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Techno-Economic and Environmental Evaluation of a Solar Energy System on a Ro-Ro Vessel for Sustainability

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Abstract: The increased use of fossil fuels in transportation is considered a major cause of environmental pollution and climate change on a global scale. In international shipping, regulations and strict measures have been introduced by the International Maritime Organization to achieve the goal of a 40% reduction in greenhouse gas (GHG) emissions by 2030, with the envisage to reach net-zero GHG emissions close to 2050. Renewable energy sources, such as solar photovoltaic (PV) systems, can be implemented on new-build or existing marine vessels as an effective alternative source for auxiliary power generation, reducing the dependency on fossil fuels and contributing to decarbonization. In the present paper, a sustainable retrofit design using PV panels on an existing Ro-Ro vessel is analyzed for its feasibility. The proposed system is used for energy production during ship cargo operations and takes advantage of the large space area on the upper deck and its continuous exposure to sunlight during its voyage. To investigate the effectiveness of the PV system as an alternative to fossil fuel consumption, an environmental and economic evaluation is performed. According to the results obtained, the solar PV system can provide approximately 88% of the required energy annually for lighting during ship cargo operations, with the corresponding fuel savings and emission reductions, making the investment economically feasible, with a high potential to contribute to environmental sustainability.

Keywords: solar energy; photovoltaic system; fuel savings; ship emissions; environmental sustainability; energy efficiency; techno-economic evaluation; marine transportation

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1. Introduction

Electricity produced from solar irradiation is considered a clean and non-polluting form of energy; it has a minimal environmental impact, and it is a sustainable alternative capable of contributing to the reduction in Greenhouse Gas (GHG) emissions in the atmosphere and the prevention of environmental pollution [1]. In accordance with the recent advances in the field of PV production and the development of efficient energy-storage devices [2], the installation of PV systems emerges as an attractive choice for electrical energy production. It is expected that solar PV technology will have a significant role in the modern world, contributing to a smart and sustainable economy. The construction and operation of PV systems serve the targets and goals for Sustainable Development set by the UN in 2015 [3] well, and are closely related to the strategy of using plastics, metals, and ceramics in a circular economy, enabling the reuse, repair, and recycling of these materials. Additionally, most commercial solar PV panels have an efficiency of 15–20% while the cost of PV panels is between USD 2.60 and 3.20/W [4], making solar energy an attractive option. In general, global primary energy consumption at the end of the 20th century increased by 10 times compared to the beginning of the 20th century [5], while the use of fossil fuels in primary energy increased by 16 times [6]. This clearly points out the necessity of energy transition from fossil-based energy systems to renewable energy sources, such as solar energy. It has been estimated [7] that by 2030, PV systems will contribute to 12–14% to the total electric energy production in the EU energy system, resulting in a notable reduction in GHG emissions.

Maritime transportation has a significant impact on environmental pollution and global warming. The burning of fossil fuels, such as coal, oil, and natural gas, for energy production results in the emission of air pollutants that are responsible for climate change, which could have a long-term effect on biodiversity as well as on human socioeconomic development. Carbon dioxide (CO_2) has been proven to be a major contributor to global warming and unless climate and energy policies are implemented, the average global temperature is projected to be 4.1–4.8 °C higher by the end of the century [8]. In addition, nitrogen oxides can enhance the greenhouse effect and are considered a possible cause of ozone depletion, while sulfur dioxide contributes to acid rain, which can harm sensitive ecosystems. The need to minimize the use of fossil fuels and at the same time to implement a greener and sustainable marine transportation led the shipping community to consider renewable energy sources, such as solar energy, offshore wind energy, hydropower, and biomass, which are environmentally friendly and abundant in the natural environment [4,9,10]. According to the Fourth IMO GHG Study 2020 [11], ship emissions are projected to increase from about 90% in 2018 to 90–130% by 2050 (compared to levels in 2008) for a range of plausible long-term economic and energy scenarios. In this regard, the IMO has adopted mandatory measures to reduce GHG emissions from international shipping through amendments to MARPOL Annex VI Regulations. Existing regulations limit the sulfur oxide (SOx), nitrogen oxide (NOx) and particulate matter (PM) emissions for ships that operate in global waters and Emission Control Areas (ECAs), while new sea territories such as the Mediterranean Sea will be established as an ECA in the forthcoming years. Furthermore, the 2023 IMO GHG Strategy [12] envisages a cutting in carbon intensity (reducing CO_2 emissions per transport work), as an average across international shipping, by at least 40% by 2030 compared to 2008, aiming to reach net-zero GHG emissions by or around 2050. A new ambition was also included in the 2023 IMO GHG Strategy, relating to the uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources that are to represent at least 5%, but striving for 10%, of the energy used by international shipping by 2030. In this context, from 1 January 2023 it is mandatory for ships to calculate their attained Energy Efficiency Existing Ship Index (EEXI) and to report their annual operational Carbon Intensity Indicator (CII).

Although the design of solar energy systems and their utilization on ships have been studied extensively in the last decade [13–17], few studies consider the techno-economic evaluation of the solar system and its influence on the ship's energy efficiency and sustainability. Only recently, researchers and scholars have focused on the application of solar PV systems on ships, investigating the system feasibility from the aspect of investment and the possibility of achieving a reduction in a ship's emissions. As the system feasibility is dependent on the vessel type, its operational profile and navigation routes, most researchers have implemented their techno-economic and environmental evaluations through case studies on a chosen ship type. Salem and Seddiek [18] have examined the effectiveness and challenges of a grid-connected PV solar system utilized for power supply for emergency lighting and navigational equipment, on a research vessel that operates in the Red Sea region. Both the economic and environmental benefits of the proposed PV system have been evaluated, and analytical calculations of the solar array cost and power grid cost based on the system specifications have been performed. Qiu et al. [19] performed a techno-economic evaluation of a PV grid-connected power system on a Pure Car Truck Carrier by proposing a mathematical model for predicting solar radiation along six main navigation routes, and investigated the techno-economic efficiency and environmental performance using single- and multi-criteria evaluation methods. The effectiveness of the application of a solar panel system for obtaining propulsion power on a short-route ferry operating in the Marmara Sea has been examined by means of a life cycle assessment [20]. In this paper, the life cycle environmental impact and the costs and benefits of the system were evaluated through a sensitivity analysis of important and uncertain parameters. Karatuğ and Durmuşoğlu [21] designed a grid-connected solar PV system for a Ro-Ro-type ship navigating between Turkey and Italy and performed its evaluation in terms of fuel consumption, emission reduction and economic profitability. An extensive review on research work concerning stand-alone and hybrid solar energy systems on marine vessels has also been included in their paper. Tercan et al. [22], conducted a technical analysis of an off-grid rooftop PV system for a small tourist boat and investigated the reduction in CO_2 emissions. In addition, a fully electric solar boat, as well as an on-grid PV plant to meet the energy demands for an entire tourist boat fleet, have been analyzed.

In addition to the previous work, some research studies have focused on the energy performance and environmental feasibility of solar hybrid systems using PV panels, diesel engines, fuel cells, and battery storage units. Ling-Chin and Roskilly performed a life cycle assessment study to estimate energy and material consumption, emissions, and the environmental impact of a new-build hybrid system [23], and a retrofit power plant [24], for a Ro-Ro cargo ship, incorporating selected emerging technologies such as lithium-ion batteries, PV systems, and cold ironing. Yuan et al. [25] designed a large-scale solar/diesel hybrid system, with a grid-connected and stand-alone control and battery energy storage unit, for a Pure Car Truck Carrier. In that paper, the energy savings and CO_2 emission reduction were verified through the analysis of the actual ship's experimental data under different PV penetration levels during arrival/departure and normal sailing. A hybrid solar PV/PEM fuel cell/diesel generator power system was simulated in [26], to provide the electric power needed for a cruise ship operating in the Baltic Sea. The fraction of renewable energy was estimated to 13.83%, corresponding to a reduction of 9.84% on GHGs and PM emissions. Yuan et al. [27] explored a stand-alone PV energy system installed onboard an inland river Pure Car Carrier as an auxiliary power source. The GHG emissions and fuel consumption of the case vessel were evaluated using EEDI analysis, while the required data were collected by actual navigation trials. A hybrid solar/wind energy/fuel cell system for an oil tanker [28] was designed and evaluated through an economic and environmental analysis, and the reduced EEDI was calculated. An excessive review on solar, wind and fuel cell energy applications was also included.

The purpose of the present article is to investigate the feasibility and sustainability of implementing a stand-alone solar PV system in a Ro-Ro cargo vessel to supply part of the energy required during the cargo operations (loading/unloading) by performing techno-economic and environmental analysis. The selection of the case study ship was based on its energy load requirements, the deck space available for PV panel installation, and the shipping routes in areas of high solar potential. The Ro-Ro cargo vessel navigates in the broad area of the Mediterranean Sea, Black Sea and on the western shores of Spain and Portugal, and has sufficient deck space for PV panel installation exposed to direct sunlight. The environmental benefits of the proposed PV system are demonstrated through the estimation of CO_2, SOx, NOx and PM emissions, considering the energy provided by the PV system, the emission factors and the fuel savings. To evaluate the economic viability of the investment, important indicators as the Net Present Value, the Internal Return Rate and the payback period are calculated considering the capital cost of the PV system, the operation and maintenance cost and the direct economic benefits from the fuel savings. Although the implementation of PV systems in cargo vessels has been examined in related studies, nevertheless, to the knowledge of the authors, a techno-economic analysis that clearly presents the long-term fuel price assumptions has not been addressed in similar previously published studies. Therefore, this study investigates the economic viability of the PV system using true current fuel prices and representative fuel-price forecast assumptions, and validates the accuracy of the methodology performing a sensitivity analysis with respect to fuel oil price-increase scenarios. The rest of the paper is organized as follows. Firstly, the methodology used for the PV system modeling and the environmental and economic analysis is carried out. Subsequently, a case study referring to the design of the stand-alone PV system on the Ro-Ro vessel is described. Finally, the results of the fuel savings as well as the economic and environmental benefits are evaluated, and the conclusions are presented.

2. Methodology

The methodology used in this study includes three stages: preparation, design, and evaluation. Firstly, to select the type and size of the case vessel for the implementation of the PV system, important information was collected, including ship specifications, deck plans, the operational profile, navigation routes, specific fuel oil consumption, and the required energy for lighting in different operation modes. The sufficient area for the location of the PV panels was determined and a market survey was conducted for the selection of the appropriate PV panels in terms of performance, efficiency, and peak power. Also, the direct normal solar irradiation in the navigation area under study was obtained from global solar radiation databases. Then, the methodology for PV system design was applied, aiming to attain the higher possible PV system capacity to cover the required energy. The maximum energy produced by the PV system and the corresponding fuel savings were calculated. Finally, ship emission reductions and economic indicators were estimated by performing environmental and economic analysis, and sensitivity analysis was used to evaluate the results.

2.1. PV System Modeling

The performance of PV devices is determined by two key parameters [2], namely, the Capacity Factor (*CF*), which is defined as the annual actual *AC* electric energy output (in kWh/year) divided by the annual generated *DC* output peak power rating (in kWp) multiplied by 8760 h/year, according to Equation (1), and the Performance Ratio (*PR*) also called the Quality factor (*Q*), which is defined according to Equation (2).

$$CF = \frac{Actual\_annual\_AC_{output}}{DC\ peak\ power\ rating \cdot 8760} \tag{1}$$

$$PR = \frac{CF}{DCpower_{(peak)} \cdot 8760 \cdot Irr_{(avg)} \cdot 10^{-3}} \tag{2}$$

where $DCpower_{(peak)}$ is the generated output peak power (in kW_p) and $Irr_{(avg)}$ is the average solar irradiation (in W/m^2) in the location.

In general, PV panels are compensated by their high reliability, very low impact to the environment and low maintenance needs. Moreover, their construction is characterized by a low demand for material utilization and a simple manufacturing process. The selection of PV panels to be installed on a ship is based on the energy requirements and the available space, taking into consideration their performance, power rating, and size. It is crucial that the panels are resistant to the marine environment, which is characterized by harsh conditions concerning humidity, salinity, and strong winds. The design of the selected PV system should take into account the construction material of the frame, and the capability of connecting it to a battery, as well as the ease of wiring. However, there are two main problems that need to be addressed: the reverse current flow from the battery to the PV panels, and faulty or partially shaded PV panels. To prevent the back discharge of the battery when the solar panel is in a lower potential, a blocking diode is connected in series to the PV panel or PV string, while to provide an alternative path for current flow in case of a faulty or partially shaded panel, it is recommended to connect a bypass diode in parallel to the PV panel. Performance also depends on degradation, shading, overheating, the presence of impurities on the PV surface and losses in blocking diodes.

A key criterion for selecting a PV panel is the peak power, which represents the maximum electric power produced by the panel under standard control conditions (STC). The efficiency of the PV panel is calculated using Equation (3):

$$n = \frac{P_m}{P_H \cdot S} \tag{3}$$

where P_m is the maximum power of the PV panel (in kW), P_H is the power density of the incident radiation (in kW/m^2) and S is the surface of the incident radiation (in m^2).

The maximum energy produced by the PV system is estimated by Equation (4) [29]:

$$E_{\max\_PVsystem} = B_n \cdot A_{PV} \cdot n_{STC} \cdot AF \cdot SF \cdot DF \cdot T_{coef} \cdot N \tag{4}$$

where B_n is the direct normal solar irradiation (in KWh/m^2), A_{PV} is the PV panel surface area (in m^2), n_{STC} is the efficiency factor of the PV panel in standard temperature conditions (STC), AF is the degradation factor, SF is the shading factor, DF is the factor of energy loss on blocking diodes, T_{coef} is the temperature coefficient and N is the number of PV panels. The temperature coefficient is calculated according to Equation (5):

$$T_{coef} = 1 - \left[\left(t_{avg} + 30\right) - 25\right] \cdot 0.004 \tag{5}$$

where t_{avg} is the average temperature in the location.

To cover the energy requirements and to maximize the system's power output, the PV panels are connected in series (forming a PV string) to increase the output voltage or/and in parallel to increase the output current. The power output of each PV sub-array is determined by the total number of the PV panels and the connection scheme [30].

Hybrid PV systems are environmentally friendly devices and have the capability to generate power using two sources; for instance, they can combine solar or wind energy with the power produced from a generator. This results in a reliable function and a continuous stable power supply [31]. The main purpose of any hybrid PV system installed on a ship is to secure the grid with the supply of constant power. Often, this is hard to achieve due to the prevailing conditions and the capacity limit of the batteries. When the amount of power produced from the PV system is not sufficient, the additional required power is retrieved from the ship's generators. The design must, therefore, include, in addition to the PV panels, a DC-to-AC Inverter, as well as batteries for storage of the excess energy (Figure 1). Solar charge controllers, the main role of which is to charge the batteries and to provide the maximum amount of the required electric power, are also incorporated in the designed installation.

The batteries store much of the energy and can supply the required electric charge to the system whenever there is a drop in the production of electric power from the PV system. The main parameter for choosing the appropriate battery is its autonomy, as well as its main characteristics determined by the nominal voltage and capacity. The autonomy of a battery determines the time period of sustaining the system's energy without the need of recharging, while the nominal voltage determines the type of the system's configuration. The capacity of a battery (in Ah) is calculated according to Equation (6):

$$C = I \cdot n_h \tag{6}$$

where I is the electric current and n_h is the battery charging time (in hours). The maximum electrical energy stored by a battery (in kWh) is calculated by Equation (7):

$$E_B = C \cdot V_B \tag{7}$$

where C is the battery capacity (in Ah) and V_B denotes the nominal voltage.

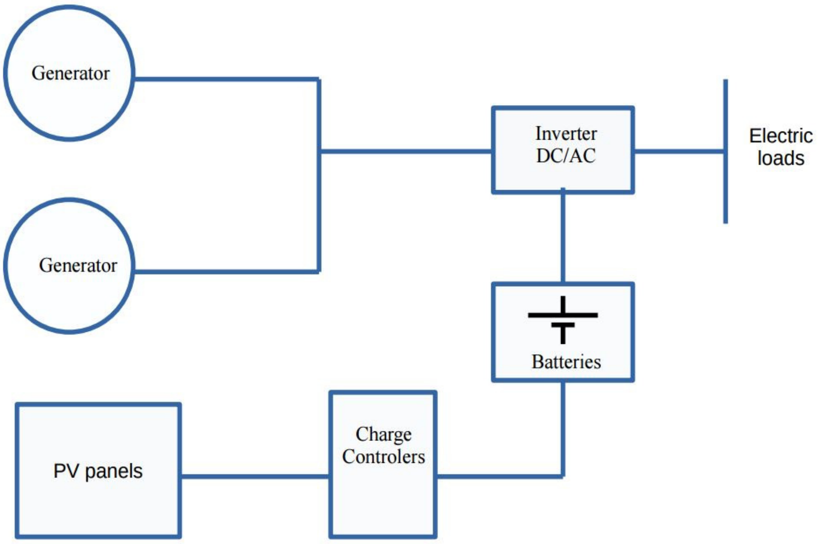

Figure 1. Schematic diagram of a stand-alone solar PV system installed onboard a ship.

The batteries can be connected either in series or in parallel depending on the required power output. The nominal capacity of the system depends on the number of sequential charging and discharging processes of the batteries. The efficiency of a battery is calculated by Equation (8):

$$n_b = \frac{E_{dch}}{E_{ch}} \tag{8}$$

where E_{dch} is the provided energy during discharging and E_{ch} is the supplied energy during charging.

2.2. Environmental Analysis

Emission gases such as CO_2, SOx, NOx, and PM are released through the combustion of the fuels used during the ship operation. These emission gases can be reduced, respectively, to the power generated from the PV system and the fuel savings. A key element for calculating the quantity of emission gases is the emission factors (*EF*s), which can depend on the fuel type, the content of the emission gas in the fuel, the specific fuel oil consumption, and engine characteristics, such as the engine speed and engine production year [32].

The CO_2 fuel-based emission factor (in g/kWh) is calculated as the following [33]:

$$EF_{CO_2} = conversion\ factor \cdot SFOC \tag{9}$$

where $SFOC$ is the specific fuel oil consumption (in g/kWh) and the conversion factor denotes the CO_2 content in the fuel type used (in g CO_2 per g of fuel).

SOx and PM fuel-based emission factors (in g/kWh) are calculated according to the following equations (Equations (10)–(12)), based on the sulfur content of the fuel used [33]:

$$EF_{SOx} = SFOC \cdot 2 \cdot 0.97753 \cdot fuel\ sulfur\ fraction \tag{10}$$

$$EF_{PM,HFO} = 1.35 + SFOC \cdot 7 \cdot 0.02247 \cdot (fuel\ sulfur\ fraction - 0.0246) \tag{11}$$

$$EF_{PM,MGO} = 0.23 + SFOC \cdot 7 \cdot 0.02247 \cdot (fuel\ sulfur\ fraction - 0.0024) \tag{12}$$

The NOx emission limit (in g/kWh) is calculated based on the Tier standards according to MARPOL Annex VI Regulations. The different Tiers are based on the ship construction date, and each Tier limits NOx emissions to a specific value that is determined considering the engine's rated speed.

2.3. Economic Analysis

To assess the financial viability of the PV system investment, the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Payback period were estimated. The NPV is the difference between the present value of cash inflows and the present value of cash outflows for a certain period and is used in investment planning to analyze the potential profit or loss of the planned investment. The Net Present Value can be estimated using Equation (13):

$$NPV = \sum_{t=1}^{T} \left(\frac{R_t}{(1+i)^t} - C_0 \right) \tag{13}$$

where C_0 is the initial capital cost, R_t is the total cash flow during the period t, i is the discount rate, and T is the number of time periods.

The discount rate is the rate of return that the investor expects to receive from the particular investment and the cash flows of the specific period. In this study, its value was set considering the respective accepted values in related studies in the literature. The term $\mathrm{R_t}$ includes the operation and maintenance cost of the investment as well as the direct economic benefits, and is discounted back to the present value. In this study, the operation and maintenance cost was estimated as a fixed price for the first year of the investment, while an annual increase was considered due to the time value of the currency and the aging of the system. The direct economic benefits, which correspond to the fuel savings that are attained due to the PV system operation, were estimated as a fixed price for the first year according to current fuel prices, while an annual increase was considered for the long-term analysis, combining published oil price forecast assumptions.

The Internal Rate of Return indicates the annual rate of growth that an investment is expected to generate and is used to assess the profitability of the potential investment. In general, when comparing investments, the one with the highest IRR is considered the more desirable. IRR is a discount rate that makes the Net Present Value of all cash flows equal to zero and can be estimated by Equation (14):

$$0 = NPV = \sum_{t=0}^{T} \frac{C_t}{(1+IRR)^t} \tag{14}$$

where C_t is the net cash flow during the period t, and T is the number of time periods.

The Payback period is the period in which the NPV of the investment equals zero and is calculated by dividing the amount of the investment by the annual cash flow. A short payback period indicates a financially viable investment as the cost of the initial investment will be quickly recovered. A long payback period is usually not desirable, as the investment could be risky due to the uncertainties in the long-term predictions.

To assess the accuracy of the proposed methodology and the reliability of the calculation results, a sensitivity analysis was performed. In sensitivity analysis, the values of critical parameters that are most likely to change and affect the system assumptions are modified, and the effect of the values' variation to the results is presented. As the economic evaluation includes long-term assumptions for the cost parameters, sensitivity analysis is also a means to understand how these assumptions affect the derived results.

3. Case Study

3.1. Vessel Information

To investigate the performance and feasibility of the solar PV system, a Roll-on/Roll-off cargo vessel of 170 m length overall, 28.02 m breadth, gross tonnage 36,902 t and carrying capacity 11,010 t DWT was selected as a case study. The vessel has a large space area on the upper deck continuously exposed to sunlight during its voyage, suitable for the installation of solar panels. The ship serves at five routes within the Mediterranean Sea between ports in Spain, France, Italy, the straits of Gibraltar, and the Marmara Sea (Gemlik), two routes on the western shores of Spain and Portugal, and one route from Gemlik to Constanta (Black Sea). It consumes heavy fuel oil (HFO) and marine gas oil (MGO) in a 60–40 ratio and is equipped with scrubbers that limit the SOx emissions of HFO to the allowed levels according to MARPOL Annex VI Regulations.

The ship operates at sea, at port (in/out), at cargo operations (loading/unloading) and at harbor, with different energy requirements at each operating mode. It is equipped with one main engine of 11,010 kW, one shaft generator of 1800 kW that runs at sea mode, two main generators of 1100 kW each that run at other modes, and an emergency generator of 150 kW. In the present case study, the PV system was designed to provide energy for the lighting loads during cargo operations. Lighting loads include machinery space lighting, accommodation lighting, deck lighting, and cargo hold lighting. According to the operational profile of the ship, a cargo operation (loading/unloading) has a duration of 5 h and lighting consumption is equal to 167 kWh. Considering a percentage of simultaneous electrical loads equal to 90%, the required energy for lighting during a cargo operation is equal to 751.5 kWh.

3.2. Solar PV Potential

Solar radiation can be exploited through the application of solar PV systems onboard ships in off-grid or grid-connected operation modes, that utilize deck spaces of high sun exposure and provide a ship with continuous power supply. Especially for ships that operate in shipping routes of high solar potential, solar energy can comprise a greener and more environmentally responsible means for transport, promoting sustainable shipping.

As the Ro-Ro vessel sailing schedule is dependent on the market demand, the sequence and the number of navigation routes is not predetermined for each month. To approximate the solar PV potential for the case study, a specific area was selected that contains representative solar radiation characteristics of the ports where the cargo operations take place, and the PV system was utilized. This area was characterized by the average of solar potentials between the port of Constanta (lower solar potential) and the port of Tanger Med in Straits of Gibraltar (higher solar potential) and included the majority of the ports along the ship's sailing schedule as well as the ports of departure and arrival.

The direct normal solar irradiation for average hour intervals in the area under study is presented in Figure 2, utilizing data obtained from the Global Solar Atlas 2.0 web-based application [34]. Figure 3 presents the in-plane irradiation for the zero tilt angle of the installed PV panels per month, utilizing data from the Photovoltaic Geographical Information System web-based application [35].

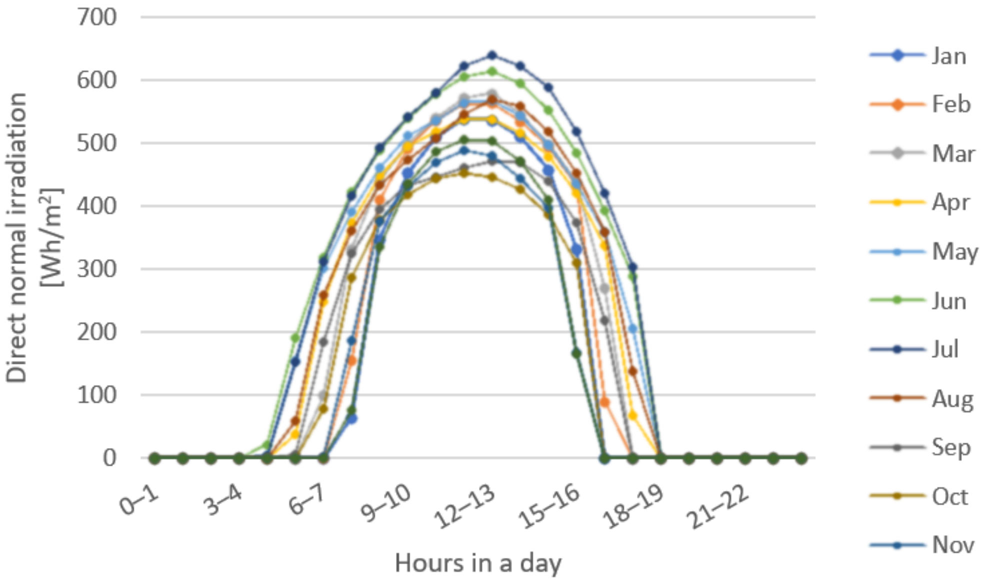

Figure 2. Direct normal irradiation for average hour profiles [34].

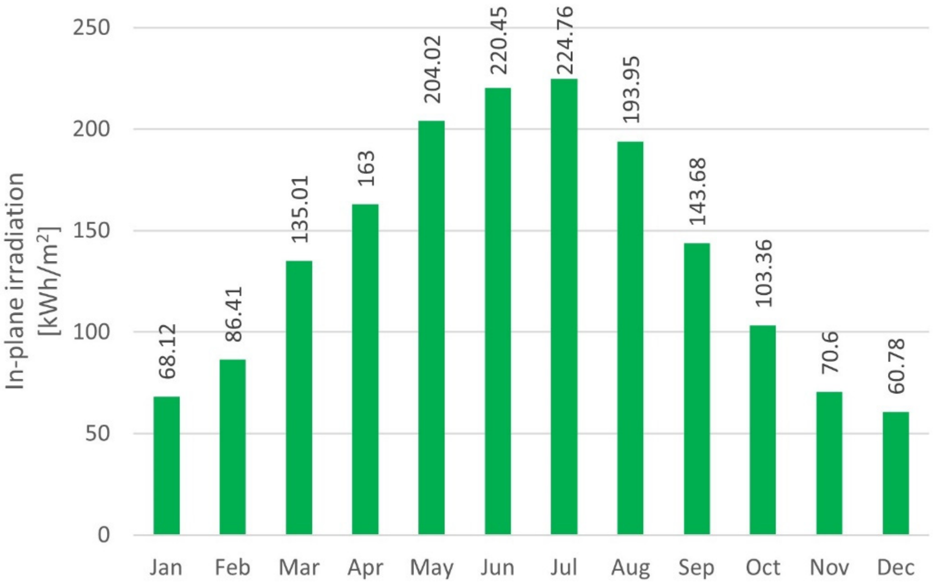

Figure 3. In-plane irradiation for zero tilt angle of the installed PV panels [35].

3.3. Stand-Alone PV System Design

Considering the available space on the decks and to ensure the maximum energy output of the solar system, 450 PV panels of a monocrystalline type, with panel dimensions of 2172 × 1303 × 35 mm and a PV peak power of 605 W, were installed. The panels were connected in 90 strings of five modules each, and mounted in zero tilt angle to avoid shading, with appropriate margins and corridors between the frames. Figure 4 presents the general arrangement of the Ro-Ro vessel and the location of the PV panels on the weather deck (space 1 and 2), the top of bridge deck (space 3) and the upper deck (space 4). Figure 5 demonstrates the stand-alone PV system diagram consisting of 450 PV panels, 45 charge controllers, 1080 solar batteries and 23 DC-AC inverters.

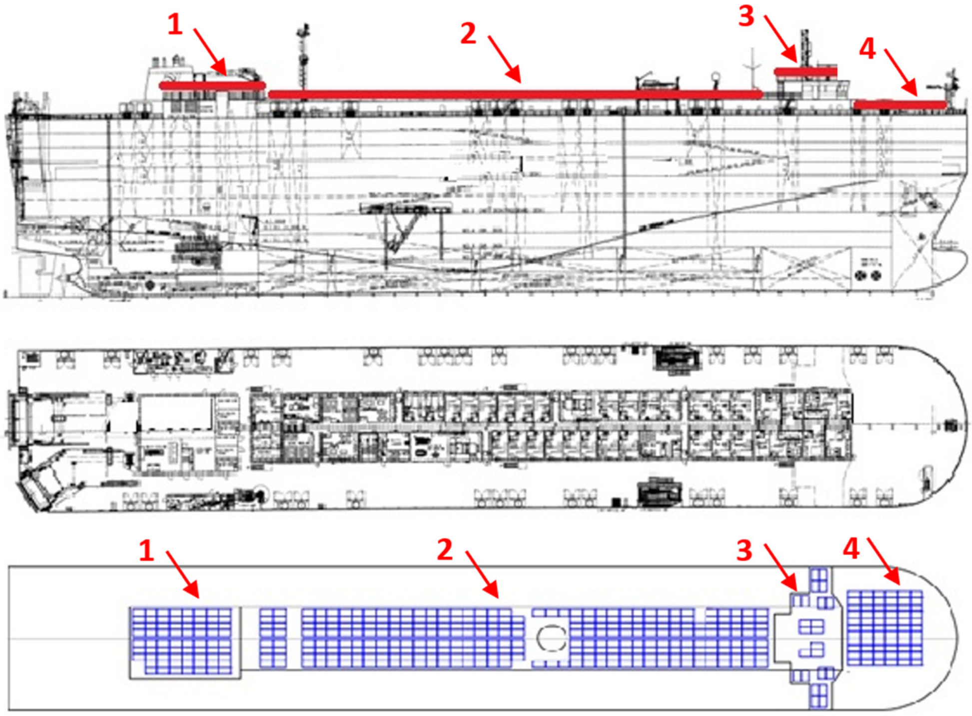

Figure 4. General Arrangement of the Ro-Ro vessel and location of the PV panels.

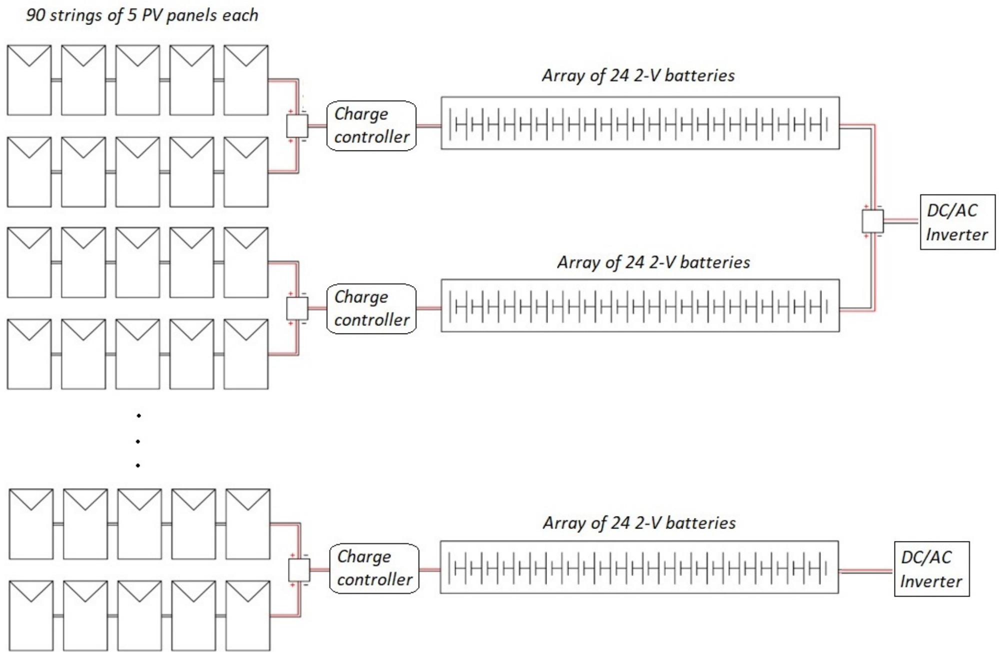

Figure 5. Stand-alone PV system diagram of the Ro-Ro cargo vessel.

To achieve the maximum input power to the batteries by adjusting the voltage and current values of the PV strings, solar charge controllers were installed. Each controller served two strings of five PV panels connected in parallel, resulting in 45 charge controllers of 250 V/100 A in total.

Solar batteries stored the excess energy produced by the PV system and provided stable energy distribution and the avoidance of fluctuations, which could affect and damage the PV system. The total required capacity was calculated to be equal to 40,931 Ah [23,30]. For the PV system, 2-volt batteries of 994 Ah capacity each were connected in a series of 24 to provide the necessary voltage of 48 V. Each array of batteries corresponded to the capacity of 10 PV panels and were connected after the charge controller.

To convert the maximum DC power generated by the PV panels, 23 DC-AC inverters of a continuous output power of 10,000 W (at 25 °C) and peak power of 20,000 W each were installed after the batteries. In particular, the 44 battery arrays were connected to 22 inverters and the 45th was connected to the remaining one. When the solar batteries reached the lowest level (cut-off voltage) which was set as equal to 15%, the two main generators were connected to the inverter inputs (Figure 1), to continue the uninterrupted supply for the loads.

Table 1 presents the maximum energy produced by the PV system according to Equation (4), considering the average temperature in the area under study, the direct normal irradiation for the zero tilt angle, and the technical characteristics of the PV panels (n_{STC} was equal to 21.4% and the factors AF, SF and DF were equal to 0.98, 0.90 and 0.99, respectively) [36].

Table 1. Maximum energy produced by the PV system based on case parameters.

Month	Days	Average Temperature (°C)	Temperature Coefficient *Tcoef*	Direct Normal Irradiation (kWh/m^2)	Maximum Energy Produced by PV System (kWh)
January	31	7.9	0.948	68.12	14,753.29
February	28	8.5	0.946	86.41	18,667.14
March	31	10.9	0.936	135.01	28,870.22
April	30	13.5	0.926	163	34,468.41
May	31	17.0	0.912	204.02	42,490.35
June	30	21.3	0.895	220.45	45,046.27
July	31	23.8	0.885	224.76	45,413.70
August	31	23.9	0.884	193.95	39,170.69
September	30	20.9	0.896	143.68	29,411.75
October	31	17.4	0.910	103.36	21,488.57
November	30	12.1	0.932	70.6	15,019.55
December	31	8.6	0.946	60.78	13,124.74

3.4. Limitations of the PV System

The installation of PV panels onboard a ship at deck areas that are greatly exposed to sunlight with no obstructions can provide a ship with the maximum energy produced by the PV system, especially when it operates in regions of high solar potential. However, there are some potential limitations that can affect the PV system performance and the coverage of energy loads. Firstly, most ships usually have a limited space for the installation of PV panels, to meet the energy demands. Also, environmental conditions such as ambient temperature, the sun's irradiation, humidity, and strong winds, impact the efficiency of the photovoltaic system regarding the conversion of solar energy into electricity. In addition, harsh weather conditions onboard the ship, such as dust, dirt and saltwater, can also affect the efficiency and lifespan of the PV panels, especially if the maintenance of the PV panels is insufficient [37,38]. However, according to trials on the 2400-passenger ferry Blue Star Delos [39], using a thin panel PV technology designed to withstand exposure to dirt and salt, their impact on the performance and the power output of the solar panels was minimal.

4. Results and Discussion

4.1. Fuel Savings

The proposed PV system was used to provide electrical energy for the lighting during the cargo operations (loading/unloading). As the sequence and the number of the vessel's navigation routes was not predetermined, the exact number of cargo operations could not be specified. The shortest and longest duration of the ship journey between two ports were 5.5 h and 4.5 days, respectively. For the calculation of the required energy, the most-demanding scenario with one cargo operation per day was assumed, which resulted in a daily required energy equal to 751.5 kWh. Figure 6 presents the required energy for lighting per month, which was calculated by multiplying the daily required energy by the number of days, and the maximum energy produced by the PV system per month. It was observed that from March to September the PV system provided the full quantity of the required energy, and the excess energy could serve other electrical needs, such as the lighting loads during at the harbor operating mode, that are also supplied by the main generators. During the remaining five months, when the system partially provided the required energy, the main generators were used for full energy coverage.

To calculate the fuel savings (FS) per month (in tons) for the operation under study, the following equation was used:

$$FS_i = E_{PV,i} \cdot SFOC_i \cdot 10^{-6} \tag{15}$$

where E_{PV} is the energy provided by the PV system (in kWh), $SFOC$ is the specific fuel oil consumption (in g/kWh) obtained from the engine logbook for each month considering mixed fuel of 60% HFO and 40% MGO, and i indicates the month.

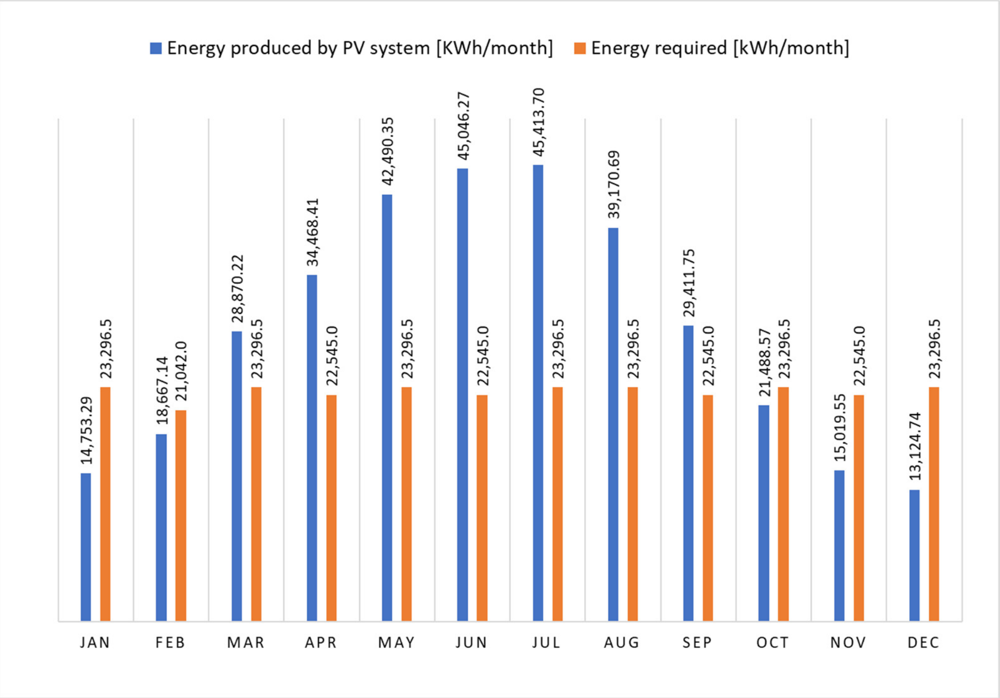

Figure 6. Required energy for lighting and maximum energy produced by the PV system.

Table 2 summarizes the calculations for *FS*, including the number of days per month that the required fuel quantity for lighting was provided by the PV system, fully or partially. According to the calculations, 38.06 t of HFO and 25.37 t of MGO could be saved by the PV system annually; that stands for 88% of the amount of fuel that was consumed for lighting during cargo operations.

Table 2. Fuel savings (in tons) based on case parameters.

Month	SFOC (g/kWh)	Energy Required (kWh)	Fuel Required (tons)	Maximum Energy Produced by PV System (kWh)	Energy Provided by PV System (kWh)	Number of Days	Fuel Savings (tons)
January	300	23,296.50	6.99	14,753.29	14,753.29	19.6	4.43
February	317	21,042.00	6.67	18,667.14	18,667.14	24.8	5.92
March	268	23,296.50	6.24	28,870.22	23,296.50	31	6.24
April	289	22,545.00	6.52	34,468.41	22,545.00	30	6.52
May	254	23,296.50	5.92	42,490.35	23,296.50	31	5.92
June	259	22,545.00	5.84	45,046.27	22,545.00	30	5.84
July	241	23,296.50	5.61	45,413.70	23,296.50	31	5.61
August	214	23,296.50	4.99	39,170.69	23,296.50	31	4.99
September	217	22,545.00	4.89	29,411.75	22,545.00	30	4.89
October	244	23,296.50	5.68	21,488.57	21,488.57	28.5	5.24
November	272	22,545.00	6.13	15,019.55	15,019.55	19.9	4.09
December	286	23,296.50	6.66	13,124.74	13,124.74	17.4	3.75
Sum		274,297.50	72.15	347,924.68	243,874.30		63.43

4.2. Environmental Indicators

To evaluate the environmental performance of the solar system as an alternative to fossil fuel consumption, the reduction in the emissions released to the atmosphere during ship cargo operations was estimated. The quantity of the emissions (in kg) was calculated separately for CO_2, SOx and PM according to Equation (16):

$$Q_{emission} = \sum_{i=1}^{12} (EF_{emission,MGO} \cdot 0.40 + EF_{emission,HFO} \cdot 0.60) E_{PV,i} \cdot 10^{-3} \quad (16)$$

where E_{PV} is the energy provided by the PV system (in kWh) which also represents the energy saved by the main generators, $EF_{emission,fuel}$ denotes the fuel-based emission factors (in g/kWh), and i indicates the month.

The CO_2 fuel-based EFs were estimated according to Equation (9) considering a conversion factor of 3.206 for MGO and 3.114 for HFO [33].

SOx and PM fuel-based EFs were calculated in accordance with Equations (10)–(12) considering a fuel sulfur content of 0.1% for MGO and 0.5% for HFO. Actually, the Ro-Ro vessel under the study consumed MGO with a fuel sulfur content of 0.1% and HFO with a high sulfur content of 3.5%. However, the ship is equipped with a scrubber system and the quantity of sulfur that is emitted from the exhausts was reduced to 0.5%, which is also the fuel sulfur limit for ships operating in global waters; therefore, this value was considered for the calculations.

The NOx emission limit (in g/kWh) was calculated by Equation (17), applying the Tier I standard since the ship's construction date is 2010,

$$NO_x\ Limit = 45 \cdot n^{-0.2} \tag{17}$$

where n is the engine's rated speed (in rpm) equal to 900 rpm.

Table 3 summarizes the emission factors and the quantities of the CO_2, SOx, PM, and NOx exhaust gases reduced per month. Adapting the proposed solar PV system, an annual reduction of 199,865 kg of CO_2, 2815 kg of NOx, 421 kg of SOx, and 97 kg of PM can be achieved, indicating that the PV system has a high environmental performance and can contribute to environmental sustainability. Furthermore, using the proposed system to provide energy during cargo operations in port constitutes a cleaner and environmentally friendly solution for reducing air pollution from ships in port areas.

Table 3. Emissions for exhaust gases (in kg) reduced per month.

Month	**EF *_CO_2 (g/kWh)**		**CO_2 (kg)**	**EF_SOx (g/kWh)**		**SOx (kg)**	**EF_PM (g/kWh)**		**PM * (kg)**	**NOx (kg)**
	MGO *	**HFO ***		**MGO**	**HFO**		**MGO**	**HFO**		
January	961.80	934.20	13,945.40	0.59	2.93	29.42	0.16	0.43	4.73	170.32
February	1016.30	987.14	18,644.81	0.62	3.10	39.33	0.16	0.37	5.37	215.50
March	859.21	834.55	19,671.90	0.52	2.62	41.50	0.17	0.52	8.91	268.94
April	926.53	899.95	20,529.05	0.57	2.83	43.31	0.17	0.46	7.71	260.26
May	814.32	790.96	18,644.26	0.50	2.48	39.33	0.17	0.57	9.55	268.94
June	830.35	806.53	18,398.01	0.51	2.53	38.81	0.17	0.55	9.02	260.26
July	772.65	750.47	17,690.03	0.47	2.36	37.32	0.18	0.61	10.13	268.94
August	686.08	666.40	15,708.16	0.42	2.09	33.14	0.18	0.69	11.35	268.94
September	695.70	675.74	15,414.55	0.42	2.12	32.52	0.18	0.68	10.86	260.26
October	782.26	759.82	16,520.31	0.48	2.39	34.85	0.18	0.60	9.22	248.07
November	872.03	847.01	12,872.02	0.53	2.66	27.16	0.17	0.51	5.63	173.39
December	916.92	890.60	11,827.09	0.56	2.80	24.95	0.17	0.47	4.56	151.51
Sum			199,865.60			421.65			97.05	2815.33

* EF: Emission Factor, PM: Particulate Matter, MGO: Marine Gas Oil, HFO: Heavy Fuel Oil.

4.3. Sensitivity Analysis of the Environmental Assessment

In the environmental assessment of the proposed PV system, the quantity of reduced emissions depends highly on fuel savings and, therefore, on the energy provided by the PV system. Critical factors that affect the performance of PV panels and the maximum energy produced are the environmental and weather conditions on board the ship, such as strong winds, cloudy sky, humidity, and dust [37,38]. For the sensitivity analysis, two scenarios of decreased maximum energy produced by the PV system (10% and 20% decrease) were analyzed, and their effect on the emissions are presented in Table 4, relative to the base case.

Table 4. Sensitivity analysis of the environmental results with respect to different PV panel performance (values per year).

	Maximum Energy Produced by PV System (kWh)	Energy Provided by PV System (kWh)	Fuel Savings (tons)	Emissions (in kg) Reduced			
				CO_2	SOx	PM	NOx
Base case	347,924.68	243,874.30	63.43	199,865.60	421.65	97.05	2815.33
Scenario 1 (−10%)	313,132.21	235,568.97	61.09	192,484.62	406.08	94.10	2719.46
Scenario 2 (−20%)	278,339.74	227,063.31	58.69	184,934.50	390.15	91.07	2621.27

The results of the sensitivity analysis show that a decrease of 10–20% in the performance of the PV panels and, consequently, on the maximum energy produced, has a small effect on the energy provided by the PV system to cover the lighting loads. In particular, and according to the analytical calculations, in the case of a 10% decrease, the PV system can provide the full quantity of the required energy from March to September, as in the base case study. For a higher decrease of 20%, the PV system can cover the energy needs from April to September. For the remaining months, the PV system partially provides the required energy; however, the differences in the results between the base study and the two scenarios are small. The robustness of the PV system is due to the high solar potential of the sailing routes of the Ro-Ro vessel, which permits a large amount of solar energy to be converted to electricity for the sunny months (usually spring and summer) that exceeds the required energy in both scenarios. According to the sensitivity analysis, the implementation of the proposed PV system comprises an effective solution for reducing ship emissions, even if the performance of the PV system is decreased due to harsh environmental and/or weather conditions.

4.4. Costs, Benefits and Economic Indicators

Economic analysis is the means to determine if the solar PV system installation is profitable. Costs and benefits as well as the generated cash flows that result from the specific investment were calculated. To assess the economic feasibility of the PV system, the NPV, IRR and payback period were estimated for an investment period of up to 20 years.

Costs to be included in the economic evaluation are the capital cost for the PV system, and the operation and maintenance cost. A market survey was conducted to determine the current price for the purchase and installation of the PV system components. All prices presented in Table 5 were fixed prices for the period of August 2022 from a global supplier, who also provided a 33% discount on charge controllers and DC-AC inverters. The purchase price for the PV panels, as well as the foundation and installation cost of the PV system, are given in EUR/kW. The operation and maintenance cost (O&M) was calculated as a percentage of 0.5% of the capital cost for small-scale PV energy systems [21,40]. This fixed value was set for the first year of the investment, while an annual increase of 1% in the O&M cost due to the time value of the currency and the aging of the system was considered for the investment period.

Table 5. Cost estimation of the designed stand-alone PV system.

Item	Quantity	Price	Discount	Total Cost (EUR)
PV panels	272.25 kW	0.32 EUR /Watt	-	87,120.00
Solar batteries	1080	EUR 260.00	-	280,800.00
Solar charge controllers	45	EUR 1003.00	33%	30,240.45
DC-AC inverters	23	EUR 4290.00	33%	66,108.90
Foundation	272.25 kW	100 EUR /kW	-	27,225.00
Installation	272.25 kW	100 EUR /kW	-	27,225.00
Sum				518,719.35

The benefits of the investment include the direct economic benefits from the fuel savings, while indirect cost benefits such as prior entrance to ports, carbon credits, etc., are neglected. According to an oil market survey, the prices were estimated at USD 1234.5/t for MGO and USD 530.5/t for HFO for the period of August 2022 (exchange rate 1 USD = EUR 1.0066 on 24 August 2022, European Central Bank, Frankfurt, Germany), and these prices were set in the economic analysis for the first year of the investment. To estimate the fuel price increase during the 20-year investment period, various long-term forecast assumptions for the price of crude oil and distillates published by energy information and other organizations [41–44] were considered. For the base case under study, the central oil price scenario assumptions from different sources were combined and an annual increase of 2.47% for the MGO/HFO fuels was assumed.

For the specific investment, the discount rate that provides foresight on profitability was set to 8%, according to the respective accepted values in the literature [19,21]. The NPV and IRR were estimated to be EUR 79,931.21 and 9.76%, respectively. It was also computed that the discounted payback of the system would be achieved in a 16.5-year period, indicating that the proposed PV system could be a long-term profitable investment with financial viability, considering that the estimated operational lifespan of a PV module is about 25–30 years [45,46].

4.5. Sensitivity Analysis for the Economic Assessment

In the base case study, the Ro-Ro vessel consumed 40% MGO fuel and 60% HFO fuel. The vessel navigates in global waters where the fuel sulfur limit is 0.5%, so the use of the MGO and HFO with a scrubber comply with the regulation. However, in December 2022, the MEPC 79 adopted amendments to designate the Mediterranean Sea as an Emission-Control Area for SOx and PM, with the new sulfur limit taking effect from 1 May 2025 [47]. In this context, it is critical to evaluate the proposed PV system for a specific case where the Ro-Ro cargo vessel consumes only MGO fuel. It is possible for this specific case to exist due to more stringent emission regulations, which could designate the whole navigation area of the vessel as ECA, where the limit for fuel sulfur content is 0.1% instead of 0.5% in global waters. In such a case, the Ro-Ro vessel would consume only the MGO fuel that complies with the emission regulations of the IMO. For the “Only MGO” case, the economic analysis was performed, considering the same parameters and fuel cost assumptions as in the base case study. The economic indicators NPV and IRR and the payback period were estimated to be EUR 405,907.15, 16.14% and 9 years, respectively, indicating that installing the proposed stand-alone PV system in such a case could be even more economically profitable for the ship-owners.

Furthermore, one of the most critical factors for the financial viability of the PV system investment is the parameter of the fuel price and its variation during the investment period. Therefore, a sensitivity analysis was conducted according to a Low scenario (1% annual increase on fuels price) and a High scenario (3.5% annual increase on fuels price). The effect of the variation of the fuel prices on the NPV, IRR and payback period are presented in Table 6 relative to the base case of MGO/HFO and the “MGO-Only” case.

Table 6. Sensitivity analysis of the economic indicators with respect to fuel price.

Case	Price Scenario	NPV (EUR)	IRR (%)	Payback Period (Years)
MGO/HFO	Low (1%)	12,613.63	8.3	20
	Central (2.47%)	79,931.21	9.76	16.5
	High (3.5%)	131,450.27	10.73	15
MGO-Only	Low (1%)	303,574.54	14.67	9.8
	Central (2.47%)	405,907.15	16.14	9
	High (3.5%)	484,223.68	17.11	8.6

For the base case of MGO/HFO, the sensitivity analysis indicates that an annual increase of 1% in the oil price (Low scenario) results in an investment with a payback period of 20 years and could lead to the rejection of the PV system project. It is assumed that this long-term scenario corresponds to a sustainable development policy scenario where strong action to reduce carbon emissions is undertaken and the oil demand weakens. The High scenario could be more attractive to ship-owners, with a payback period of 15 years and IRR equal to 10.73%. This long-term scenario responds to a case where current energy policies are put into practice and the global market is characterized by low oil supply and high oil demand. The central scenario (base case scenario) is assumed to be the most realistic scenario to happen long-term (2035 onwards) and corresponds to new energy policies and interventions on emissions reductions as well as a central oil demand.

For the specific case of MGO-Only, all three scenarios can be financially viable and attractive for the ship owners. However, if policies and measures are adopted in the following years for sustainability and further ship emission reductions, the MGO-Only Low scenario seems to have very good prospects, with an NPV, IRR and payback period estimated to be EUR 303,574.54, 14.67% and 9.8 years, respectively.

4.6. Comparison to Previous Studies

A comparison between the results of the economic and environmental analysis between this study and previously published studies on the designed PV systems, on similar sizes and types of vessels [13,15,21,25], is presented in Table 7. The economic indicators and the quantity of the emission reductions depend mainly on the fuel savings according to the specific case study. Fuel savings are related to SFOC and the power generated from the PV panels, which depends on the solar irradiance at the vessel route, the PV panel efficiency, and the actual installation area of the PV panels on the ship. Therefore, a larger available deck area increases the capacity of the PV system and consequently the fuel savings. The values of the economic indicators also depend on the capital cost of the PV system, which is the cash outflow in the analysis. In the case of a grid-connected PV system, the capital cost of solar batteries that comprise a basic component of the stand-alone system is not included.

Table 7. Comparison of economic and environmental results between this study and previously published studies.

Study	Vessel	PV System	Area (m^2)/ No of PVs	NPV (USD)	Payback Period/Discount Rate	Fuel Reduction (tons)	Emissions (in kg) Reduced			
							CO_2	NOx	SOx	PM
Qiu et al. [13]	Pure Car Truck Carrier	g-con. *	900/-	165,977.2	7.84/8%	-	163,338	2753	107	70
Yuan et al. [25]	Pure Car Truck Carrier	g-con./ s.a. *	1050/540	-	-	4.02%	8.55%	-	-	-
Yuan et al. [21]	Pure Car Carrier	s.a.	-/135	-	7–20/3.5%	16	28,500	50	630	-
Karatuğ et al. [15]	Ro-Ro vessel	g-con.	2593.5/1274	3,362,397	11.2/8%	73.51	232,393	3942	312	114
This study Base case	Ro-Ro cargo vessel	s.a.	1280/450	79,407.12 **	16.5/8%	63.43	199,865	2815	421	97
This study MGO-Only Low scenario	Ro-Ro cargo vessel	s.a.	1280/450	301,584.09 **	10/8%	63.43	-	-	-	-

* g-con.: grid-connected, s.a.: stand-alone; ** The NPV values have been converted to USD according to the exchange rate used in the study.

The main contribution of this paper, relative to previous studies, is the use of representative fuel price assumptions for three scenarios (Low, Central, High) combining various long-term forecast assumptions published by energy information organizations [32–35]. To strengthen this assertion, we presented the following elements:

Qiu et al. [13] used a price of fuel oil equal to 0.709 USD/L, while no mention was made for future price predictions. Yuan et al. [25] used the historical average price of marine diesel oil from 2014 to 2017, equal to USD 837.96/t, while no mention is made for future price predictions. Yuan et al. [21] used a fuel price equal to RMB 0.426/kWh, and the payback period was estimated according to a different market-price growth rate of fuel to the order of 10–50%, but no information about the sources of these predictions was presented. Karatuğ et al. [15] performed an analysis in which no detailed fuel prices were mentioned. In other studies of small-size vessels, Tercan et al. [22] simulated a PV system of 15 panels for a small tourist boat, using gasoline prices taken from the Global Petrol Price Index, without mentioning these values, and Wang et al. [20] presented a PV system of 206 PV panels on a short route ferry and used a fuel price equal to 401 USD/t according to Istanbul Bunker Prices, without taking into account future price predictions.

5. Conclusions

The present study focused on the design of a photovoltaic system on a Ro-Ro cargo vessel for electrical energy production for lighting during cargo operations. In this base, the installation of a stand-alone solar PV system that comprised 450 PV panels, solar charge controllers and solar batteries was examined from an environmental and economic point of view. PV panels were installed with a zero-tilt angle, and the technical characteristics n_{STC}, AF, SF and DF were equal to 21.4%, 0.98, 0.90 and 0.99, respectively (Equation (4)). The vessel consumed 40% MGO and 60% HFO and was equipped with a scrubber that limited the SOx emissions of the HFO to the allowed levels. The findings of the study are as follows:

(a) By adopting the proposed PV system, the analysis performed indicates that approximately 88% of the required energy for lighting can be provided by this renewable source of energy. This implies annual fuel savings of 63.43 t and a concomitant reduction in ship direct operating costs.

(b) From March to September the PV system provides the full amount of the required energy and the excess energy can be consumed for other purposes, such as the lighting loads at a harbor operating mode. For the remaining months the main generators can be used for full energy coverage.

(c) According to the environmental analysis results, the annual reduction in exhaust emissions sums up to 199,865 kg of CO_2, 2815 kg of NOx, 421 kg of SOx, and 97 kg of PM, contributing to a cleaner environment in the port areas.

(d) The sensitivity analysis for two scenarios of decreased maximum energy produced by the PV system (10% and 20% decrease) indicates that the PV system can fully cover the lighting loads from March to September and from April to September, respectively, while for the remaining month, the decrease of 10–20% has a small effect on the coverage of the required energy.

(e) The results of the economic analysis of the base case (40% MGO and 60% HFO) indicate that the PV system investment is profitable in the long term, with a Net Present Value of EUR 79,931.21, an Internal Rate of Return of 9.76%, and a payback period of 16.5 years (considering a discount rate of 8% and an annual increase in the fuels price of 2.47% for a 20-year period).

(f) The investment can be more profitable if the ship owners decide to change to Only MGO fuel, considering possible future regulations regarding emissions and ECAs. In such a case, the Net Present Value, the Internal Rate of Return and the payback period are estimated to be EUR 405,907.15, 16.14% and 9 years, respectively.

(g) The sensitivity analysis for two scenarios of different long-term fuel price assumptions (1% and 3.5% increase in fuel price) indicates that if new strategies for a sustainable low carbon economy and stricter regulations on ship emissions are adopted, the MGO-Only case seems to have a promising potential for financial viability.

The findings presented in this paper can lead the field researchers and the shipping community to consider solar energy not only as an effective alternative source for auxiliary power generation that reduces the ship emissions and the dependency on fossil fuels, but also as an economically viable investment. Ship owners and decision makers can assess the economic indicators obtained for the different fuel price scenarios in this study and conclude whether a similarly designed PV system is a profitable investment for a new-build or existing vessel. In addition, it is anticipated that further advancements in renewable energy technology will be implemented in the near future, specifically in photovoltaic systems, in terms of their efficiency and durability. The forthcoming developments are expected to reduce the reliance of marine transportation on fossil fuels, leading to very low or zero emissions and the development of energy-efficient ships.

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