Zero Emissions Ferries Utilizing PV/ Shore Connection Hybrid Power System

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Abstract

The use of non-clean energy sources such as fossil fuels is a major threat to the environment and the general climate change. The quick economic development has increased the energy demand and conventional fuel consumption, thus increasing the pollution and environmental impacts. The societies and most countries are now turning to renewable sources like: solar, wind, hydroelectric, biomass, and geothermal energy to produce clean energy and to reduce emissions. The need to search for renewable sources of energy in Egypt is important in terms of economic and environmental impacts, due to Egypt's geographical location and the vital role of the Suez Canal. The present study aims to present renewable energy sources for ship propulsion. Renewable solar energy and electric storage systems are the beneficial solution to achieve the major target of the present research. A conversion of 35 Suez Canal car/passenger ferries to use photovoltaic (PV) solar panels combined with a battery bank instead of conventional propulsion system. The ferries are operating between Port Fouad and Port Said. The proposed propulsion system of the case study cars/ passengers ferry consists of electric output power from PV solar panels in conjunction with an appropriate battery bank system combined with charge shore connection. The results of the study indicate that the ship power generation using PV system is appropriate for long term investments. In addition, solar energy utilization reduced the output emissions by 38.76 tons of NOx, 1421.15 tons of CO_2 and 2.92 tons of particular matter (PM) annually. The financial calculations show that the conversion costs per ferry will be recovered after three years, and the annual operation costs saves more than 262,000 $ each year when compared to traditional operation. Finally, it is noted that the installation of photovoltaic solar panels on the board ferry does not affect its stability.

1) Introduction

Over the past 50 years, the average global temperature has rapidly increased. The public societies are focusing on climate change, one of the major contributions to global warming is the marine industry [1]. The number of emissions emitted into the atmosphere increases day by day due to rising fuel consumption. Recent studies of greenhouse gases (GHG) estimation conducted by International maritime organization (IMO) in the maritime field in 2009 indicated that about 870 million tons of carbon dioxide is released into the atmosphere by maritime transportation sectors. The ratio of CO_2 emitted to the atmosphere is expected to increase by 5% in 2050 [2]. The International Convention for the Prevention of Pollution from Ships (MARPOL), specifically, Annex VI of MARPOL addresses air pollution emitted from ships. The international air pollution requirements of Annex VI establish restrictions on nitrogen oxides (NOx) and Sulphur oxides (SOx) emissions and require the use of fuel with lower sulfur content. The requirements apply to vessels operating in the United States of America and within 200 nautical miles of the coast of North America, it is known as the Emission Control Area (ECA) [3]. In order to reduce GHG and air pollution from domestic and international shipping alternative sources of energy are used [4].

The United Nations developed a navigational safety system, which can help respond to growing demands for optimization of port and shipping performance, monitoring of emission data and trade forecasts called "Automatic identification system". A ship's emissions depend on numerous factors, including vessel size, engine type, speed, fuel used and route. Automatic identification system data combined with information on the ship's engine and fuel can help assign carbon dioxide emissions to the country of the vessel's flag or the country's waters where the carbon dioxide is being emitted [5]. The private sector leads an initiative called "Getting to Zero Coalition" which suggests that shipping's de-carbonization can be the engine that drives green development across the world [6].

Green shipping is one of the major topics across the world with an adverse anticipation that the reserves of fossil fuels would be used up in the future. Member states of IMO agreed in 2018 to reduce the total annual greenhouse gas emissions by at least 50 per cent by 2050 [7]. To achieve this objective, the international chamber of shipping and other maritime industry associations proposes the establishment of a research and development fund to help cut emissions [8].

Renewable energy can transform the global shipping fleet at all levels and in varying magnitudes. Renewable power applications in ships of all sizes include options for fully electric or hybrid, as well as onboard and shore-side energy use. Potential renewable energy sources for shipping applications include wind, solar photovoltaic, Bio-fuels, wave energy and the use of super capacitors charged with renewable sources [9]. A great development of battery technologies has been leading a greener future in the maritime industry, with hybrid and electrical vessels. The electrification of marine vessels has been evolving over several decades, to move toward zero-emission sea transportation. However, large marine vessels are still facing challenges due to the high cost of batteries and low-energy density. Thus, most vessels with purely electrical operations are currently short-distance ferries or local coastal transportation [10].

1.1 Scope of work

35 car/passenger ferries connect the two banks of the Suez Canal at Port Said Governorate and hold individuals and vehicles with no charge, the ferries transport nearly 20 million people and more than 5 million vehicles per year. The Suez Canal Authority (SCA) is responsible for the execution of orders, the maintenance and repair processes for these ferries. It takes these ferries 10 minutes to travel from one bank to the other. The scope of the present paper aims to evaluate the contribution of solar energy as a proposed propulsion power source for a selected ferry; the retrofit process is compared to the conventional diesel engine propulsion system. The modification, outfitting, and installation requirements for the PV solar panels / electric batteries storage technology and onshore electric connections were discussed and explained. This proposed design could be applied to the rest of the ferries.

1.2 Literature review

Alternative energy sources are the twenty-first century trend. They reduce fuel consumption and gas emission that increase ocean acidification, oil spills, NO_x, and SO_x. Therefore, clean and environmental energy sources such as solar, wind, wave energy and fuel cell are used on marine vessels in both hybrid and individual systems. There are two different kinds of operation models in the solar photovoltaic system that are integrated in the ship power system, the off-grid and grid connected mode. The optimization of energy management of the photovoltaic-ship power systems

(PSPS) and the optimization of the operation control strategy of multiple inverter equipment under grid connected mode are investigated [11]. A comprehensive study tests a configuration model of a hybrid power generation system between diesel generators and renewable energy as a solution to meet the electricity needs for 24 hours. The simulation results provide a configuration model of the first optimal hybrid power plant of PV (50%) and Diesel (50%) configuration to reduce fuel consumption per year by 47.1%. The second configuration model is PV (70%) and Diesel (30%) configuration to reduce fuel consumption per year by 64.3% [12]. The solar boat will be powered by energy processed from the solar energy to minimize environmental pollution and costs of fuel. Solar energy extracted from the panel was optimized by using quadratic maximization maximum power point tracking (MPPT) with KY converter to generate high output power which is found to be more reliable, efficient and economic. In case of any hazardous condition a backup power system that is integrated with photovoltaic cells would continue to operate the vessel [13]. In 2020 a novel approach was demonstrated for the layout of solar arrays within a Ro-Ro type marine vessel navigating between Pendik /Turkey and Trieste/Italy, the performance of the designed system was theoretically evaluated. The system indicated that a 334.6 MWh power could be supplied to the main grid of the vessel at the end of year and the ship output emissions reduced by 0.312, 3.942, 232.393 tons of SO_x, NO_x and CO_2 respectively [14]. Many experimental and computational fluid dynamics (CFD) numerical results were simulated and predicted the application of solar power onboard ships [14, 15]. A life cycle analysis (LCA) was applied on a short route ferry operating in turkey and the costs of changing from conventional ferry into hybrid solar ferry were illustrated from cradle to grave. These results indicated a reduction in GHG emission around 3 x 10^6 kg during the 25 years of its lifespan, as the payback time period of the solar panels system was estimated at three years. The fuel cost saved after 25 years of operation could reach approximately 300,000$ and about 130,000$ in present value [16].

2) Methodology

The objective of the present study is to convert the existing diesel propulsion machinery of Suez Canal car/passenger ferries to a fully electric propulsion operation. A ferry operating between Port Said east bank to Port Fouad west bank is chosen as a case study.

The conventional propulsion of the existing ferry is illustrated with all the main principal dimensions and particulars, the ferry operating scenario and fuel consumption with emissions are discussed, the weather and Meteorological ferry operating site data is considered to know the sunshine hours and intensity. Finally, the technical, environmental and economical concepts of photovoltaic solar panels/ rechargeable batteries system are discussed and analyzed.

2.1 Existing car/ Passengers ferry

The case study ferry is certified by Lloyd's Register as an inland waterway vehicle. The technical specifications of the ferry are given in Table 1 [17, 18]. The ferry steel hull is subdivided into different watertight compartments by 6 transverse and two longitudinal bulkheads. The propulsion and auxiliary machinery with the propeller’s mechanism are located in four compartments after the fore and aft peak. The general arrangement and machinery installation is shown in figure 1.

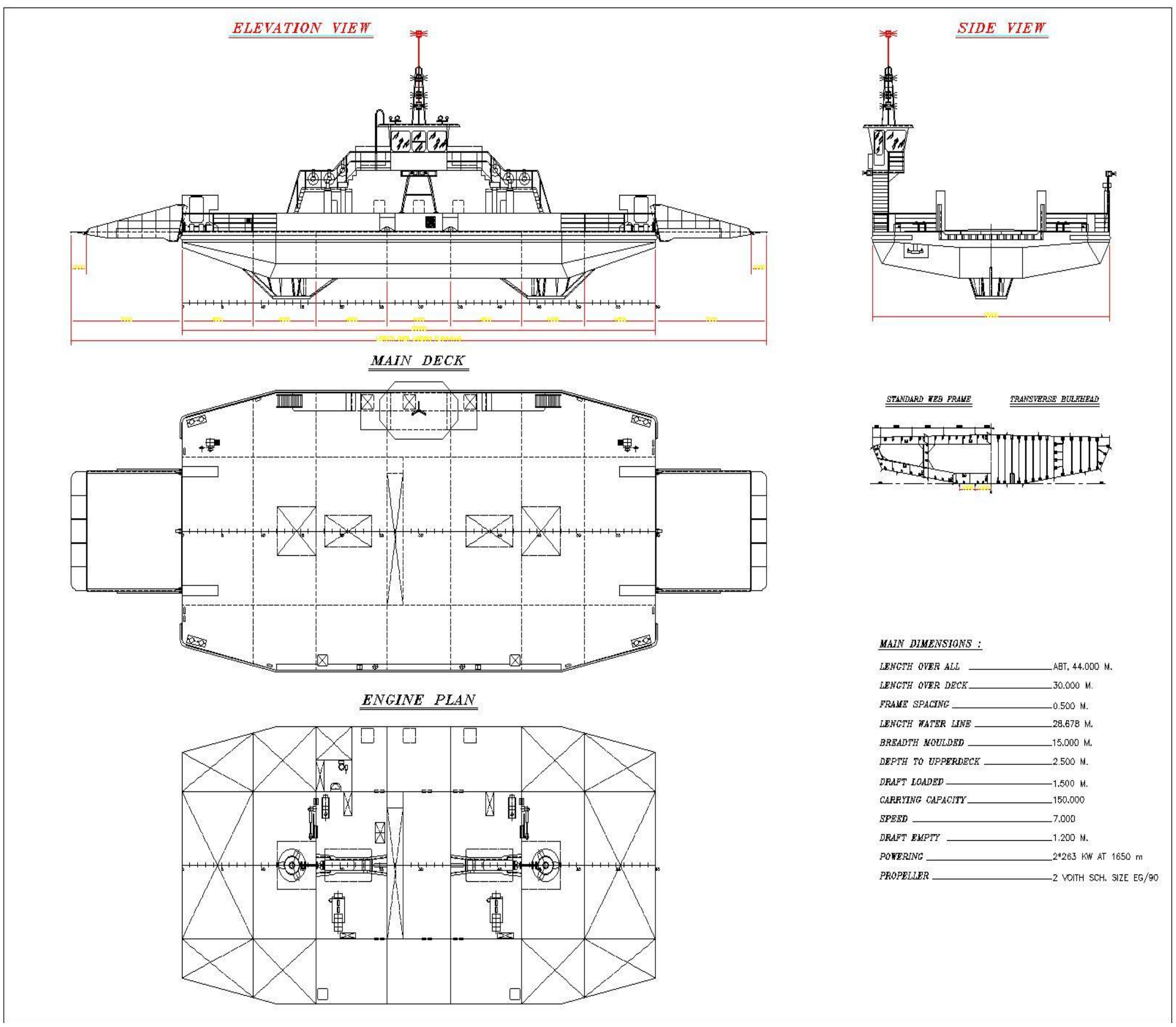

Figure 1 General arrangement of the car/passenger ferry

The total weight of the main engines and diesel generators are about five tons. The propulsion engines are connected with a pair of Voith Schneider Propellers (VSP).

Table 1 the principal dimensions and main particulars of the existing ferry

Length over deck (m)	30
Depth Mold (m)	2.50
Deadweight (Ton)	150
Breadth L.O.A. (m)	15.34
Draught light (m)	1.50
Service speed (Knot)	7
Main Engines	2 x Deutz model SBA 6M 816,340 HP, 253.5 KW
Diesel AC Generators	2 x MWM D226-6, 65 HP, 49 KW

2.2 The ferry sailing route

The sisters Suez Canal ferries are shown in figure 2, each ferry can load 21 cars, 60 cyclists, in addition to 100 individuals. The ferry takes approximately 30 minutes per trip including the loading and unloading of vehicles and individuals [18]. The trip itself alone takes around 10 minutes as shown in Table 2.

Table 2 The envisaged scenario of ferry operation

Operating scenario of Suez Canal car/passenger ferries	
Item's description	Time in Minutes
Loading passengers and vehicles	5.0
Departure and maneuver	2.5
Route between both banks of channel	10.0
Arrival and maneuver	2.5
Unloading passengers and vehicles	5.0
Allowance for heavy traffic in the channel	5.0
Total duration	30.0

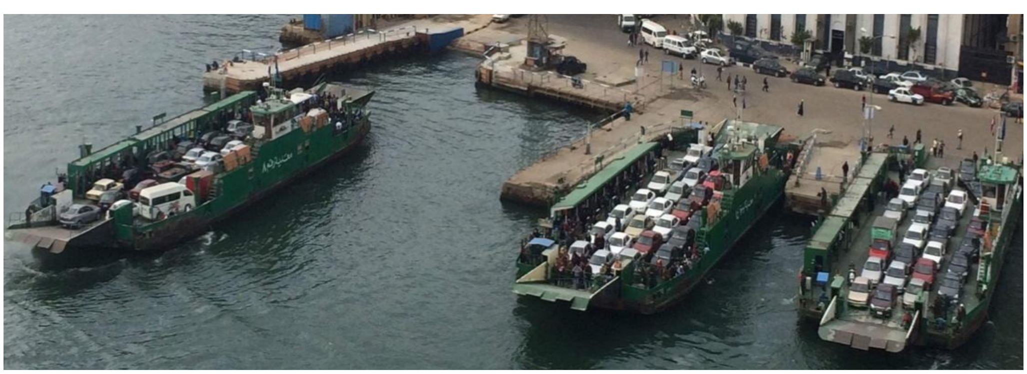

Figure 2 Suez Canal Car/Passenger Ferries

2.3 Fuel consumption

Based on the tabulated scenario of the ferry operation in Table 2, the daily total turning time of main engines and generators are 12.5 and 13.5 hours respectively to perform an annual running of about 3750 hours for main engines and 4050 hours for generators. The annual fuel consumption was calculated for the two main engines and one of the two diesel generators which is 465 ton per year.

2.4 Emission and Environmental pollution

The overall amount of the emission released to the environment is calculated using the environmental protection Agency (EPA) formula. In the EPA method, Equation (1) is used to estimate the emission amount (E) of certain pollutants from the ship's engines [19, 20].

$$E = P \times L_f \times T_a \times E_f \quad (1)$$

Where, E is the engine emission (gm), P is the engine power (kW), L_f is the load factor for main and auxiliary engines, T_a is the activity duration (h) and E_f is the emission factor (g/Kwh). Emission factor (E_f) may be estimated by using Equation (2). Where a, b and x are the coefficient specific to each air contaminant and are tabulated as shown in Table 4 [21].

$$E_f = a(L_f)^{-x} \times b \qquad (2)$$

Table 4 Marine engine Emission Factor Coefficients

Pollutant	x	a	b
PM	1.5	0.0059	0.2551
NO_x	1.5	0.1255	10.4496
HC	1.5	0.0667	Not significant
CO_2	1	44.1	648.6
CO	1	0.8378	Not significant

The ferry annual emission parameters are tabulated in table 5.

Table 5 Ferry annual emission parameters

Air pollutant	CO_2	NO_x	PM	HC	CO
Amount of Emission Ton	1421.15	38.76	2.92	1.56	7.71

2.5 Meteorological Data of ferry operating site

According to the solar atlas of Egypt, in winter the sun shines an average of 10.31 hours (hrs). In spring the sun shines for a period of 12.53hrs, in summer it shines an average of 13.48 hrs. On the other hand, in fall it shines for an average of 11.27 hrs. To simplify the solar power calculation, eight solar hours per day are taken as an average to be used at all seasons,[22]. Egypt receives annually 2,400 hrs of solar operation with high intensity of solar radiation equivalent to 2,600 KWh/m^2 [23]. PVsyst is a photovoltaic simulation software that uses a meteo database to visualize a virtual model used to calculate the global horizontal irradiance values shown in Figure 3.

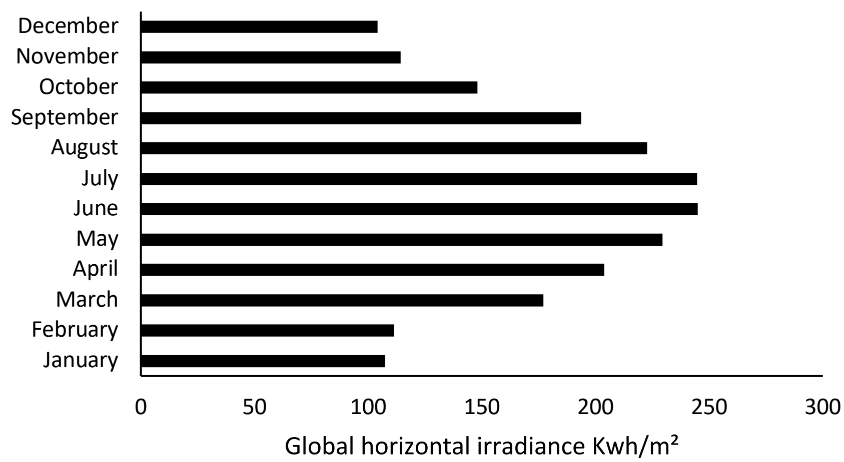

Figure 3 Global horizontal irradiance values predicted by Photovoltaic simulation software

2.6 Photovoltaic solar system

Photovoltaic solar (PV) system consists mainly of four components, PV solar panels, charging controllers / solar regulators, storage batteries and solar inverters as shown in Figure4. The components are set out as follows: Solar Photovoltaic Panels, Charge Controllers / Solar Regulators, Storage Batteries, and Solar Inverters.

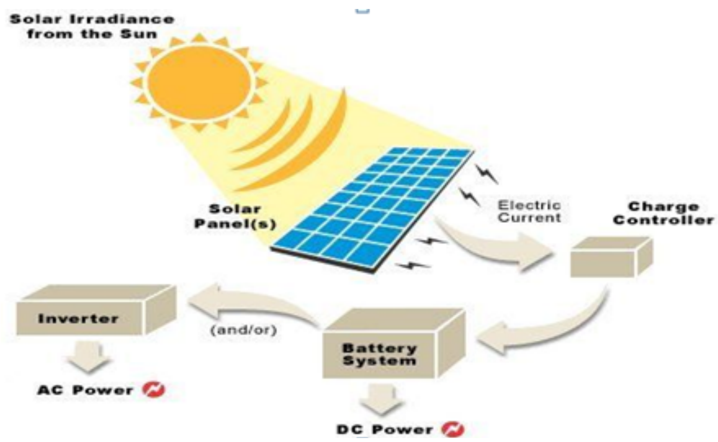

Figure 4 photovoltaic solar power arrangements

3) Design of Proposed Electric Propulsion System of the Case study

The Suez Canal Car/ Passenger ferry operates for two rounds, each round concludes in half an hour. It needs approximately 122.17 KWh to operate per round table 6 illustrates the electric motor as well as the electric load.

Table 6 Vessel Operating conditions (One Round)

Operating Mode	Time (Hr)	Electric Propulsion Load (kw)	Electric appliance Load (kw)	Total Electric Loads (kw)	Power demand (kwh)
Cruising	0.1667	511.2	10	521.2	86.88
Berthing	0.1667	127.8	10	137.8	22.97
Maneuvering	0.1667	63.9	10	73.9	12.319
Total	0.5	702.9	30	732.9	122.17

3.1 Praxis Electric Propulsion Motor (EPM 230)

The modified ferry uses two Voith Schneider propeller shafts connected to two individual mega-guard electric propulsion motors which is an efficient permanent magnet motor producing 255.6 KW instead of the existing diesel propulsion engines. The specifications of electric motors are given in Table 7. The motors are connected to an Electric Energy Storage (ESS) through a central inverter. An average motor's efficiency of 98% is taken for calculations as recommended by the manufacturer and approved by classification societies [24].

Table 7 Electric motor Specification (EPM 230)

Motor Length (mm)	MotorØ (mm)	Torque (NM)	RPM=3600 Power(kw)	RPM=1800 Power(kw)	RPM=900 Power(kw)	RPM=450 Power(kw)	Weight (kg)
540	276	678	255.6	127.8	63.9	31.95	125

3.2 Batteries

The vessel would use LFP-CB by Victron energy, these batteries are chosen due to several factors; they save 70% of space and weight, long life expectancy, and safe li-ion battery type [25]. Lithium iron phosphate batteries are illustrated in Table 8 which produces a maximum charging current of 400 A, 200 Ah nominal voltage.

Table 8 Specification of Victron Energy Batteries

Manufacturer	Victron Energy	Storage temperature	-45°C to +70°C
Model	LFP-CB 12.8v / 200ah	Cycle life discharge 80% 70% 50%	--- 2500 3000 5000
Nominal Voltage	12.8v	Dimensions (L*H*W)	237 * 321 * 152
Nominal Capacity	200 Ah	Weight	20 Kg
Maximum charging current	400 A	Maximum Discharging Current	400 A

3.3 Solar Panel

It is proposed to partly charge the batteries with LG 395N2T-A5 bifacial panel which is described in Table 9, manufactured by LG electronics, mono-crystalline type of cells in the solar panels, 2064 mm of length, 1024 mm of width, 40 mm of thickness and 22.0 kg of weight. It produces 395 W with 18.5% efficiency. The solar panels will be installed on the ferry roof, they would take up 370 m^2 from the total area of 460 m^2. They would be placed as five modules each containing 35 strings;175 solar panels could be fitted in the stated area, which generate 120,181 kWh per annum translated to an average of daily electrical power 264 kW [26]. The technical specification of the solar panel is given in Table 9.

Table 9 Specifications of a 395W N2T-A5 Solar panel at STC

Manufacturer	LG Electronics	Dimensions (L * W * H) mm	(2064 * 1024 * 40) mm
Model	LG395N2T-A5	Product warranty	25 YEARS
Maximum Power (Pmax)	390	Open Circuit Voltage (Voc)	49.2
MPP Voltage (Vmpp)	41.4	Short Circuit Current (Isc)	10.15
MPP Current (Impp)	9.43	Module Efficiency	18.5

3.4 Charge Controllers

A maximum power point tracker (MPPT) is an electronic DC to DC converter that optimizes the match between the solar array, and the battery bank or utility grid. They convert a higher voltage DC output from solar panels down to the lower voltage needed to charge batteries. The charge controller should be able to control the I-short circuit of the panels [27]. A proper MPPT charge controller shown in Table 10.

Table 10 JINGE MPPT Controller

Manufacturer	JINGE	PV max. input power	24 kW
Model	JN-HV Series	Dimension	453*300*132 mm
Battery voltage	265 V	Weight	8.2 kg
Battery voltage range	180 V – 320 V	Maximum input current	100 A
Number of controllers = 2 Controllers			

3.5 Inverters

The inverter is chosen according to the total produced power from the PV array and the total power stored in the battery bank systems. The battery bank stores low voltage direct current, typically around 10 to 15 volts. Furthermore, the onboard ship's loads are powered by alternative current. Inverters should be bigger than the electric power of the ferry by 20-25%, it needs to have the same nominal voltage of the battery chosen. According to the ferry's electric balance power sheet the current appliance's total power equals 122 kWh for one round. The specification of the inverter is given in Table 11. [28]

Table 11 Specification of ABB central Inverter PVS800-57-0500 kW-A

Type designation	PVS800-57-0500 kW-A	Nominal output Voltage	300 V
Maximum input power	600 kW_p	Output frequency	50/60 Hz
Maximum Dc voltage	900 V (1000 V*)	Dimensions W/H/D	3030 / 2130 / 644
Maximum Dc current	1145 A	Weight	1800 kg
Nominal output power AC	500 kW	Number of inverters	1
Nominal AC current	965 A		

3.6 Shore to Ship Charger

E-ferry charging Power Adapt provides a fast connection and disconnection for e-ferries to maximize the charging capacity during off and on- loading of the ferry. Power Adapt uses Cavotec APS (automatic plug-in system) technology. The system is formed by two main sub-systems, one installed on the ship side, the other on the shore side. The vessel installation is featured by a fixed funnel for power connection and its shipboard control equipment. The shore installation is featured by a fixed structure, holding cablings, control equipment and counterweight system and by a mobile unit: the APS Box. This system is sufficient to charge the batteries, it takes around 10 minutes which is enough for one round. In addition, the connection and disconnection cycle take less than 60s [29].

4) Result and Discussion

4.1 Ferry New Design

The fully electric system contains two battery banks Port and STB, each bank room contains 3 packs in parallel and each pack contains 20 Lithium iron phosphate batteries to maintain the package volt of 256 and a total capacity of 606 Ah. The 3 pack produces 140 KWH (80% DOD), these batteries are connected to a ship automation system that automatically discharges when fully charged and simultaneously charge the other storage room, separately each storage room will be responsible for navigating one round. Ferry new design illustrated in Table 12.

Table 12 Modifications of the vessel

Removed Items	Location	Weight (kg)	Added Items	Location	Weight (kg)
Main engine	Aft E/R	2000	Elec. Propulsion motor	Aft E/R	160
Main engine	Forward E/R	2000	Elec. Propulsion motor	Forward E/R	160
Diesel Generator	Aft E/R	372	Inverter	Center	1800
Diesel Generator	Forward E/R	372	2 Controller	STBD / P	16
Fuel Tank	STBD	4560	60 Batteries	STBD	1200
Fuel Tank	P	4560	60 Batteries	P	1200
Total (STBD + P)		9120	Total		4536
Total (Aft + Forward)		4744	175 Solar panels	Roof Top	3500
Total removed items		13864	44 Pillars		2500
Reclaimed Weight		3328	**Total Weight Added**		10536

Monthly power generation is calculated based on the ship's voyage in the relevant months shown in Figure 4. The results show that the most beneficial time for the PV system is from May to August, while it is observed that the lowest production time is between November and February.

The most efficient month generates about 13457 kwh power in June, while 5976 kwh of power is generated in December which is the lowest efficiency.

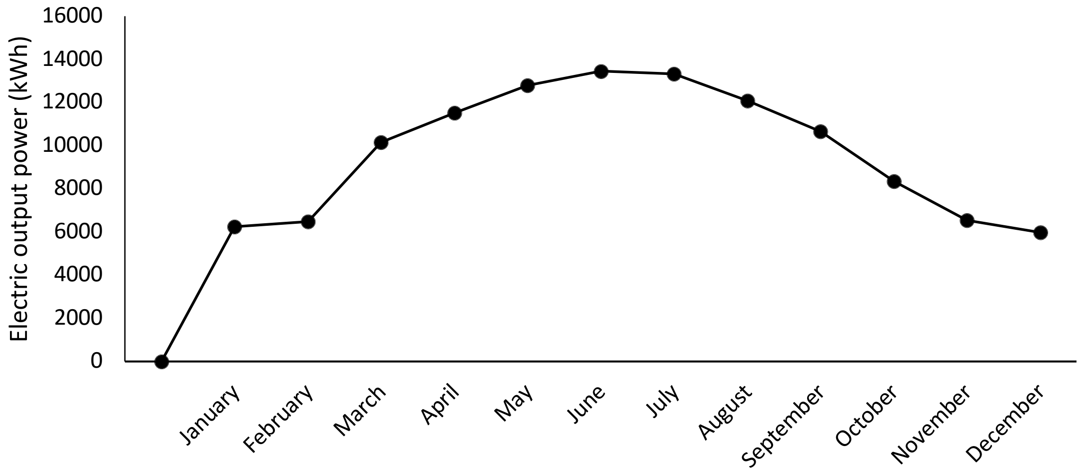

Figure 2 Monthly Electric Output Power

4.2 Operating scenario with proposed green system

The ferry works for 24 rounds and it needs 122 kwh to work for one round, solar panel present in the ferry provide approximately 263 kw/day, which will be provided by:

- The first method, which is the main source of energy for the batteries, is the shore connection. It takes around 10 minutes to fully charge one storage room which is approximately the time passengers ascend and descend from the ferry. The power in storage room P is enough to work up for one round.
- The second method, the alternate source of energy, comes from the solar panels which produce 263 kw during the day and the remaining power needed will be used from the shore charge.
- It should be noted that the main source of energy for the ferry is the dual battery bank, which is charged from the shore charge connection, while the solar panels are the secondary source of energy which is used to decrease the electricity usage of the government which will save costs in the long run.

4.3 Financial feasibility study

The capital cost of the conventional ferry was 21,000$ including: two main diesel engines and two diesel generators. On the other hand, the capital cost of the proposed ferry is about 288,000$, inclusive of the two electric motors, solar panels (0.75 $ x 395w x 175 panel), batteries module, inverters, charge controllers, battery management system, and ship automation system. The running cost per year of the conventional system of the ferry was 262,000$ including: diesel fuel, maintenance, lubricant oil, while the running cost of the proposed system would be 1% of the capital cost 2,880$ per year [30]. The capital cost of the modified model would require a large start up investment; however, the running costs are decreased significantly in the proposed model which will amount to a large amount of savings due to the reduction of diesel fuel and other maintenance costs required in the conventional model. According to these numbers the net present value (NPV) is 363,555 $ after 3 years, the discounted payback period is 1.2 years and the cash flow return rate 22.67% per year [14].

5) Conclusion

The ferry conversion results in cleaner operation and zero emissions. The Solar energy/Electric propulsion system promises to not only minimize emissions, but also to extend the ferry's life. However, the proposed design provides a cost effective alternative focusing on the long run compared to the relative costs of diesel fuel.

The conversion of existing conventional car/passenger ferry into electric propulsion operation has a positive effect on environmental emissions. The solar energy utilization reduced the annual output emissions by 38.76 tons of NOx, 1421.15 tons of CO_2 and 2.92 tons of PM.

In addition, the results of the study indicate that the power generation using photovoltaic systems is useful for long term investments, nevertheless it requires a sizable investment. The financial calculations show that the ferry conversion cost will be recovered within 1.2 years, and the annual operation saving due to diesel fuel, lubricating oil and other diesel related services is more than 262,000$ per year. Meanwhile, the study found that the installation of photovoltaic solar systems on board of the ferry does not affect its stability.

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