrated solar energy in their microgrids for higher environmental and operational efficiency (Zhang et al., 2022). Solar PV panels have been installed on the ports' administration buildings, cargo terminals, pavilions, etc. to supply electricity for the ports' operations as well as the berthed ships. Also, many large ports around the world have implemented PV systems in their microgrids for ports' loads including SSP including: Rotterdam, Amsterdam ports in Netherlands, Antwerp in Belgium, Gothenburg in Sweden, Shanghai in China, Auckland in New Zealand, etc. (Roy et al., 2020). Moreover, many initiatives have been developed to provide SSP systems implementing renewable energy for berthed ships. However, there is still a long way to go to overcome the administrative, investment, operational, legislation and legal challenges which requires further studies (Innes and Monios, 2018).

For more environmentally friendly and sustainable Egyptian ports, SSP concept has been identified as a key indicator for the green performance of ports in Egypt (Elzarka and Elgazzar, 2014). However, little work has been done on the application of SSP for the Egyptian ports and coastal cities. This despite the fact that Egypt has 54 ports and hundreds of terminals on the Mediterranean Sea, Red Sea, Suez Canal, and River Nile with thousands of boats and ferries which can benefit from the SSP concept. Also, there is still a gap in knowledge about the utilization of renewable energy sources for ports and ships operation (Hoang et al., 2022). Therefore, more work is required to investigate the impact of supplying ships with their need of electricity from the shore using renewable energy sources rather than using their generators around the Egyptian ports and coastal areas.

Currently, Egypt has installed a shore side power system in Damietta port, one of its oldest ports on the Mediterranean Sea, and issued a decree in 2015 to make the port authority in charge of providing the berthed ships with their needs of electricity. Also, Egypt has provided the berths of Alexandria port with the required equipment to supply vessels with their electricity supplies from the shore (Mohamed and Salah Eldine, 2020). In (Seddiek et al., 2013), SSP concept has been studied for high-speed crafts berthed at Safaga port on the Red Sea in Egypt where the investigated SSP sources included the national grid, fuel cells, and dual fuel engines.

Furthermore, previous studies on SSP systems have almost exclusively focused on large ports and terminals with only a few works on small applications (Innes and Monios, 2018). Therefore, this study aims to investigate the economic and environmental potential of SSP concept for an inland waterway in Egypt which connects the Suez Canal banks between Port Said and Port Fouad cities through ferries. The performance of the proposed SSP system in this study is enhanced by integrating the concept of solar sunshade structures of the ferry terminal to generate green electricity. This concept has previously been examined only for road transportation systems of electric vehicles and buses as can be found in the literature (Nunes et al., 2016) with no prior studies for maritime applications which is another gap to be filled. The green generated electricity can be then fed to the SSP system and the national electricity grid which reduces the negative environmental impacts of shipping and electricity production. A total area of about 12000 m^2 is available on both sides of the Suez Canal for the examined ferry terminals with great solar potential. Considering the real ferry electrical load demand, a grid connected solar-based SSP system with different areas and different operational strategies is investigated in this study. The ferry diesel generator, batteries, and PV system are mathematically modelled, validated, and implemented in the flexible environment of MATLAB/Simulink.

The rest of the paper is organized as follows; Section 2 introduces the examined ferry, its terminal, and the proposed concept. Section 3 illustrates the mathematical modelling and simulation of the current ferry system as well as the proposed system while Section 4 shows the simulation results and discussion. Finally, Section 5 presents conclusions.

2. Case study description

The Suez Canal is considered one of the most important and extensively used shipping routes due to its unique location and the shortcut it provides between the Atlantic Ocean and the Indian Ocean. Also, in order to link the River Nile valley with Sinai Peninsula, about 36 ferries operate alongside the Suez Canal at 14 locations (Suez Canal Authority, 2022). This ship traffic, which is expected to increase, is responsible for millions tonnes of GHG emissions emitted annually in the Suez Canal waterway which deteriorates the air quality in coastal cities such as Port Said (El-Taybany et al., 2019) and increase the emissions concentration and air quality indices several times above the World Health Organization (WHO) recommended limits (Egyptian Ministry of Environment, 2017). Therefore, the Suez Canal Authority (SCA) is keen to mitigate these GHG emissions and preserve the environment while achieving the required sustainable economic growth.

2.1. The ferry

This study considers one of the double ended car and passenger ferries owned by the SCA. The canal authority is also responsible for the building of these ferries and their operation and maintenance. These ferries sail constantly across the Suez Canal between Port Said and Port Fouad 24 hours a day and its main particulars are shown in Table 1. This ferry service play a key role in the transportation system carrying over 20 million people and 6 million cars per year. The route is about 1 *km* distance as shown in Figure 2 with an average voyage time of 7 minutes and wait time on terminal of about 8 minutes for loading and unloading. The number of working ferries at one time varies between 5 and 7 depending on the demand except for the time between midnight and dawn when only 2 ferries are in operation.

The ferry is equipped with 2 Volvo marine generator sets with a power output of 62 *kW* to supply the ferry's electrical loads where one generator is running and the other generator is standby. The ferry is also equipped with the necessary power-receiving interface to connect the ferry with the shore power supply. From the ferry electrical load balance sheet provided by the SCA, the required ferry electrical load while berthing at the terminal during loading and unloading is 36.95 *kW*. As the ferry starts to sail, about 2.4 *kW* is required for the ferry ramp to be stowed then the ferry electrical load reaches 47.27 *kW* during its normal sea operation. Real-time measurements of the ferry operational profile during sailing, loading, unloading, etc. have been made and averaged to have the time window of each phase. Then, by taking into consideration the efficiency of the switchboard, transformers, and converters, the ferry electrical load can be found in Figure 3.

Table 1: Main specifications of the examined ferry

Parameter	Value
Length	50 m
Breadth	15 m
Depth	2.5 m
Draft	1.44 m
Service speed	8 kn
Carrying capacity	320 tons
Propellers	2 Azimuth propellers
Powering	2 Volvo D13 main engines of 294 kW
	2 Volvo D5AT marine generator of 62 kW

Figure 2: Route of the examined ferry

Based on the typical electrical loads requirements shown in Figure 3, the ferry electrical load demand profile for a daily operation of 8 hours is shown in Figure 4 to be used as an input for the system simulation as will be discussed. These loads include the bridge, deck, and engine room equipment of pumps, supply and exhaust fans, lighting, ferry ramps, etc.

2.2. The ferry terminal

The ferry terminal on Port Said side of the Suez Canal has 4 slips for the ferries to dock as shown in Figure 5a. The vehicles' queue area on Port Said side has 7 lanes and it is equipped with a sunshade structure to provide protection from sun and rain for vehicles and people with an approximate area of 4000 m^2. On the other side of the canal, Port Fouad terminal has 5 slips for

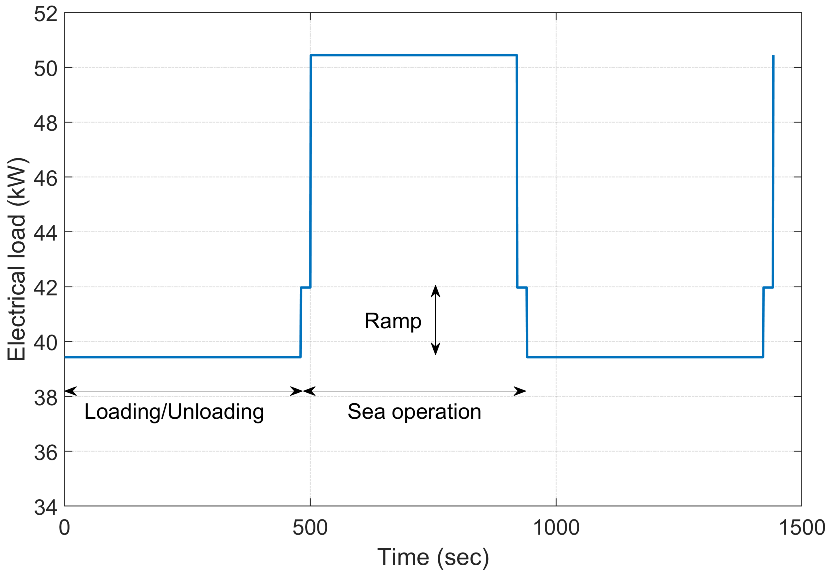


Figure 3: Part of the electrical load demand of the examined ferry

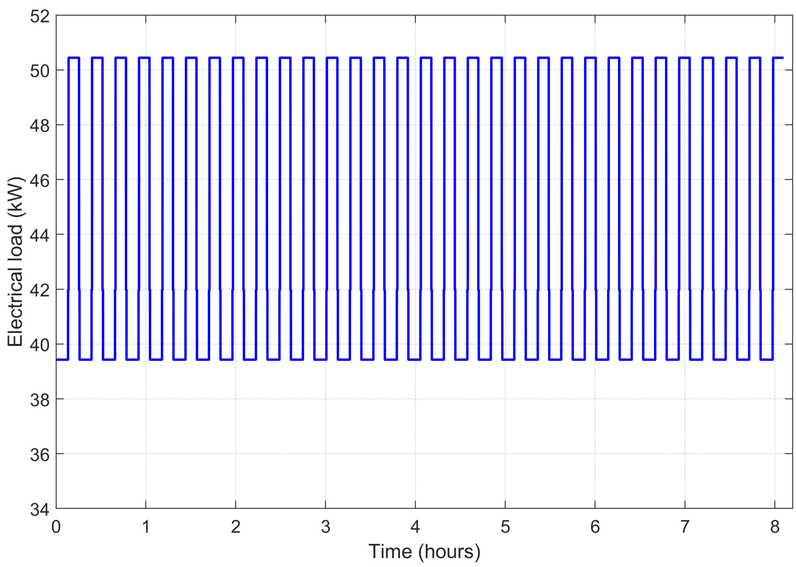
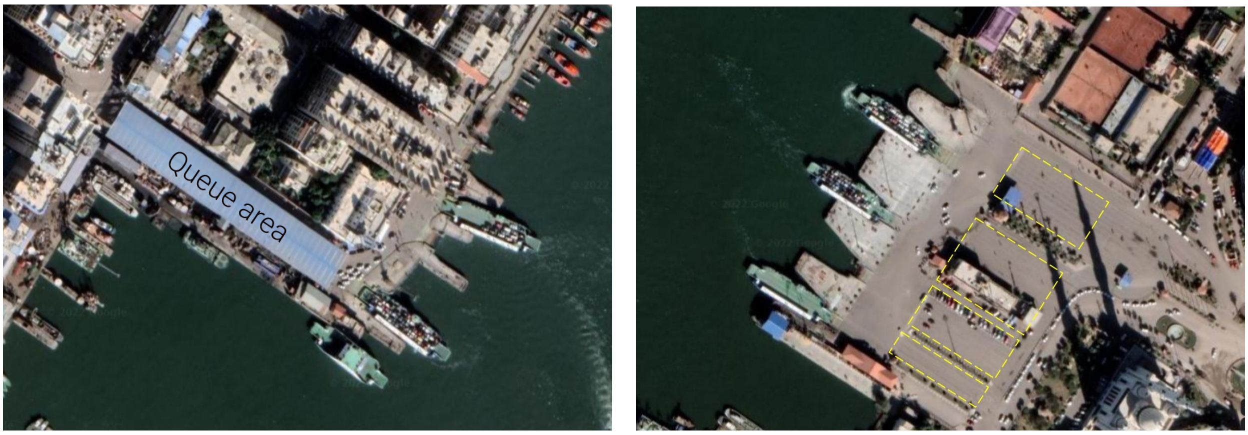


Figure 4: Electrical load demand of the examined ferry for a daily operation of 8 hours

the ferry docking and 32 lanes to load and unload the ferries in an open area of about 8000 m^2 without shade as shown in Figure 5b. Some of these lanes on both sides of the terminal are left for emergency and law enforcement vehicles.

According to the traffic volume demand, the number of ferries operating between the two banks is decided. For example, the traffic increases during public holidays and in summer months than in winter months. As shown in Figure 6, the number of ferries varies normally between 5 and 7 except for the early morning when the traffic is minimal and 2 ferries only sails across the Suez Canal between Port Said and Port Fouad.



(a) Port Said ferry terminal

(b) Port Fouad ferry terminal highlighting the areas available for solar panels

Figure 5: Terminals of the Suez Canal ferry on Port Said and Port Fouad sides

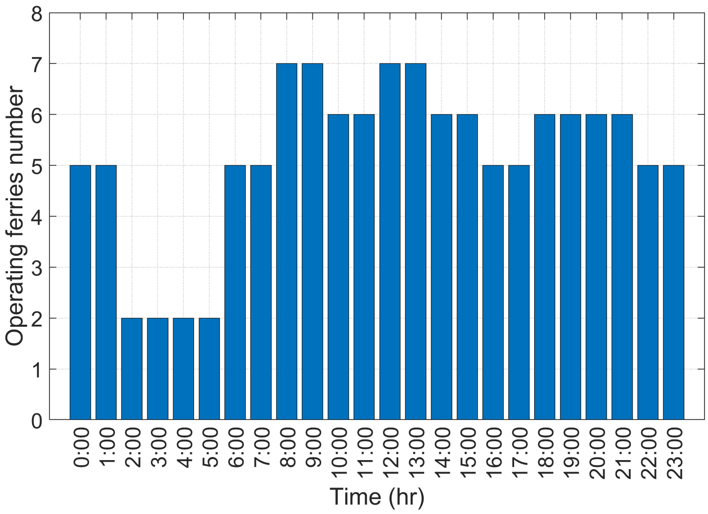


Figure 6: Number of operating ferries between Port Said and Port Fouad per hour during the day

2.3. Proposed solution

In this study, it is proposed to use a shore side power system to supply the 7 ferries operating across the Suez Canal with electricity while docking at the terminal and replace the ferry conventional diesel generators with batteries to meet the ferry electrical load during normal sailing. Thus, the ferry fuel consumption, emissions, and noise are reduced which improves the operational and environmental efficiencies of the ferries operating around the Suez Canal coastal areas.

For more sustainable and green operation, the shore side network electricity mix contains a high percentage of renewable solar energy beside electricity from the national grid if needed. This is due to the high potential of solar irradiation in this area as shown in Figure 7. For this purpose, it is suggested to equip the currently existing sunshade structure on Port Said side with solar PV modules. Also, the vehicles' queue open area on Port Fouad side is also proposed to have a PV sunshade structure to generate electricity for the SSP system while providing shade. The proposed solar-based SSP system is a grid connected system due to its simplicity, efficiency, profitability and lower cost (De Lima et al., 2017). Moreover, this grid connected system is not equipped with an energy storage system such as batteries due to the technical and economic viability of such systems (Da Silva and Branco, 2018; Tomar and Tiwari, 2017).

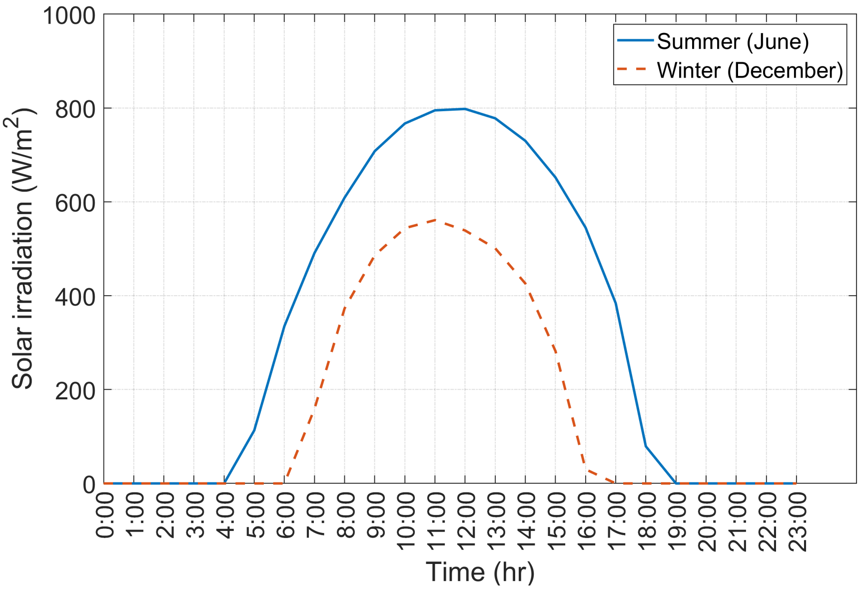


Figure 7: Average hourly profile of the direct normal irradiation in the proposed ferry terminal (Global Solar Atlas, 2022)

3. Mathematical modelling & simulation

3.1. Diesel generator

As explained in Section 2, the ferry electrical load demand is supplied by a Volvo diesel generator. The fuel consumption of this diesel generator F_d can be calculated as a function of the generator power output during operation P_d and the rated power output of the generator P_d^{rated} as follows,

$$F_d = a \, . \, P_d + b \, . \, P_d^{rated} \tag{1}$$

where a and b are constants which are used to reflect the characteristics of the diesel generator consumption curve (Lan et al., 2015). The diesel generator mathematical model using Equation 1 is validated against the manufacturer specifications as shown in Figure 8 with a maximum error of less than 3%.

For the generator emissions calculations, fuel-based emission factors are used in conjunction with the generator total fuel consumption in Equation 1 to estimate the emissions using the bottom-up approach as discussed in the latest IMO GHG study (Faber et al., 2020). According to the IMO GHG previous studies, the main emissions factors for auxiliary engines using marine diesel oil as a fuel are shown in Table 2.

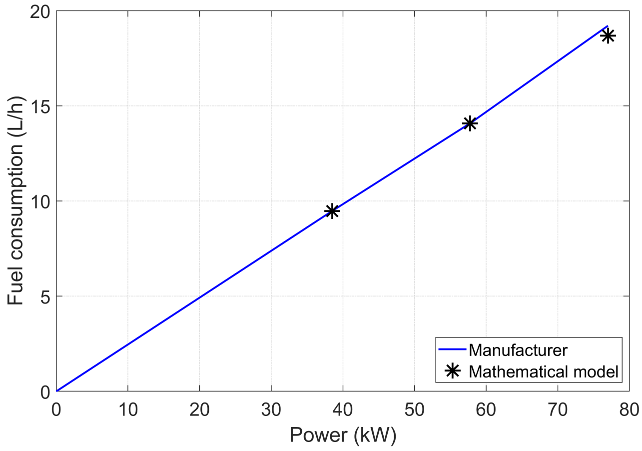


Figure 8: Validation of the diesel generator fuel consumption

Table 2: Fuel-based emissions factors (Faber et al., 2020; IMO, 2014)

Emission factor	Value ($kg/tonnefuel$)
CO_2	3206
NOx	36.12
PM	6.34
CO	2.77
SOx	1.4

3.2. Battery

Among the available energy storage technologies, batteries have become the main energy storage system for transportation applications; especially lithium-ion batteries due to their higher efficiency, higher energy and power density, and longer lifetime (Wang et al., 2019c). The Simscape library of Simulink includes a generic battery model which can accurately represent the battery dynamic behaviour. Therefore, this model is utilized in this study. This model has been also validated with experimental results with a maximum error of 5% when the battery state of charge (SOC) ranges between 10% and 100% (Mathworks, 2022). However, it is not recommended to discharge batteries below 30% for battery health and safety reasons (Shen et al., 2020).

In this model, the battery SOC is calculated as a function of the battery capacity Q and the battery current i with time t as follows,

$$\text{SOC} = 100\left(1 - \frac{1}{Q}\int_0^t i(t)\,dt\right) \tag{2}$$

3.3. PV system

The electrical potential energy of a PV solar system E_{PV} can be estimated as a function of the average solar irradiation H and the PV panel efficiency r as follows,

$$E_{PV} = H\,.\,r\,.\,A_{PV}\,.\,PR \tag{3}$$

where A_{PV} is the available area for the PV system and PR is the performance ratio which defines the system complete PV system losses (Fitriaty and Shen, 2018). According to the Global Solar Atlas, the solar resources data of the selected sites can be obtained and used to preliminary calculate the solar energy potential of the considered options assuming a PV tilt angle of 30° facing south as recommended for the application site (Elminshawy et al., 2019) with Monocrystalline silicon PV panel efficiency of 15% (Fitriaty and Shen, 2018) and 77% performance ratio of the complete PV system.

For more detailed PV performance simulation, a circuit-based single-diode model as shown in Figure 9 is recommended due to its simplicity and acceptable accuracy (Nguyen-Duc et al., 2020).

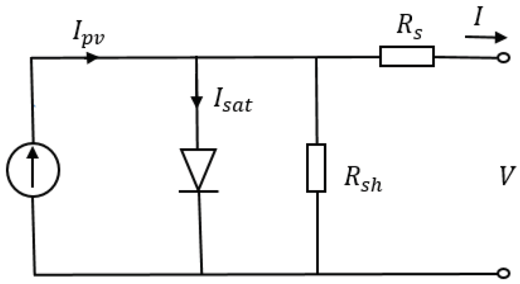


Figure 9: Single-diode equivalent circuit of a PV cell (Nguyen-Duc et al., 2020)

This model takes into consideration the PV cells temperature T and its effect on the diode reverse saturation current I_{sat} and consequently the operating current I and voltage V as follows,

$$I = I_{\text{pv}} - I_{\text{sat}} \left[\exp\left(\frac{V\, q}{A\, Ns\, K\, T} \right) - 1 \right] - \frac{V + I\, R_S}{R_{sh}} \tag{4}$$

where I_{pv} is the photo-generated current, q is the electron charge, A is a fitting factor of the $I - V$ curve of the PV module, Ns is the number of PV modules connected in series, K is the Boltzmann's constant, R_S, and R_{sh} are the series and shunt resistances respectively.

4. Results & analysis

4.1. Conventional system

Considering the electrical load demand in Figure 4, simulation results show that the diesel generators have an oil fuel consumption of about 11 litre/hour for one ferry operation which includes berth and navigation activities. The total annual fuel consumption of the ferries generators operating across the Suez Canal between Port Said and Port Fouad is about 437 tonnes taking into consideration the ferries operation frequency in Figure 6. Accordingly, the total annual fuel cost of generators is about $545,813 assuming a marine gas oil fuel price of 1250 $/tonne (Ship&Bunker, 2022). Also, the total annual atmospheric emissions from the ferries diesel auxiliary engines is about 1420 tonnes based on the emission factors in Table 2 which are dominated by CO_2 emissions as shown in Table 3.

Table 3: Annual total emissions from the auxiliary engines of the Suez Canal ferries operating between Port Said and Port Fouad

	Auxiliary engines emissions (*tonne*)
CO_2	1399.9
NOx	15.8
PM	2.8
CO	1.2
SOx	0.6

4.2. Proposed system potentials

These fuel consumption and emissions can be reduced or eliminated by replacing the diesel generators on the 7 ferries with batteries and supplying their electricity demand from the shore which comes from renewable solar energy and the national grid. In this study, it is proposed to replace the ferry's diesel generators with lithium-ion batteries due to their higher power and energy densities, higher efficiency, and durability compared to other battery types which is required for maritime transportation applications (Ovrum and Bergh, 2015).

The main specifications of the selected battery module are shown in Table 4. In addition to the battery module, the battery system also includes the required transformer, AC/DC rectifier, and the DC/AC inverter for the power conversion between the AC form of the required loads and the grid and the DC form of the batteries and PV system. Also, the battery system includes the cooling system of the battery modules. The capital cost of the battery system as well as the battery replacement and Operations and Maintenance (O& M) costs are also included in this study (Mayyas et al., 2022; García-Miguel et al., 2022).

Table 4: Specifications of the lithium-ion battery module

Energy	16 kWh
Capacity	40 Ah
Rated voltage	400 V
Maximum/ Minimum voltage	448/ 324 V
Continuous discharging current	320 A
Dimensions	736x515x284 mm
Weight	145 kg
System capital cost	350 \$/kWh
Battery replacement cost	100 \$/kWh
O& M cost	0.02 \$/kWh

Based on the ferry electrical load in Figure 4, the required energy for the ferry daily operation can be calculated. This energy requirement takes into consideration the electrical losses in the switchboard, transformers, and converters as explained earlier. Then, according to the battery specifications shown in Table 4, 25 lithium-ion battery modules are found to be sufficient for the ferry electrical demand during navigation without deeply discharging the batteries below a state of charge threshold value of 30% as recommended (Shen et al., 2020) as shown in Figure 10. Later, after the daily operational shift, the ferry's batteries can be fully recharged for the following operation. Meanwhile, the SSP system only supplies the ferry with electricity during berthing at the terminal for the loading and unloading.

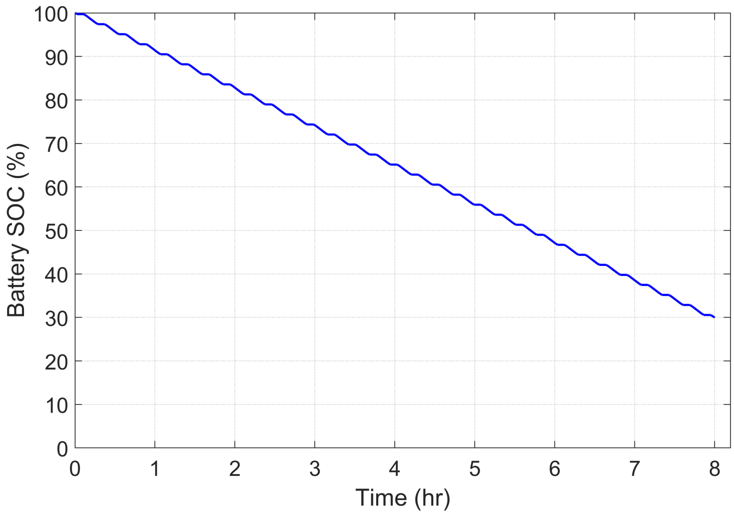


Figure 10: Battery system SOC during operation without charging the 25 battery modules by the SSP while berthing

The number of battery modules can be reduced if the SSP system is used to supply the ferry with sufficient electricity for both the ferry's electrical load as well as charging the battery system. As shown in Figure 11, by charging the battery system from the SSP during the ferry loading/unloading with a standard C-rate of 0.2C, a battery system of 15 modules can be sufficient for the daily ferry operation with a final battery SOC higher than the threshold of 30%. Consequently, the required battery system cost, weight, and size can be reduced. However, the consecutive charge/discharge cycles will affect the battery's cycle life. Also, by charging the battery system in addition to supplying the ferry electrical load, more power will be required from the SSP system.

As discussed in this study, the vehicles' queue areas sunshade structures on both sides of the Suez Canal are proposed to be covered with solar PV modules to generate green electricity while providing shade. Two options are considered in the analysis; Option A is to equip the currently existing sunshade structure on Port Said side with PV panels and Option B is about installing the PV panels on both vehicles' queue areas on Port Said and Port Fouad.

For Option A where an area of 4000 m^2 is available for the PV system, the required energy of the SSP system for the ferries' electrical load without charging the batteries can be covered by the PV system during the whole year with an annual surplus energy of about 356 MWh. This surplus energy can be fed to the national grid which reduces the national grid emissions by about 190 tonnes/year of CO_2 emissions with an emission factor of 0.533 $t\mathrm{CO}_2/MWh$ for Egypt's grid (Takahashi and Louhisuo, 2022). This also can result in an annual electricity cost saving of \$20,668 assuming a national grid power cost of 0.058 $\$/kWh$ for businesses applications (globalpetrolprices, 2022).

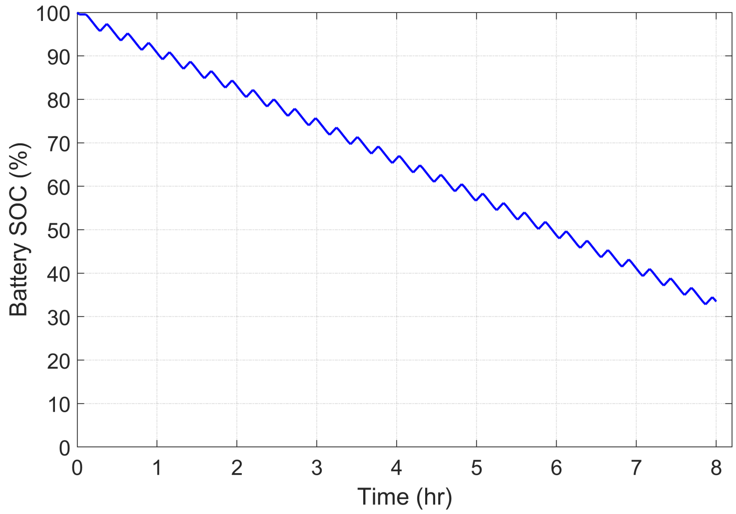


Figure 11: Battery system SOC during operation with charging the 15 battery modules by the SSP while berthing

However, Option A will not be able to provide the SSP required power to both supply the ferries' electrical load and charge the batteries except for month June as shown in Figure 12. The maximum average monthly PV production gets about 108 MWh per month in June while the maximum monthly SSP energy requirement is about 109 MWh per month. Consequently, for Option A, an annual electrical energy of about 332 MWh will be required from the national grid to support the PV system in supplying the required energy for both the ferries' electrical load and charging the ferries' batteries. As a result, about 177 tonnes/year of CO_2 emissions would be produced from the electricity generation by the national grid for the SSP system with an annual cost of $19,234.

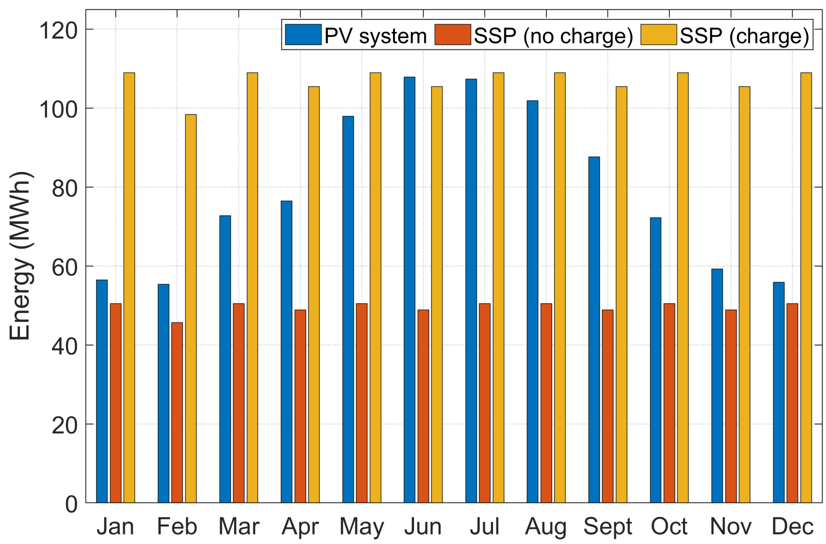


Figure 12: The monthly average PV system production of Option A compared to the SSP system requirements

For Option B where both vehicles' queue areas on Port Said and Port Fouad are covered with

PV panels with a total area of 12000 m^2, the PV system will be able to provide the required energy by the SSP system to supply the ferries' electrical load or supply the ferries' electrical load and charge their batteries as shown in Figure 13 with extra energy that can be fed to the national grid. The maximum average monthly PV production of 324 MWh per month is obtained in June with an excess energy in this month of 275 or 218 MWh depending on the SSP requirements which can be fed into the electricity grid.

The annual excess PV energy which can be supplied to the grid with Option B is about 2259 or 1571 MWh depending on whether the SSP system will charge the ferries' batteries in addition to supplying their electrical loads or not. As a result, the environmental and economical potentials of the proposed SSP Option B increases by reducing the national grid emissions by about 1204 or 837 tonnes/year of CO_2 emissions and saving an annual electricity cost of $57,788 or $40,188 due to the surplus PV electricity. However, Option B will require higher investment costs for the PV system than Option A due to the higher installed PV area and capacity.

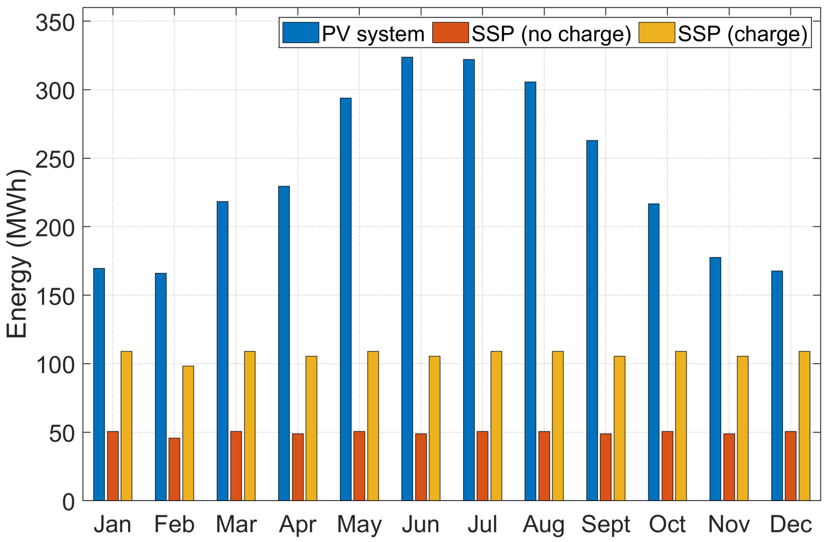


Figure 13: The monthly average PV system production of Option B compared to the SSP system requirements

The average hourly energy production of both options of the PV system with different areas is illustrated in Figure 14 which fluctuates seasonally between winter and summer conditions. The peak performance of the PV system around 12:00 noon fluctuates from 259 kWh in December to 369 kWh in June for Option A. While, due to the larger PV system area, Option B average peak daily performance fluctuates from 778 kWh in December to 1106 kWh in June. Figure 14 also shows the SSP energy requirements over the day for the two considered operational strategies of supplying the ferries' electrical load or supplying the ferries' electrical load in addition to charging their batteries. As shown in Figure 14, the SSP system energy requirements fluctuates according to the number of working ferries. These energy requirements can be supplied partially from the PV system during day hours according to the available PV area and the solar energy. Meanwhile, during night hours and early morning, the SSP energy requirements can be supplied from the national grid.

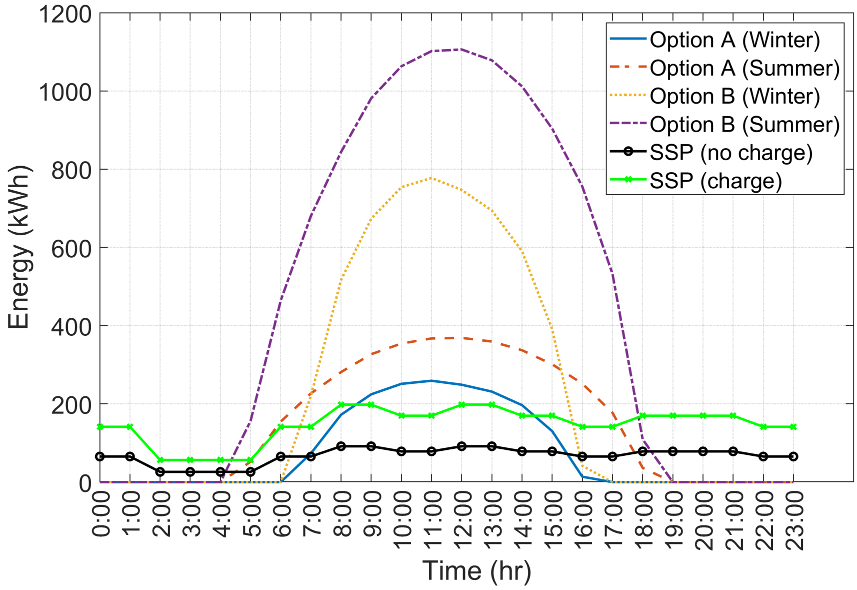


Figure 14: Hourly PV system power production in summer and winter compared to the SSP system requirements

4.3. Cost analysis

In terms of investment costs point of view, the capital cost of the PV system which includes the installation, mounting, wiring, and control can be estimated at around 550 $\$/m^2$ (Mohammadi et al., 2014). Also, the SSP onshore infrastructure cost would be about \$1 million while no modifications costs are required for the ferries since they are equipped with SSP connection capabilities (Hall, 2010). Moreover, an annual operation and maintenance cost of 5% of the SSP infrastructure cost can be considered (Innes and Monios, 2018). The diesel generators' O& M cost is also 0.01 \$/hour according to (Ghenai et al., 2019). However, these costs should be compared with the cost benefit and the socioeconomic impact of reducing the exhaust emissions introduced by the SSP system.

In addition to saving the cost of the total consumed diesel fuel of the ferries' generators and their O& M costs, green electricity from the PV system that can be fed to the national grid, and the environmental damage cost of air pollution should be also taken into consideration. This is due to the fact that air emissions cause several types of damage to the surrounding environment, human health, and quality of life. These impacts can be monetized to reveal the economic impact of this pollution to help governments and decision makers in adopting more stringent regulations, taxes, or fees to reduce these negative impacts (Van den Bijgaart et al., 2016). For the carbon footprint, an average environmental damage cost value of 48 $\$/t\mathrm{CO}_2$ is used in this study (Van den Bijgaart et al., 2016).

As shown in Figure 15, by taking into consideration the environmental damage cost of the carbon emissions form the ferries and national grid into consideration in addition to the fuel and electricity cost, Option B has the highest annual savings with about \$0.69 to \$0.75 million due to the higher available PV system area. However, with a PV area of 12000 m^2, an energy payback period (PBP) of 11.8 to 12 years is required to recover the PV system, batteries, and SSP onshore infrastructure costs that ranges between \$8.4 to \$8.9 millions according to the batteries number.

On the other hand, Option A has an annual savings of about \$0.54 to \$0.59 million with a lower payback period of about 7.4 years because it has lower PV system area than Option B with a PV system and SSP onshore infrastructure costs of about \$3.9 to \$4.5 millions according to the batteries number. It should be noted, however, that both options have payback periods less than the PV system's lifetime.

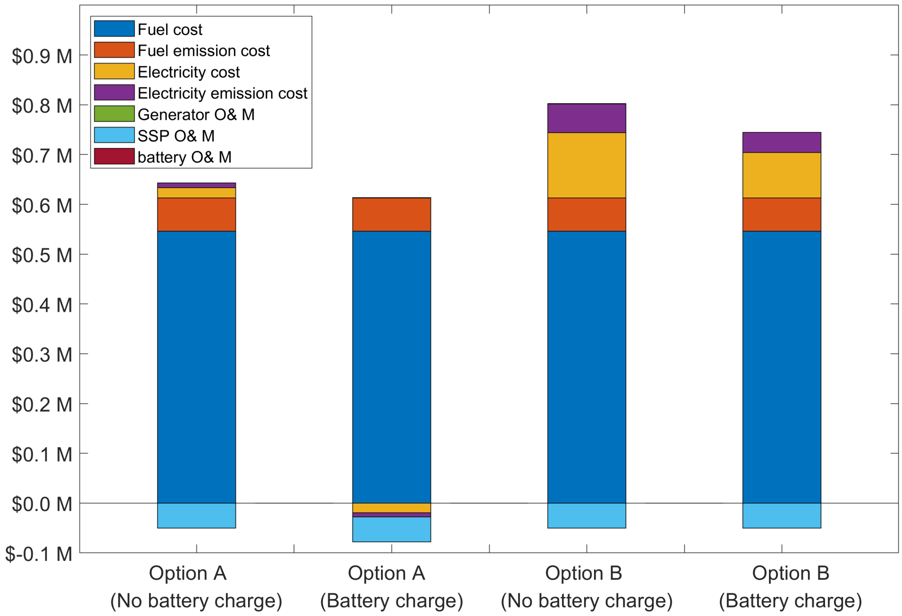


Figure 15: Annual saving costs of the examined SSP system with different PV system areas and operational strategies

It should be also mentioned that the payback period (PBP) indicator does not take the time value of money into consideration and calculates the required time, usually in years, to recover the project investment cost from the expected annual Cash Flow (CF) as follows;

$$PBP = \frac{\text{Initial Investment}}{CF} \tag{5}$$

By taking into consideration the money discount rate to find the present value of the expected Cash Flow during the project lifetime and compare it with the initial investment, the Discounted Cash Flow (DCF) as well as the Net Present Value (NPV) are calculated according to the following formulas;

$$\begin{gathered} DCF = \sum_{n=1}^{n=N} \frac{CF_n}{(1+r)^n} \\ NPV = -\text{Initial Investment} + DCF \end{gathered} \tag{6}$$

where r is the discount rate of 5% and N is the project lifetime of 20 years. As can be found in Table 5, both Options A & B with different operating strategies are profitable with positive DCF and NPV values. Option B has higher DCF than Option A because it has higher PV system area which increases the expected cash flow. However, for the same reason, Option B has lower NPV at the end of the project lifetime due to the higher investment cost. Also, the DCF and NPV for both options are higher when the SSP system is responsible for supplying the ferries' electrical load while berthing only and not supplying the ferries' electrical load in addition to charging their batteries.

Table 5: Discounted cash flow and net present value of the proposed SSP system with different PV system areas and different operational strategies

	Option A (Charge)	Option A (No charge)	Option B (Charge)	Option B (No charge)
DCF ($)	6,676,125	7,392,445	8,657,768	9,374,088
NPV ($)	2,720,125	2,932,445	301,768	514,088

4.4. Sensitivity analysis

The economic performance of the proposed SSP system and the reported DCF and NPV depend considerably on the sale prices of the electricity and the diesel fuel which are partly determined by the government authorities. The cost analysis reported to this point corresponds to a national grid electricity cost of 0.058 $\$/kWh$ for businesses applications and a fuel price of 1250 $/tonne. Therefore, in order to study the impact of varying electricity and fuel prices on the financial viability of the proposed SSP system in terms of NPV, different electricity and fuel sale prices are used as shown in Figure 16. The NVP is chosen as a reliable indicator since it shows the difference between the investment cost and the recovered amounts of cash during the expected project lifetime.

As shown in Figure 16, the proposed SSP system has higher positive NPV at higher electricity and fuel sale prices with different PV system areas and different operational strategies. This is due to the fact that at higher sale prices of electricity and fuel, more cash flow can be returned from selling PV electricity to the grid and from saving the ferry generators' fuel consumption.

For Option A where the currently existing sunshade structure on Port Said side only is equipped with PV panels, the NPV is positive at different prices of electricity and fuel for the two considered operational strategies of supplying the ferries' electrical load or supplying the ferries' electrical load in addition to charging their batteries as shown in Figures 16a, 16b. On the other hand, for Option B where the PV panels are installed on both vehicles' queue areas on Port Said and Port Fouad, the NPV can be negative at low selling prices of electricity and fuel as shown in Figures 16c, 16d. This is because Option B has higher installed PV system area and consequently higher initial investment cost than Option A. Therefore, Option B is more sensitive to the selling prices of electricity and fuel and can have negative NPV.

5. Conclusions & Recommendations

Much research in recent years has focused on shore side power (SSP) technology as an efficient measure for the reduction of vessels' emissions, noise, and vibration at berths by supplying these vessels with electricity from the shore network instead of operating their auxiliary engines. Nevertheless, the economic and environmental performances of SSP systems rely considerably on the source and generation method of the electricity supplied to the berthed vessels. Also, the

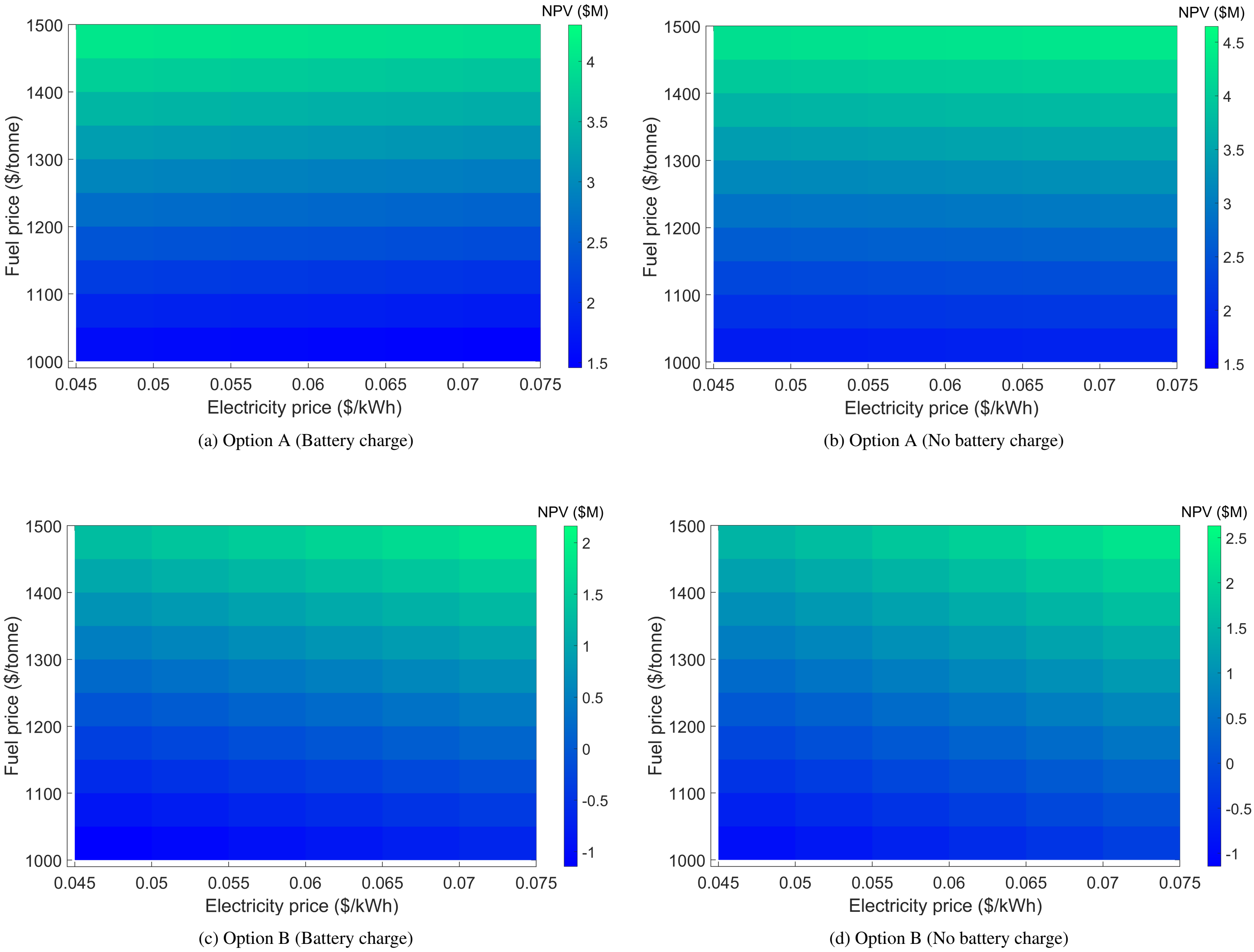


Figure 16: Impact of electricity and diesel fuel prices on the net present value of the proposed SSP system with different PV system areas and different operational strategies

literature review regarding SSP systems is dominated by larger ports applications due to their higher power demands and emissions. Therefore, to fill this gap, the contribution of this paper can be summarized as follows:

- This paper investigates an SSP system for a small inland waterway across the Suez Canal in Egypt.
- It is proposed in this study to equip the sunshade structures around the ferry terminal with photovoltaic (PV) systems and integrate it with the investigated SSP system to increase its environmental potentials and exploit the plentiful solar potential of Egypt.
- Furthermore, different PV system areas as well as different operational strategies of the SSP system have been considered.
- Moreover, it has been proposed to replace the ferries' diesel generators with batteries to eliminate their emissions. For this purpose, the examined ferry diesel generator, battery, and PV system have been modelled and implemented in MATLAB/Simulink for time-domain simulations.

This study has demonstrated that it is feasible economically and environmentally to install SSP technology for inland waterways in Egypt and integrate it with renewable solar energy using PV system installed on the sunshade structures around the ferry terminal. For the examined waterway's ferries sailing between Port Said and Port Fouad, two options regarding the PV system area have been studied. One option (A) is to equip only the sunshade structures on Port Said side with PV panels of 4000 m^2 and the second option (B) is to equip the area on both sides on Port Said and Port Fouad with PV panels of 12000 m^2. From the obtained results, it has been shown that both options (A& B) can eliminate the ferries' diesel generators emissions of 1420 tonnes/year. Also, the proposed solar-based SSP system can feed the national grid with green electricity except for Option A in case of providing electricity for the ferries' electrical load and recharging their batteries. The annual surplus electricity fed to the national grid would range between 356 MWh to 2259 MWh depending on the PV system area and the selected operational strategy. Beside eliminating the ferries generators' emissions of 1420 tonnes/year, this excess electricity can reduce the national grid emissions by 190 to 1204 tonnes/year of CO_2.

By taking into consideration the diesel fuel cost saved by the SSP system and the surplus electricity fed to the national grid in addition to the saved environmental damage cost which could be resulted from the emissions of the ferries generators and the national grid, the investment costs of the equipped PV systems and the SSP infrastructure onshore can be recovered within 7.4 to 12 years. The cash flow during the project lifetime and the net present value after its lifetime have been also investigated showing good profitability. Moreover, a sensitivity analysis has been made with different selling prices of electricity and fuel. This analysis shows that the profitability of the proposed SSP system becomes better at higher energy prices which can help the local authorities with deciding the selling prices of the national grid electricity. However, a more detailed economic analysis of the proposed SSP system viability is required to calculate the levelized cost of energy for the whole project lifetime with a sensitivity analysis of the assumed SSP and PV system associated costs. Furthermore, the proposed SSP and battery systems in this study are investigated to replace the Suez Canal ferries' generators to supply the auxiliary power. In the same way, a technical, economical and environmental investigation of a fully battery-powered ferry should be made with a comparison to the conventional propulsion system.

Besides the financial burden, the integration of SSP concept faces some challenges and issues that need to be discussed. For example, the share of renewable energy in the electricity generation energy mix, which is currently dominated by natural gas in Egypt (Mondal et al., 2019), needs to be increased. As a result, the carbon content of the national grid electricity can be reduced which improves the environmental performance of SSP systems. Moreover, an issue such as the SSP utility's ownership and responsibility; it should be discussed which government department or authority will be responsible for the introduction, regulation, and operation of the SSP system. Regarding SSP operation, the cable management system connecting and disconnecting should be easy and user-friendly for more safe and quick operation. Also, a global regulations and environmental legislation for the deployment of SSP systems are required because there are differences between regulations in different countries.

As mentioned in Section 2, there are 39 car and passenger ferries owned by the SCA and operate at 14 different locations alongside the Suez Canal in Port Said, Port Fouad, Ismailia, and Suez. These ferries are ideal candidates for the proposed solar-based SSP concept which will further reduce the emissions and improve the sustainability alongside the Suez Canal coastal areas. Also, due to the well distributed solar energy potential across the whole country, it is recommended to assess the potential of the proposed system at the national scale with hundreds of terminals on the River Nile and ports on the Mediterranean Sea and the Red Sea with thousands of boats and ferries of different sizes which can benefit from it.

CRediT authorship contribution statement

Ameen M. Bassam: Conceptualization, Data analysis, Methodology, Investigation, Writing – original draft. **Alexander B. Phillips:** Conceptualization, Results analysis, Writing – review & editing. **Stephen R. Turnock:** Conceptualization, Supervision, Writing – review & editing. **Philip A. Wilson:** Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, Ameen M. Bassam, upon reasonable request.

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