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RESEARCH PAPER

The Financial and Economic Evaluation of Using Photovoltaic Electricity to Supply Marine Propulsion in Merchant Ships in Iran

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Abstract

This study investigated the feasibility of equipping merchant ships of the Persian Gulf and the Sea of Oman in southern Iran with solar-electric propulsion systems from the perspective of private and public sectors in 2019. The cost-benefit analysis approach was used. The results indicated that 0.26 units of profit is obtained for each unit of cost from the perspective of the private sector and the payback period is 18 years. Thus, replacing solar electricity is not cost-effective. The results of the social cost-benefit analysis revealed that this technology is economically viable for society by considering the benefits of reducing pollution. In addition, the results of sensitivity analysis in the financial cost-benefit case of the discount rate and the annual fuel price of ships indicated that if the discount rate (financing opportunity cost for the private sector) is less than 5% or the average annual price of fossil fuels increases by 40%, the project will be financially viable from a private sector perspective.

Keywords: Coastal Prolusion, Financial Evaluation, Merchant Ships, Photovoltaic Propulsion, Solar Energy.

JEL Classification: G00, P18.

1. Introduction

Transport has long been and is significant for developing societies. Every country can produce a set of products according to its geographical location and political, cultural, and social conditions.

If producing a product exceeds the domestic consumption capacity, an opportunity will be provided to export the product to other countries and if a country has a shortage in the production of one or more products, it will tend to import that product from other countries. In this regard, the infrastructure of the transport network including roads, railways, airways, waterways, and pipelines can play a determining role in trade (Stopford, 2009). Marine transport which is the process of transporting people, goods, animals, etc. by boat, ship, and other watercrafts from the seas, oceans, lakes, canals, and rivers is often used for commercial, recreational, and other purposes and is a branch of transport which is regarded as one of the best transport ways due to advantages like the low cost of transporting goods, payment of money against valid documents, and high speed in shipping a large volume of goods. Many countries have a fleet of merchant ships for transporting goods including general cargo, dry bulk carrier, oil tanker, Ro-Ro, container ship, passenger ship, reefer ship, hopper barge, etc. Today, almost 90% of world trade is conducted by merchant ships. The length of these ships is up to 500 meters and the amount of cargo carried by them is up to 4000 tons or a maximum of 18000 containers (Mofor et al., 2014).

A coastline of about 3000 km, access to the sea in the north and south of Iran, access to the open waters of the Indian Ocean, location on the route of north-south transit corridors, and the connector of Central Asian countries with southern waters are among the potentials of Iran in the maritime field. To take advantage of this potential in the country, Iran Shipping Company has 130 merchant ships with a capacity of 4.9 million DWT, which can be used to carry more than 22 million tons by using 6000 naval personnel and 1000 onshore personnel (Shipping of the Islamic Republic of Iran, 2017).

Despite the many advantages of merchant ships in maritime transport, making global trade impossible, such ships often cause many problems for the climate by burning fossil fuels and emitting destructive environmental pollutants. Some studies indicated that a large cargo ship produces polluting gases in one year, equivalent to 50 million vehicles, which can lead to allergic diseases and increased risk of cancer. The amount of sulfur in the fuel used by cargo and passenger ships is two thousand times the amount of sulfur in the fuel of light and heavy vehicles. This comparison is enough to introduce ships as the biggest culprits of air pollution (IRENA, 2019).

The International Maritime Organization (IMO), as the specialized agency of the United Nations and the provider of international shipping regulations in all areas, plays a key role in reassuring the international community about ship pollution control. In the late 1980s, the IMO began working in the field of reducing air pollution by ships, leading to the ratification of the MARPOL: Maritime pollution and its enactment in 2005. Since then, ship owners have been looking for ways to reduce fuel consumption due to the increasing importance of pollutant emissions in the maritime transport industry, stricter IMO regulations, and the high cost of fuel for ships because it reduces the emission of pollutants into the air and saves costs by reducing fuel consumption (Power, 2018).

This issue was ignored before 2000 because the place of ship pollutant emission was located far from residential areas. However, the studies by Schwartz (1989) indicated that the average displacement rate of nitrogen and sulfur oxides is about 400 km per day. By considering the survival of these gases for one to three days, these pollutants can reveal their destructive consequences on average 400-1200 km away from the place of emission (Schwartz, 1989). However, other studies indicated that about 70% of the emissions of international ships show their harmful effects up to 400 km distance (Corbett et al., 1999; Endresen et al., 2003).

Solar Silver's research on merchant ships equipped with a photovoltaic system indicated that fuel consumption and emissions can be reduced by an average of 8-10% using the existing technologies. In a sample made by this company called 76 Pax Tourism, fuel consumption, and emissions were reduced by up to 48% (equivalent to a reduction of 1247 tons of carbon dioxide and 474000 liters of oil and gas per year) (Mofor et al., 2014).

In this study, the idea of using a new marine propulsion technology based on solar energy was considered to reduce fuel consumption and reduce emissions. In this regard, implementing various solar-electric technologies on merchant ships in Iran was studied from a financial (from the perspective of the private sector) and economical (from the perspective of the public sector) perspective.

2. Literature Review

Solar energy is a critical renewable resource that is easily accessible in many parts of the world and has a favorable life cycle cost with extensive advances in its specific technologies. There are 300 sunny days in Iran annually in 90% of the regions and 5.5 kWh of solar energy per square meter shines every day. The total solar energy shining on Iran is 3.5×12^{11} kWh per day. In other words, if only 1% of the area in the sun is covered with a 10% efficiency, 9000 GWh of energy can be received from the sun every day. This amount of energy is about 2000 times the final energy demand of the entire country. Energy experts claim that if the desert area of Iran is equipped with radiant energy receiving systems, not only will the energy needs of the entire country be met, but also Iran can become one of the major exporters of electricity. The studies of DLR indicated that more than 60000 MW of solar thermal power plants can be installed in an area of more than 2000 square kilometers. If an area equal to 100 × 100 square kilometers is allocated to the construction of a photovoltaic power plant, its electricity production will equal the total electricity production of the country.

Solar energy can be obtained from different methods and systems including solar chemical, solar thermal, and solar electrical. In the solar electrical method, some converters are used to convert solar energy into electricity and supply the power required for spacecraft, moons, telecommunications, and other electrical devices on Earth. In the systems based on solar electrical, solar energy is converted into electrical energy without using dynamic and chemical mechanisms, and operating based on the photovoltaic phenomenon. Photovoltaic effect means the production of voltage or its corresponding electric current in a material due to exposure to light. The term photovoltaic is a combination of the Greek word photo meaning light and volt meaning generating electricity from light. The discovery of the photovoltaic phenomenon is attributed to the French physicist Alexandre Edmond Becquerel (1820-1891), who published an article in 1839, presenting his experiments in the field of wet cells. Becquerel observed that the cell voltage increases when its silver panels are exposed to sunlight. The main element of photovoltaic technology is solar cells. Fig. 1 shows the structure of a solar cell.

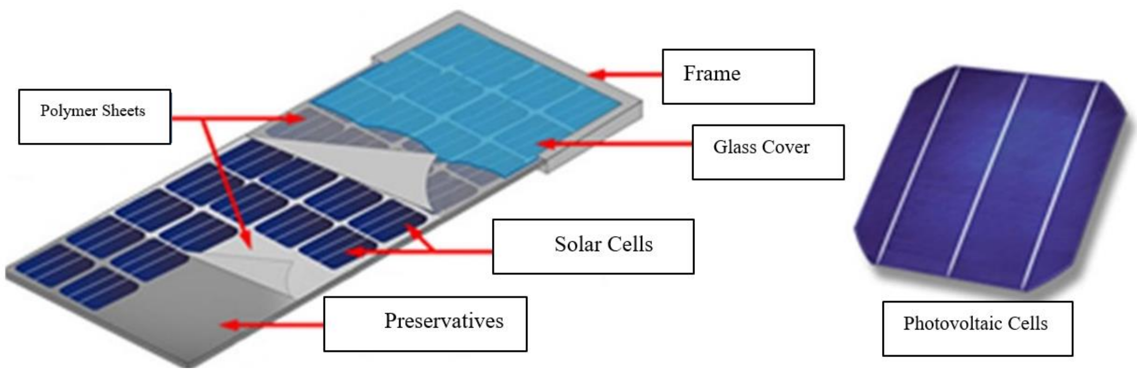

Figure 1. Solar Cell Structure
Source: Energy Research Institute, 2015.

Photovoltaic cells generate electricity by irradiating the sun with a difference in electrical pressure across the semiconductor. Since photovoltaic cells are small and fragile and generate only a small amount of electricity, they are formed as modules. Modules are available in a variety of sizes, but they rarely exceed 90 cm in width and 150 cm in length for ease of movement.
There are some studies on the economic feasibility of using solar energy in the deck of ships such as the study of Glaykz et al. (2010). In this study, the received energy is a function of the area of solar panels and the area of Earth in which the watercraft travels. Then, the amount of fuel consumption savings was calculated for each of the six regions of Earth which were divided according to the amount of energy based on

NASA studies. Assuming the global price of solar panels and inverter systems, the results for different parts of Earth showed that implementing a photovoltaic hybrid propulsion system is only economically justified near the equator and the return on investment will take approximately 20 years (Glaykz et al., 2010). In addition, Qiu et al. (2019) analyzed the implementation of the photovoltaic system on the Cosco ship, used the economic indicators of net present value, internal rate of return, payback period, and energy equivalent cost, and indicated that the use of this system, in addition to environmental benefits, has an economic justification for ship fuel consumption.

In Peng et al. (2019), the feasibility of applying solar energy and wind energy to ships was analyzed, and the structural composition of the ship power system incorporating renewable energy sources was studied. In this study, a simulation experiment is provided to prove the access of the battery can well suppress the grid-connected power fluctuation caused by the rolling of the ship, which has an important impact on the stability of the ship power system with renewable energy. Also, in the study of Karatuğ and Durmuşoğlu (2020), a novel approach is demonstrated for the layout of solar arrays within a Ro-Ro type marine vessel navigated between Pendik/Turkey and Trieste/Italy in 2018, and the performance of the designed system is theoretically evaluated. According to the following methodology, 7.76% of energy efficiency is carried out and 7.38% of the fuel requirement of the stated vessel is met by the designed solar system. 0.312 tons of SOx, 3.942 tons of NOx, 232.393 tons of CO2, and 0.114 tons of PM are prevented from releasing to the atmosphere. Besides, the investment in the solar system is analyzed under three different economic indicators and is found to be economically profitable to implement on the ship.

Therefore, reviewing the literature indicated that no study, to the best of our knowledge, has been conducted on the feasibility of using solar energy in the propulsion of merchant ships in the Persian Gulf and the Sea of Oman. Therefore, this issue was considered as the objective of this study.

3. Methodological Framework

Investors and private owners of commercial watercraft, as well as merchant ships, will use solar energy and replace it with energy produced from fossil fuels in the ship when the investment is affordable due to the real market conditions, fuel prices, costs, and incomes. Otherwise, they will continue the current procedure. Thus, examining the cost-benefit analysis of the watercraft with the system based on solar energy determines whether using such watercraft is economically justified from a private sector perspective. Is this policy feasible or does it require government support and subsidies? For this purpose, this section presents the foundations and assumptions of calculating financial evaluation indicators.

3.1 Average Solar Energy Received by Photovoltaic Panels

The average solar energy received by photovoltaic panels in a certain period depends on solar radiation density, efficiency refractive due to heat and environmental pollution, efficiency, and area of photovoltaic panels and is calculated based on Equation 1 (Glaykz et al., 2010):

$$E(\pi, \sigma_\theta, \sigma_\rho, S, n) = \pi \times \sigma_\theta \times \sigma_\rho \times S \times n \quad (1)$$

where E represents the average solar energy received by photovoltaic panels in a certain period (e.g. hour, day, year, etc.) in kWh, π indicates solar radiation density in kWh per square meter in a year, σ_θ shows the efficiency refractive index due to ambient heat, σ_ρ refers to the efficiency refractive index of photovoltaic panels due to environmental pollution, S means the area of photovoltaic panels in square meters, and n is considered as the efficiency of photovoltaic panels in percentage.

Solar radiation density (π) is the average solar energy received over some time (e.g. day, month, year, etc.) at a surface area of one square meter, which is a function of latitude and seasons.

Latitude is the most determining factor in calculating the density of solar radiation. In general, the closer the geographical point to the equator, the more the value of π. The effect of seasons on the amount of solar radiation density indicates that the density of solar radiation during spring and summer is higher than in autumn and winter (Rezaei-Latifi and Hosseinibalam, 2015).

NASA studies from 1983 to 2005 aimed at estimating the density of solar radiation for different parts of Earth, which indicated that the area of Earth could be approximately divided into six regions based on the density of solar radiation as shown in Table 1 (Stackhouse, 2012).

Table 1. Average Values of Solar Radiation Density Based on Latitudes

Areas (i)	(degree)Latitude	The amount of solar radiation (kWh/m^{2}day)density
1	0 – 29 northern	5.610
2	30 – 59 northern	3.720
3	60 – 89 northern	2.339
1-	1- 29 southern	5.703
2-	30 – 59 southern	3.646
3-	60 -90 southern	2.739

Source: Stackhouse and Whitlock (2012).

Based on the values in Table 1, the amount of solar radiation density in each of the divided areas of Earth can be calculated based on Equation (2).

$$\pi_{Zone-i} = c({}^{kWh}/_{m^2 day}) \quad (2)$$

where the index i is the same areas specified in Table 1.

3.2 Saving Fuel Consumption for a Solar Ship

Diesel engines in large watercraft emit high-sulfur fuels, and consequently carbon dioxide (CO2), sulfur dioxide (SO2), nitrogen oxides (NOx), methane (CH4), ozone (O3), and particulate matter (PM). The results of previous studies indicated that the emission factor of the number of particulates in ships is about 10 factors more than diesel engines equipped with particulate matter, while it is about 2 factors than diesel engines without particulate matter, and it is about 60 factors more than old gasoline (Lamas and Rodríguez, 2012; Jonson et al., 2011).

Saving fuel consumption is the most tangible economic benefit that can be considered for a solar ship. Small and large merchant ships typically use oil, gas, and fuel oil for supplying propulsion. Based on the thermodynamics laws, the combustion of a certain volume of fuel including oil, gas, and kerosene, in a diesel generator produces a certain amount of energy, the values of which are presented separately according to the type of fuel in Equations 3 and 4 (Hill et al., 2012).

$$1\ liter\ Fuel\ oil = 11.86\ kWh \quad (3)$$

$$1\ liter\ Gas/Diesel\ oil = 10.88\ kWh \quad (4)$$

The above equations indicated that 11.86 and 10.88 kWh of electricity, or in other words, for each kWh of electricity is generated per the combustion of one-liter fuel oil and gas oil in a diesel generator, respectively. 0.084 and 0.092 liters of fuel oil and gas oil can be saved per 1 kWh of electrical energy from alternative resources such as solar energy. In this way, the fuel conversion factor for fuel oil and gas oil can be represented in Equations 5 and 6.

$$coversion\ factor_{Fuel\ oil} = 0.084\ {}^{liter}/_{kWh} \tag{5}$$

$$coversion\ factor_{Gas\ oil} = 0.092\ {}^{liter}/_{kWh} \tag{6}$$

It is now possible to obtain the annual fuel savings of a solar ship based on the type of fuel according to Equation 7.

$$Fuel\ saving(liter)_j = E(S,n) \times Conversion\ factor_j$$
$$\begin{cases} Marine\ Fuel\ oil & ;\ j = 1 \\ Marine\ Gas/Diesel\ oil & ;\ j = 2 \end{cases} \tag{7}$$

where j represents the fuel type, and fuel saving indicates the amount of fuel consumption in liters. If saving the fuel consumption for a solar ship is in Rial, the relevant fuel price should be estimated over plant life.

For this purpose, the prices of the coming years can be predicted according to the prices of the previous years. If the average annual fuel price increase of type j (X_j: Fuel price increase j) is estimated by regression models, the cost of fuel saved per year can be calculated based on Equation 8.

$$Fuel\ Saving(Rial)_{j,t} = E(S,n) \times Conversion\ factor_j \times Fuel\ price_{j,t=0} \times (1 + X_j)^t \tag{8}$$

$t: 0, 1, 2, 3, \dots, PL$

where the index t represents the year. For example, $Fuel\ price_{j,t=0}$ represents the fuel price of type j in the base year (t = 0).

The total cost savings in fuel consumption of a solar ship from the year of exploitation to the year of PL are calculated according to Eq. 9 without considering the time value of money.

$$Total\ fuel\ saving(Rial)_j = \sum_{t=1}^{PL} Fuel\ saving_{j,t}$$
$$= E(S,n) \times Conversion\ factor_j \times Fuel\ price_{j,t=0} \times (\sum_{t=1}^{PL} (1 + X_j(\%))^t) \tag{9}$$

Although only the benefit of saving fuel consumption is considered in the financial evaluation of a solar ship, the benefits of saving fuel consumption along with saving in the emission of pollutants are considered in the economic evaluation of this project.

A certain amount of emissions of each type of pollutant is saved according to Equation 10 per one kWh of solar-electric energy supplied to the diesel generator in a ship.

$$Emission\ saving(gram)_{j,k} = E(S,n) \times Emission\ factor_{j,k} \quad (10)$$

where the index k indicates the type of pollutant emitted by the combustion of type j fuel (e.g. carbon dioxide, nitrogen oxides, etc.). $Emissionfactor_{j,k}$ shows the emission index of pollutant k for fuel j, which is in gram / kWh. This index indicates that a few grams of pollutant K will be emitted if one kWh of electricity with fuel j is generated in the generator.

If saving the pollutants emission is based on Rial value, Equation 11 can be used for calculating the emission savings.

$$Emission\ saving(Rial)_j = E(S,n) \times \sum_{k=1}^{K} (Emission\ factor_{j,k} \times VED_k) \quad (11)$$

where VED_k represents the value of environmental damage of the k^{th} pollutant imposed on society.

3.3 Cost of Setting up a Photovoltaic System

The cost of investing in a photovoltaic system installed on the upper deck of a ship is a function of the power of the photovoltaic system (P). In other words, as the power of the installed system is greater, more costs should be spent on its implementation. The power of a photovoltaic system based on Equation 12 is the amount of electrical-solar energy generated per hour, which is a function of the area and efficiency of photovoltaic panels.

$$P(S,n)(kW) = \frac{E(S,n)(kWh)}{Time(Hour)} = \frac{\overline{\pi\left(\frac{kWh}{m^2 year}\right)} \times \overline{\sigma_\theta} \times \overline{\sigma_\rho} \times S(m^2) \times n}{8765\ hours/year} \quad (12)$$

By calculating the system power, the investment cost ($C_{Invetment}$) is calculated according to Equation 13.

$$C_{investment}(Rial) = P(S,n)(kW) \times C_{capital\ cost-per-\ kW}(\$/\mathrm{kW}) \times \left(\frac{Rial}{\$}\right) \quad (13)$$

3.4 Calculating the Net Present Value of the Project

The benefits of the project "setting up a photovoltaic system on the deck of merchant ships to supply propulsion" include fuel savings (B1) and reduction of pollutants emission (B2) and its costs include investment costs (C).

The net present benefit (NPB) is presented in the following equation by considering the time value of money for Equations 14 and 15.

$$NPB_j = E(S,n) \times \left[Conversion\ factor_j \times Fuel\ price_{j,t=0} \times \sum_{t=1}^{PL} \left(\frac{1+X_j}{1+r}\right)^t + \sum_{k=1}^{K} (Emission\ factor_{j,k} \times VED_k) \times \left(\frac{(1+r)^{PL}-1}{r(1+r)^{PL}}\right) \right] \tag{14}$$

Equation 14 is the present value of fuel and emission savings for the solar ships with j-type fossil fuel, where r represents the discount rate for adjusting the time value of revenues. In the financial evaluation, only the benefits of fuel savings are considered while the economic evaluation considers both the benefits of fuel savings and emission reduction.

Similarly, the net present cost (NPCs) is presented as follows based on Equation 6.

$$NPC = P(S,n) \times C_{capital\ cost-per-\ kW} \times (Rial\_Dollar\ ratio) \tag{15}$$

Since the net present value (NPV) is the difference between the net present benefits (NPB) and the net present cost (NPC), this economic index can be obtained according to Equations 14 and 15 as follows.

$$NPV_j = \bar{\pi} \times \overline{\sigma_\theta} \times \overline{\sigma_\rho} \times S \times n \times \left[Conversion\ factor_j \times Fuel\ price_{j,t=0} \times \sum_{t=1}^{PL} \left(\frac{1+X_j}{1+r}\right)^t + \sum_{k=1}^{K} (Emission\ factor_{j,k} \times VED_k) \times \left(\frac{(1+r)^{PL}-1}{r(1+r)^{PL}}\right) - \frac{C_{capital\ cost} \times (\frac{\text{Rial}}{\$})}{8765} \right] \tag{16}$$

Equation 16 indicates that the size and symbol of the net present value (NPV) are a function of 13 main parameters described in Table 2. Among the above-mentioned parameters, some affect the net present value index (NPV). In other words, they cause net present value or non-acceptance of the project while some others only affect the size of the index.

Table 2. Classification of Parameters Affecting Net Present Value Based on the Effect on NPV

Parameter	symbol	Unit	Effect on NPV economic index		
			symbol	value	Type of relationship
Solar radiation density	$\boldsymbol{\pi}$	$kWh/m^2 year$	×	✓	direct*
Refractive index due to heat	$\boldsymbol{\sigma_\theta}$	-	×	✓	direct
Refractive index due to pollution	$\boldsymbol{\sigma_\rho}$	-	×	✓	direct

Area of photovoltaic panels	S	m^2	×	✓	direct
Efficiency of photovoltaic panels	n	%	×	✓	direct
Type of fossil fuel	J	-	✓	✓	-
Fuel price in the base year	Fuel price $_{t=0}$	Rial	✓	✓	direct
Percentage of increase in fuel prices	X	%	✓	✓	direct
Discount rate	r	%	✓	✓	indirect□
Life cycle	PL	Year	✓	✓	direct
Social cost of pollutants	VED	Rial/gram	✓	✓	direct
Implementation cost	$C_{capital\ cost}$	$/kW	✓	✓	indirect
Dollar price	IRR per $	-	depends*		depends*

Source: Research finding.

Based on Equation 7, the project is economically justified when the NPV is higher than or equal to zero, while the project is not be accepted when the NPV is negative.

3.5 Other Indicators of Economic Evaluation

- The NPV/I index indicates how many units of net present value are earned per unit of investment (one Rial or one dollar). If the value of this index is more than or equal to zero, the project has a net present value, while the project is not accepted if it is negative.
- The internal rate of return is the discount rate at which the net present value of the project becomes zero. Based on Equation 17, if the internal rate of return is more than or equal to the discount rate r, the project is economically justified, while the project is not accepted when it is less than the discount rate.

$$NPV(r) = 0 \ \gg\gg\gg \ IRR = \bar{r}$$
$$\begin{cases} Rejection, \bar{r} < r \\ Acception, \bar{r} \geq r \end{cases} \tag{17}$$

Net Annual worth (NAW) is the difference between the equivalent uniform annual benefit (EUAB) and the equivalent uniform annual cost (EUAC). For this purpose, the present value of benefits and costs is converted to equivalent benefits and costs over the plant life using the levelization factor (LF) according to Equation 18.

$$NAW = EUAB - EUAC = (NPB - NPC) \times LF = NPV \times LF$$
$$LF = \frac{r(1+r)^{PL}}{(1+r)^{PL} - 1} \tag{18}$$
$$\begin{cases} Rejection, NAW < 0 \\ Acception, NAW \geq 0 \end{cases}$$

- Benefit to cost ratio (BCR) indicates how much revenue is earned per one unit of cost in a project. Based on Equation 19, if this ratio is more than or equal to one, the project benefits will be more than its costs and the project will be economically justified while if it is less than one, the project will not be accepted.

$$\mathrm{BCR} = \frac{\mathrm{EUAB}}{\mathrm{EUAC}} = \frac{\mathrm{NPB}}{\mathrm{NPC}} \tag{19}$$
$$\begin{cases} \mathrm{Rejection, BCR} < 1 \\ \mathrm{Acception, BCR} \geq 1 \end{cases}$$

- Discounted payback period (DPB) is the time it takes for the net cumulative cash flows of a project to be zero. In other words, it is the period that the project costs are returned to investors as calculated according to Equation 20.

$$\mathrm{Investment} = \sum_{t=1}^{T} B_t \ \ggg\ggg \ \mathrm{DPB} = \overline{\mathrm{T}} \tag{20}$$

This indicator does not determine the economic justification or non-acceptance of the project, but it helps investors to determine the attractiveness of the project. Obviously, a project with a shorter payback period is more attractive than a project with a longer payback period.

In calculating the DPB index, the time value of money is not considered, and cash flows are added by assuming the same value in different years. Since considering the time value of money adds to the accuracy of calculations, the dynamic discount payback period (DDPB) index was defined instead of the DPB to solve this problem. Based on Equation 21, cash flows are added together after discounting.

$$\mathrm{Investment} = \sum_{t=1}^{T} \frac{\mathrm{Fuel\ saving}_t + \mathrm{Emission\ saving}_t}{(1+r)^t} \ \ggg\ggg \ \mathrm{DDPB} = \overline{\mathrm{T}} \tag{21}$$
$$\begin{cases} \mathrm{Acception}, \overline{\mathrm{T}} \leq \mathrm{PL} \\ \mathrm{Rejection}, \overline{\mathrm{T}} > \mathrm{PL} \end{cases}$$

In the above equation, the project will be economically justified if the DDPB is less than project life cycle (PL).

- The levelized cost of energy (LCOE) represents the levelized cost of the project for the production of one unit of energy (one kWh) and is calculated according to Equation 22.

$$\mathrm{LCOE}\left(\frac{\mathrm{Rial}}{\mathrm{kWh}}\right)=\frac{\mathrm{EUAC(Rial)}}{\mathrm{E(kWh)}}=\frac{\mathrm{NPC}\times\mathrm{LF}}{\mathrm{E}} \tag{22}$$

where E represents the solar-electric energy generated by the photovoltaic panels installed on the deck of the ship as indicated in Equation (1). Among the several photovoltaic technologies which can be installed on the deck of a ship, the technology with the lowest energy equivalent cost is an economic priority. However, this comparison is acceptable provided that the net present value of the projects is positive (Qiu et al., 2019).

3.6 Studied Scenarios and Options

This study investigated three common technologies of photovoltaic panels called wafer-based silicon, thin film, and Multi-junction, which are commercially available in Iran. Table 3 indicates the efficiency and cost of investment in such technologies (Energy Research Institute, 2015; Gorter, 2014).

Table 3. Investment Cost and Efficiency of Common Commercial Photovoltaic Technologies in Iran

photovoltaic technology	Symbol (technology code)	Initial investment (dollar/kW)cost	Module efficiency (Percentage)	Life cycle (year)
Wafer-based silicon	PV1	4000	14	30
Thin film	PV2	3000	7	30
Multi-junction	PV3	6000	250	30

Source: Energy Research Institute (2015), Layeghi (2015), and Gorter (2014).

From the perspective of the private sector (ship owners), the subsidized price of available fuel can be examined in the form of two types of fuel. In this study, the following scenarios were considered.

A. Scenario 1 in terms of fuel oil price

B. Scenario 2 in terms of gas oil price

From the social sector perspective, the cost of environmental pollutants damage and the FOB price of fuel used by ships in the Persian Gulf are considered, as examined in the form of two scenarios:

1- Scenario 1; Analyzing the FOB in the Persian Gulf for fuel oil price with environmental considerations (Emission reduction)
2- Scenario 2; Analyzing the FOB in the Persian Gulf for Gas oil price with environmental considerations (Emission reduction).

3.7 Data Collection

The data used in this study according to Table 4 were extracted from similar studies or by field study method:

Table 4. Description of Data and Their Estimation Method

Required data	**Symbol**	**Parameter value or its estimation method**
Solar radiation density in the Persian Gulf and the Sea of Oman	π	6.02 $kWh/m^2 day$
Refraction of photovoltaic panels due to heat	σ_θ	0.9 without unit
Refraction of photovoltaic panels due to dirt	σ_ρ	0.93 without unit
Area of photovoltaic panels on the deck of the ship	S	500-10000 m^2 Depending on the size of the dimensions Merchant ships of Iran
Efficiency of photovoltaic panels	n	Based on Table 3
Subsidized and FOB prices of fuel oil in the Persian Gulf	Fuel oil price	Regression estimation (dollars per liter)
The social cost of pollutant emission	VED	By pollutants Cent/gr
Emission factor of fuel oil	EF	By pollutants gr/kWh
Investment cost (panels, inverters and cells)	I	Based on the technology type of photovoltaic panels ($/WP)
Plant life	PL	30 years
Economic (social) discount rate	r	15%
Financial discount rate	r	25%
Salvage value of equipment	SV	Assumed as zero
operational and maintenance costs in photovoltaic panels	C_k	0.0001 Cent/kWh
Increased operational and maintenance costs	$O\&M - cost - increase$	2%
Dollar rate	IRR/$	110000 Rials

Source: Kagaraki, 2001; Rezaei and Hosseini, 2015; Layeghi, 2015; Shipping of the Islamic Republic of Iran, 2017; Endresen et al., 2003; Ministry of Energy (1986-2016); Meteorological Organization of Iran, 2019; Organization of Renewable Energy and Electricity Productivity, 2018 (Photovoltaic).

To facilitate cost-benefit calculations and determine the economic range of each parameter, macro writing in Microsoft Excel software was used and the base year and basis of economic evaluation based on the latest reports and available resources from relevant institutions (Maritime and Ports Organization, Shipping Organization, Marine Industries Organization, Central Bank, etc.) were considered in 2019.

4. Data Analysis and Results

4.1 Energy Received by Photovoltaic Panels Installed on the Deck of Merchant Ships

After determining the area of "the Persian Gulf and Sea of Oman" as the spatial scope, the average density of solar radiation (π) in kWh per square meter each year ($kWh/m^2 year$), data were received from the World Atlas of solar energy. According to Equation 1, the energy received by photovoltaic panels installed on merchant ships can be used according to the type of used technology and the available area of the sun deck (in the range of 500-10000 square meters) in terms of kWh per day as shown in Figure2.

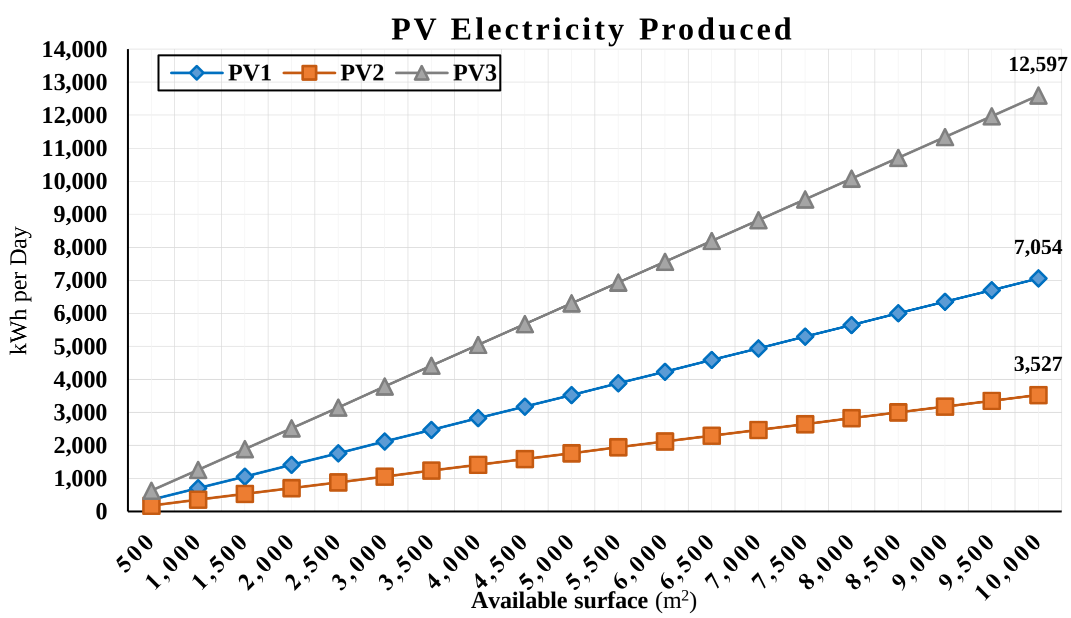

Figure 2. Energy Received by Photovoltaic Panels Installed on Merchant Ships by Technology

Source: Research finding.

The amount of extracted energy increases over a specified period (E) when the efficiency in technology is more and the available area of the sun deck is wider. Based on Equations 12 and 13, increasing the area of photovoltaic panels (S) and improving the efficiency in used technologies (n) do not necessarily mean the net present value of the project. When the efficiency and area increase, the installed power increases the produced energy, and consequently the cost of initial investment ($C_{Investment}$).

4.2 Investment Cost by Technology Type

In the zero year of the project, the investment cost ($C_{Investment}$) is conducted for installing and implementing the photovoltaic propulsion system, and no benefit is obtained from saving fuel consumption and emitting pollutants during the construction life.

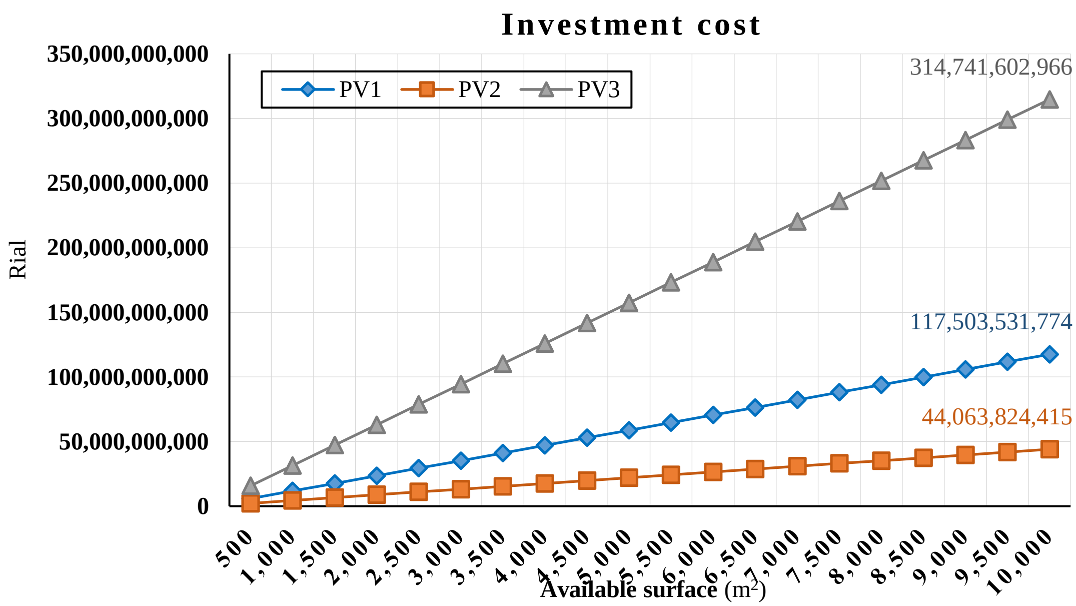

Figure 3. Investment Cost of Equipping a Merchant Ship with a Photovoltaic Propulsion System by Technology Type
Source: Research finding.

As shown in Figure 3, approximately 44-315 billion rials of investment is required depending on the type of used technology when 10000 square meters of a sun deck is equipped with a photovoltaic propulsion system.

4.3 Calculating the Amount of Fuel Savings

By calculating the energy received by the photovoltaic panels installed on the ship (E), the amount of fuel-saving can be calculated by the type of fuel and the type of technology, the results of which are for fuel oil and gas oil as presented in Figures 4 and 5, respectively.

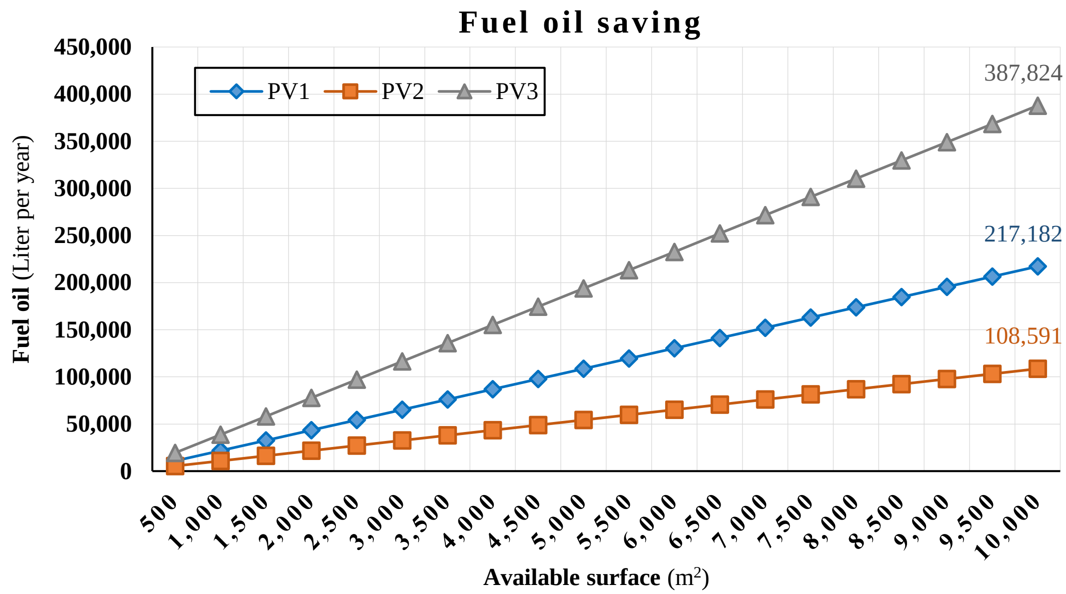

Figure 4. Saving the Amount of Fuel Oil for a Ship Equipped with Photovoltaic Propulsion by Technology Type

Source: Research finding.

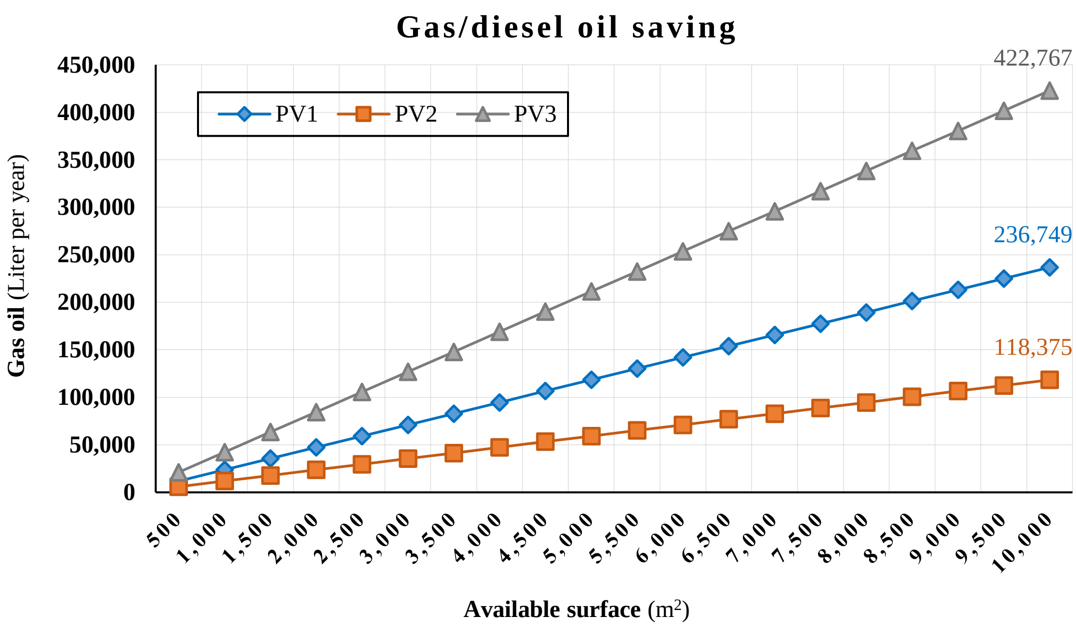

Figure 5. Saving the Amount of Gas Oil for a Ship Equipped with Photovoltaic Propulsion by Technology Type

Source: Research finding.

The results of Figures 4 and 5 indicate that merchant ships in the Persian Gulf and the Sea of Oman, equipped with solar-electric propulsion systems, can save 5430-422767 liters of fuel per year, the exact amount of which depends on the available deck space (S) and technology type (n).

A large merchant ship consumes approximately 7000 tons of fuel per year (Notteboom and Cariou, 2009). Thus, renewable solar energy can provide approximately 5.2% of the energy consumption of a merchant ship and consequently reduce emissions from fuel combustion by 5% (Table 5).

Table 5. The Share of Solar Energy in Energy Supply (Propulsion and Other Non-Propulsion Costs) of a Merchant Ship

Average annual fuel consumption of a merchant ship	7000 tons
Amount of savings in annual fuel consumption of a solar ship	366 tons
Amount of savings in the emission of pollutants	3253 tons
Average annual rial value of savings	78,837,712,696 Rials
Share of solar energy in the energy consumption of a merchant ship	5.2%

Source: Hill et al. (2012).

It is worth noting how the price of ship fuel changed to the subsidized and FOB values of the Persian Gulf during the last three decades, and what is expected from the price trend over the plant life is the basis for calculating the rial value of fuel economy savings so that a cash flow diagram can be drawn for each scenario.

Excel 2016 software was used for predicting fuel prices. Based on the regression estimates, the exponential functions in the form of Ae^{Bx} have the best adaptation to the previous prices and achieve a high degree of reliability in predicting the coming years. In other words, based on the form of the function $f(x)=Ae^{Bx}$, the average annual price increase equals $X(\%)= e^{B}-1$, which is used in Equation (9) for calculating the rial value of fuel consumption savings (Table 6).

Table 6. Ship Fuel Price Forecast by Fuel Type and Pricing Method

Average price increase (percentage)	Factor of safety (percentage)	Forecast function	Required data
7.7	78	$f(x) = 4.9\, e^{0.07\, x}$	FOB price of fuel oil
6.6	72	$f(x) = 9.2\, e^{0.06\, x}$	FOB price of gas oil

Source: Research finding.

4.4 Calculating the Amount of Reduction in Pollutants Emission

By calculating the energy received by the photovoltaic panels installed on the ship (E), the amount of emission saving can be obtained by the type of pollutant, type of fuel, and type of technology based on Equation 10, the results of which are used as sample for carbon dioxide (CO2) in Figure 6 and for a variety of pollutants such as carbon monoxide (CO), nitrogen oxides (NOx), particulate matter (PM), sulfur oxides (SOx) and unburned hydrocarbons (HC).

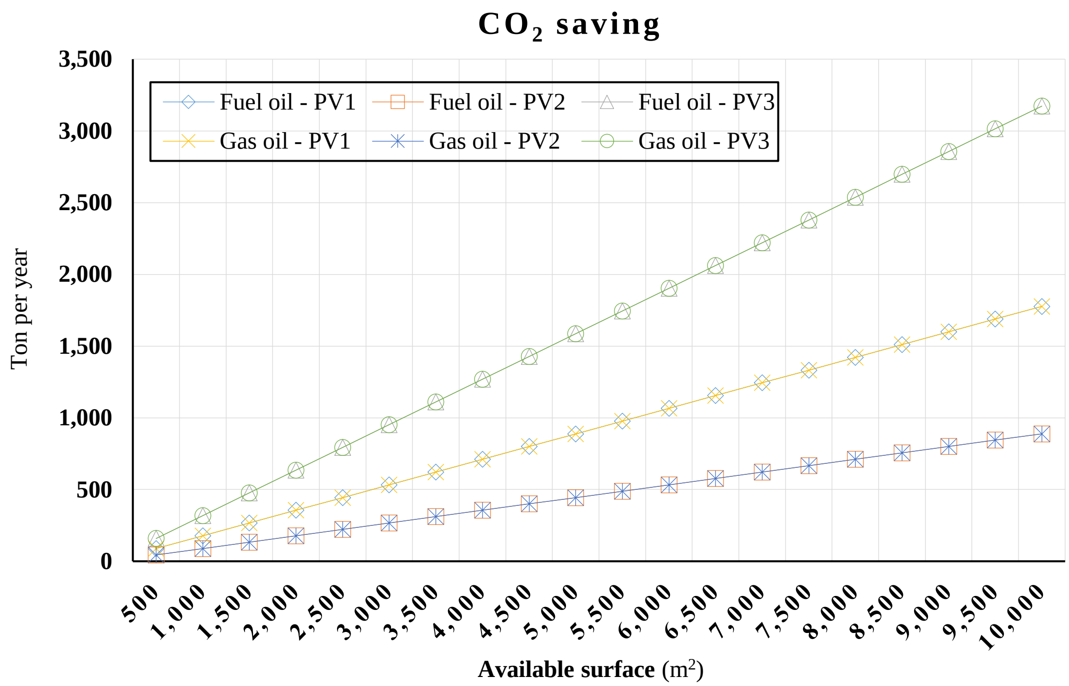

Figure 6. CO2 Emission Savings of a Ship Equipped with Photovoltaic Propulsion by Technology Type and Fuel Type

Source: Research finding.

4.5 Cost-benefit Analysis Results from a Private Sector Perspective

However, considering the cost-benefit perspective of the private sector that the benefits only include fuel economy savings, the main question raised is whether the amount of investment is cost-effective or not. The question can be answered by evaluating the cash flow of research scenarios based on the calculation of benefits and costs during the plant life.

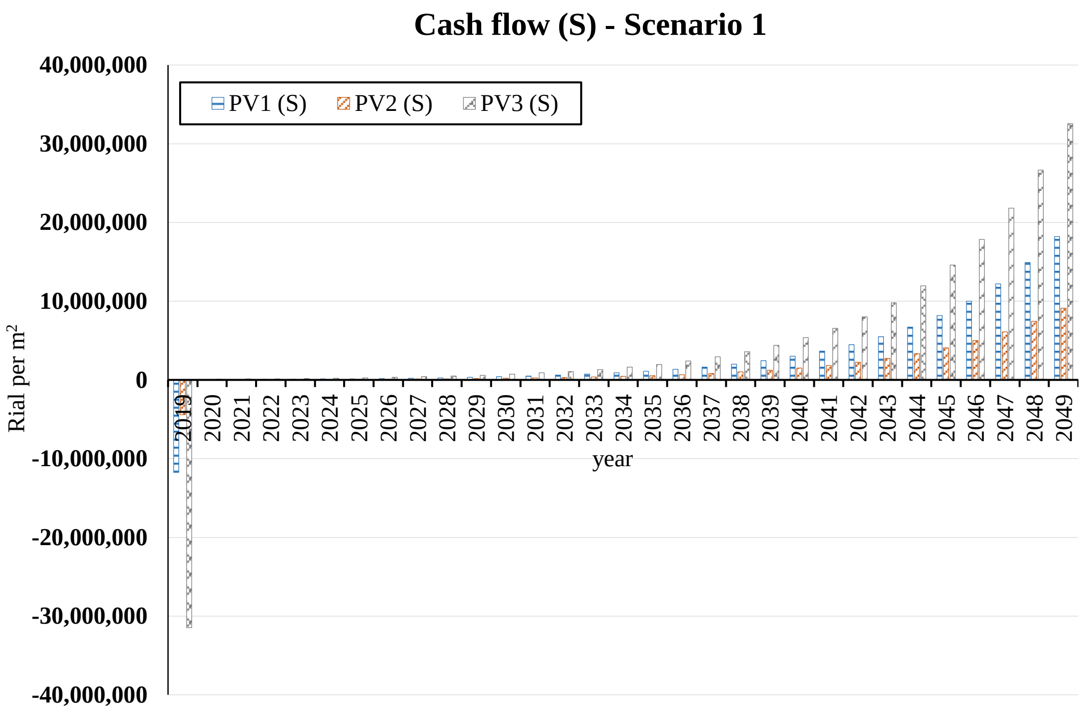

Figure 7. Cash Flow Diagram Of Scenario 1 (from the Perspective of the Private Sector for Merchant Ships with Oil Fuel)
Source: Research finding.

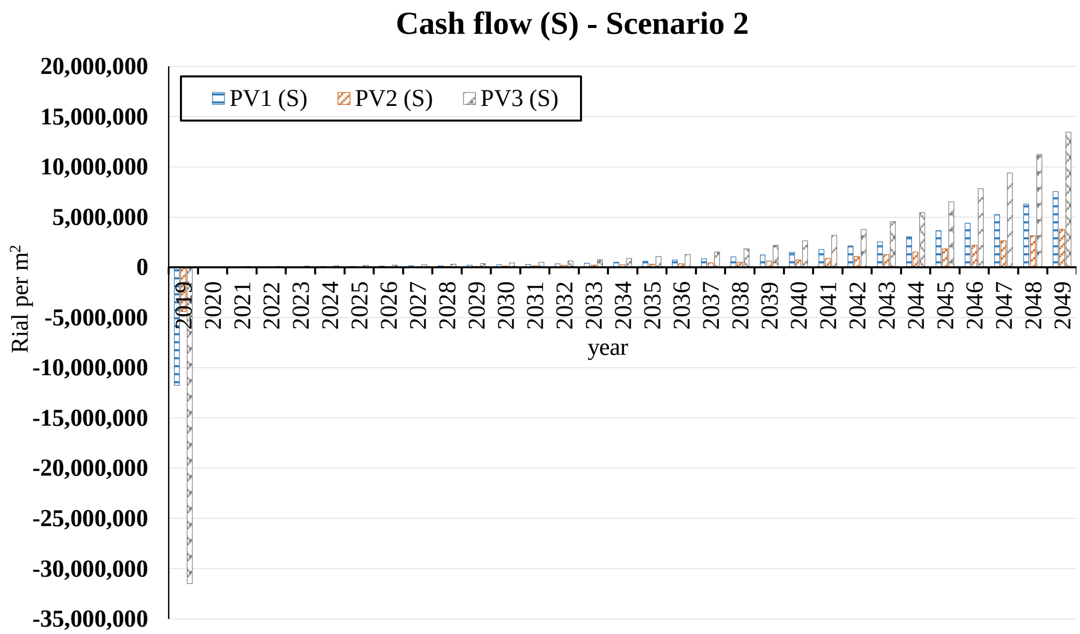

Figure 8. Cash Flow Diagram Of Scenario 2 (From the Perspective of the Private Sector for Merchant Ships with Gas Fuel)
Source: Research finding.

Figures 7 and 8 display the inflow and outflow of project liquidity over a limited period (plant life) that the positive and negative values of each year are the benefits and costs of the project in each option of the solar technology, respectively. Table 7 provides the results of financial evaluation indicators separately for the two scenarios of subsidized fuel and each option of the photovoltaic technology.

Table 7. Results of Financial Evaluation Indicators by Research Scenarios

status Acceptance	DDPB	DPB	LCOE	BCR	IRR	NPV/I	NPV(S)	NAW(S)	Scenarios / Indicator	
	year	year	Rial/kWh	-	%	-	Rial/m^2	Rial/m^2		
×	> 30	19.4	4841	0.19	9.2	-0.92	(10,789,083)	(1,005,853)	PV1	Scenario 1
×	> 30	18	1815	0.26	10.6	-0.89	(3,925,747)	(347,118)	PV2	
×	> 30	21.4	12967	0.13	7.3	-0.95	(29,757,606)	(2,909,085)	PV3	
×	> 30	22.6	4841	0.11	5.7	-0.95	(11,200,779)	(1,108,905)	PV1	Scenario 2
×	> 30	21.1	1815	0.15	7.1	-0.94	(4,131,595)	(398,644)	PV2	
×	> 30	24.8	12967	0.07	3.9	-0.97	(30,492,777)	(3,093,105)	PV3	

Source: Research finding.

As Table 7 indicates, equipping the deck of merchant ships with photovoltaic propulsion systems is not cost-effective from a private sector perspective. The results of the variables determining the attractiveness of the project such as cost-benefit ratio (BCR) and return on investment (DPB) represented that 0.26 units of profit is obtained for each unit of cost in the project from a private sector perspective and return on investment takes more than 18 years.
Considering the 25% discount rate in all options and scenarios, the internal rate of return is much lower than the discount rate and the net present value index is negative. Nevertheless, the least loss is related to the PV2 option in the first scenario.

4.6 Results of Cost-Benefit Analysis from the Social Perspective

In the following, a cash flow diagram of each scenario is provided based on calculating the benefits and costs from the social perspective during the plant life cycle, which is considered for each scenario separately in terms of technology and type of fuel in Figures 9 and 10.

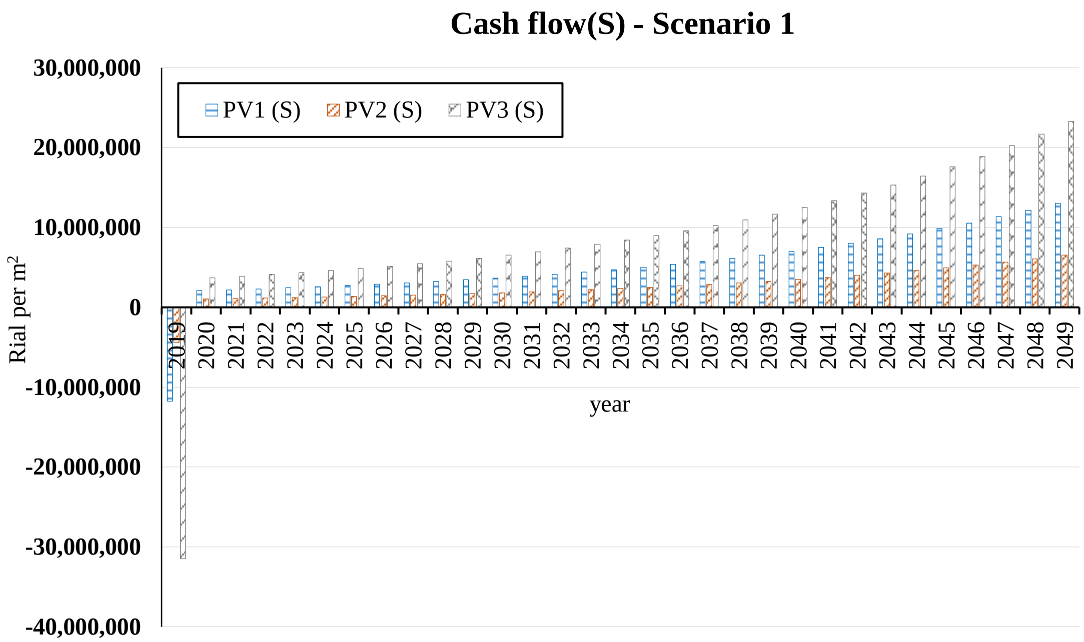

Figure 9. Cash Flow Diagram Of Scenario 1 (From a Social Perspective for a Merchant Ship with Oil Fuel)

Source: Research finding.

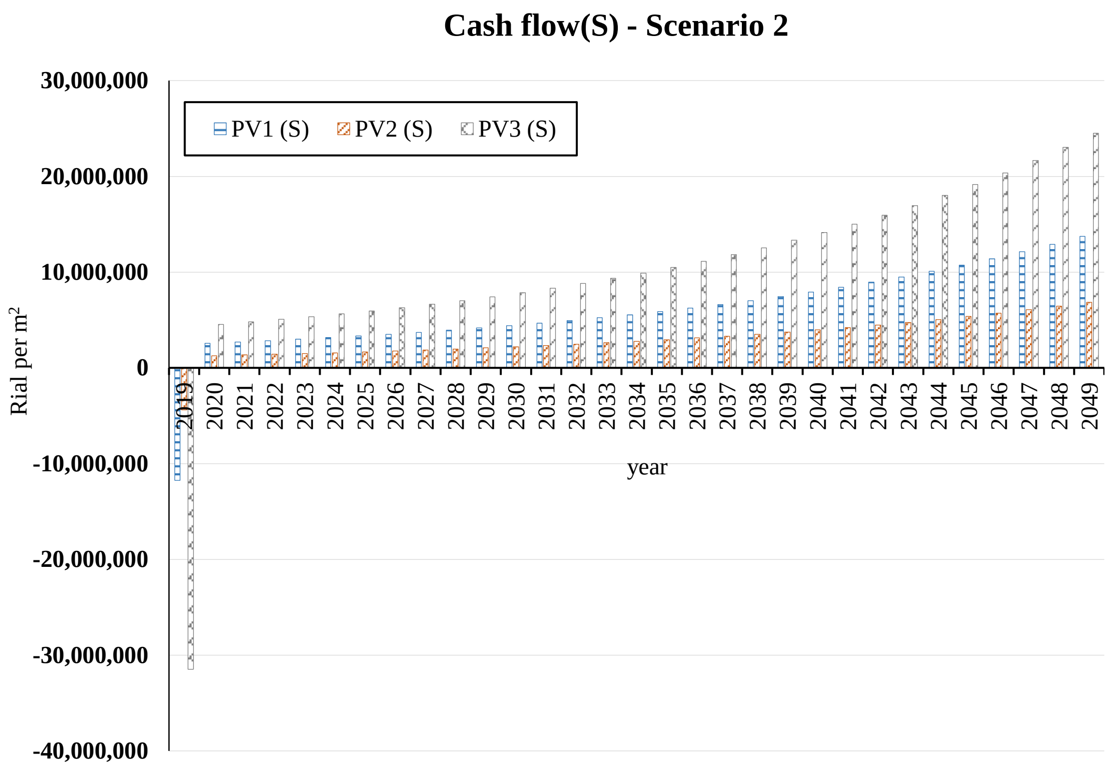

Figure 10. Cash Flow Diagram of Scenario 2 (From a Social Perspective for a Merchant Ship with Oil Gas)
Source: Research finding.

In addition, Table 8 presents the results of the main indicators for each scenario to determine the net present value of the technology.

Table 8. Results of Economic Evaluation Indicators by Research Scenarios

Acceptance status	BCR	NPV(S)	NPB(S)✦	NPB(S,n)★	NPB2(S,n)□	NPB1(S,n)*	Scenarios /Indicators	
	-	Rial/m^2	Rial/m^2	Rial/m^2	Rial/m^2	Rial/m^2		
✓	3.02	23,698,788	35,449,141	253,208,151	42,756,065	210,452,087	PV1	Scenario 1
✓	4.02	13,318,188	17,724,571	253,208,151	42,756,065	210,452,087	PV2	
✓	2.01	31,827,878	63,302,038	253,208,151	42,756,065	210,452,087	PV3	
✓	3.54	29,868,644	41,618,997	297,278,550	32,398,317	264,880,232	PV1	Scenario 2
✓	4.72	16,403,116	20,809,498	297,278,550	32,398,317	264,880,232	PV2	
✓	2.36	42,845,477	74,319,637	297,278,550	32,398,317	264,880,232	PV3	

Source: Research finding.

Notes: Net present benefit of fuel saving (a function of area and efficiency)

The net present benefit of emission savings (a function of area and efficiency)

★Net present benefit of fuel saving and emissions (a function of area and efficiency)

✦ Net present benefit of fuel and emission savings (a function of area)

As shown in Table 8, equipping the deck of merchant ships with a photovoltaic propulsion system is economically justified from the social perspective. The project generates approximately 2-4 units of benefits and the investment made returns at best within 2-3 years.

The results of Table 8 from the social perspective reveal that implementing a photovoltaic propulsion system on merchant ships that gas oil is more economical than the merchant ships that use fuel oil. The reason for this can be analyzed in the FOB price of gas oil for the coming years so that according to the proposed regression forecasts, the FOB price of gas oil is expected to be higher than the fuel oil in the coming years. It should be noted that according to the emission factor of each fuel (EF_j), the amount of pollutants produced by the production of one unit of energy (one kWh) of gas oil and fuel oil is almost the same.

4.7 Sensitivity Analysis of Financial Indicators to Justify the Project from the Private Sector Perspective

Due to the lack of net present value for using photovoltaic technology in the private sector and merchant ship owners, this section analyzes the sensitivity of the discount rate and fuel price to indicate that the photovoltaic project will be profitable for the private sector if the financing decreases and the price of fuel for electricity generation increases in the current situation. The discount rate is one of the sensitive parameters of the project, the slight changes of which have a great effect on the net present value and economic attractiveness of the project.

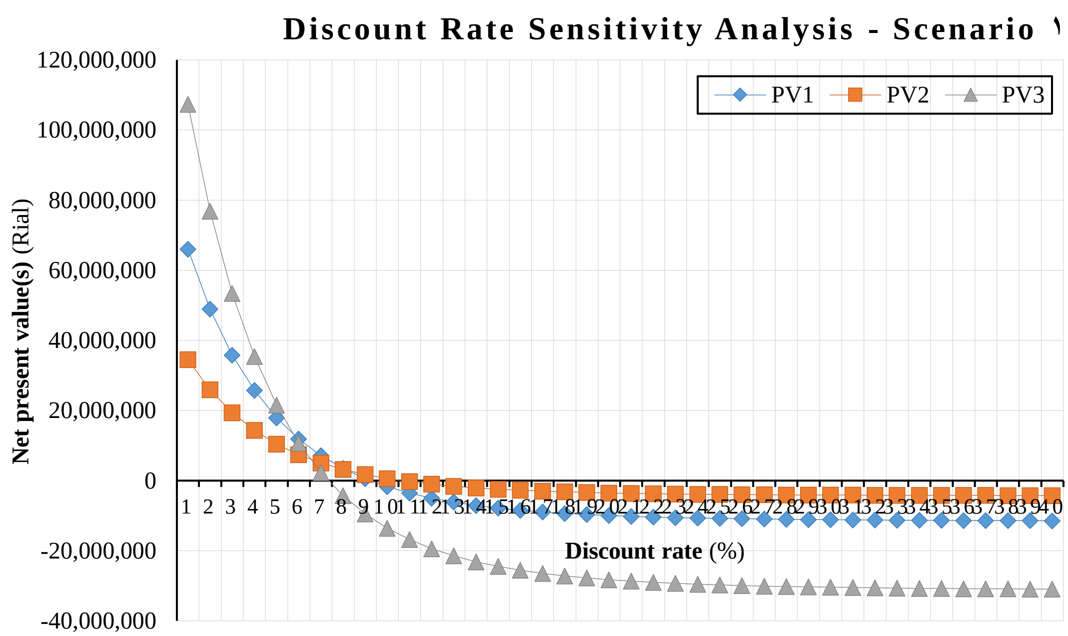

Figure 11. Sensitivity of the Project Net Present Value (NPV) To the Discount Rate Parameter for Scenario 1

Source: Research finding.

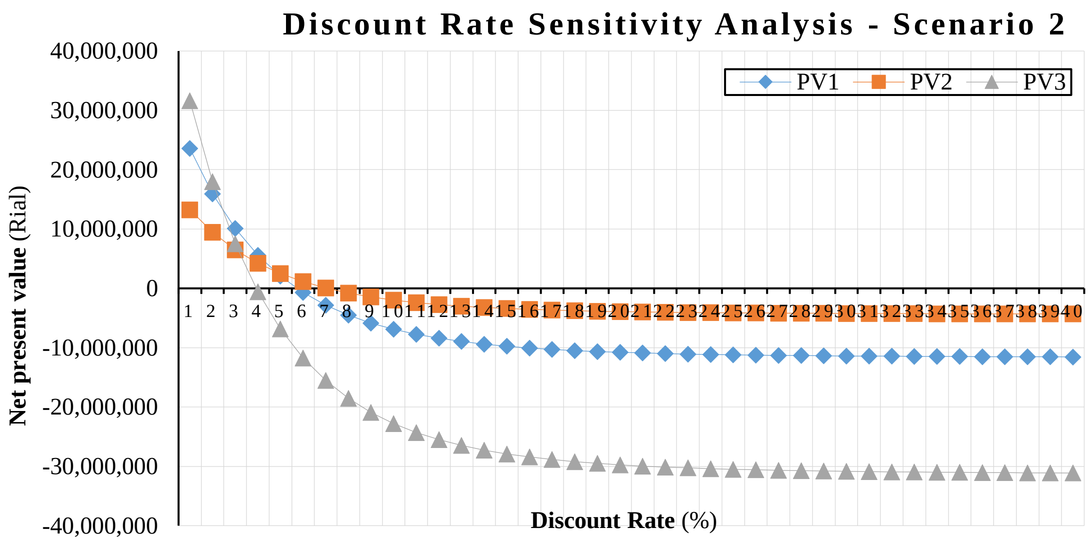

Figure 12. Sensitivity of the Net Present Value (NPV) To the Discount Rate for Scenario 2
Source: Research finding.

In this study, the discount rate from the private sector perspective is assumed to be 25% (r = 25%), but the sensitivity of economic indicators to the discount rate (r) indicates that implementing a photovoltaic propulsion system on merchant ships in southern Iran is cost-effective and economically attractive from a private sector perspective if the discount rate in Iran is less than 5% as in developed countries.
In this study, the average increase in subsidized prices for fuel oil and gas oil was estimated at 22.2 and 19.8%, respectively ($X_{\text{Fuel oil}}$ = 22.2% & $X_{\text{Gas oil}}$ = 19.8%).
Figure 13 presents the combined effect of these two sensitive parameters on the net present value of the project from the private sector perspective.

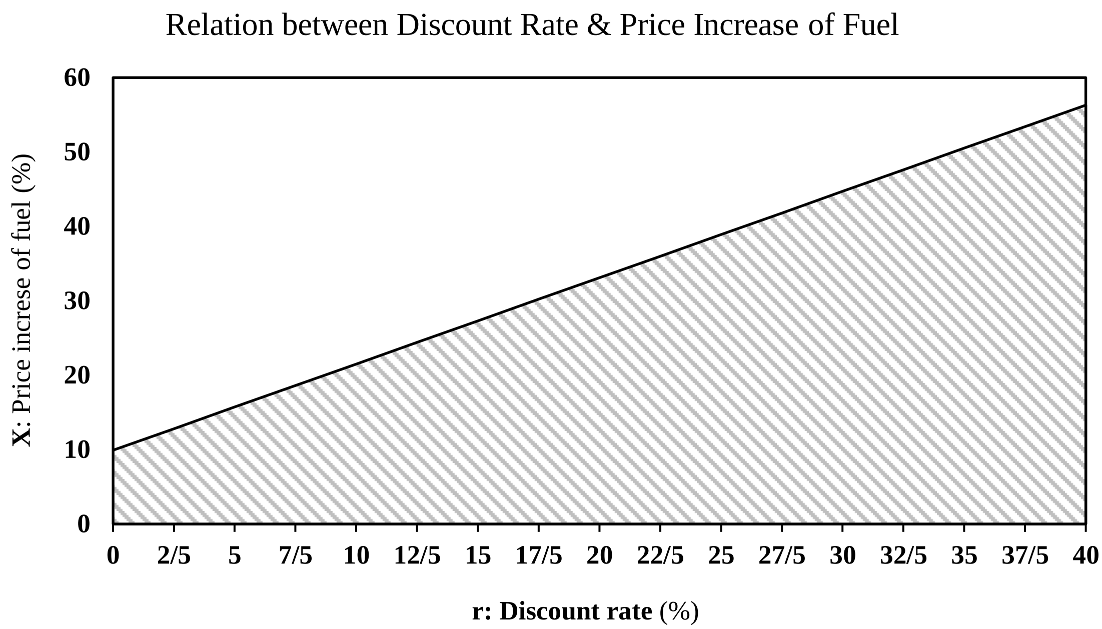

Figure 13. A Set of Values of the Discount Rate (R) and Average Fuel Price Increase (X), Making the Project Cost-effective from a Private Sector Perspective
Source: Research finding.

The relationship of the ordered pairs (X, r) according to which the project has a net present value from the private sector perspective is presented as Equation 23.

$$(X^{*} = x\,, r^{*} = r) \quad >>> \quad r \leq 0.86\,X - 8.49 \qquad (23)$$

where the unit of parameters X and r is in percentage, and X * and r * represent the ordered pairs for which the project is accepted from the private sector perspective.
From the macro-policy perspective in the field of energy, it can be stated that photovoltaic propulsion systems become more competitive than fossil fuel engines from the private sector perspective and the use of solar energy becomes prior to fossil fuels if the average growth of subsidized prices for fuel oil and gas oil reaches 20 - 40% or the price of fossil fuels moves towards liberalization policy with a slope twice the current situation (approaching the real prices in the global markets such as the FOB price in the Persian Gulf).
Implementing the photovoltaic propulsion project to supply the propulsion of merchant ships in southern Iran becomes affordable from the perspective of private ship owners if economic conditions at the macro level of society improve and the

discount rate reflecting the time value of the national currency becomes less than 5% as in many developed countries.

In this case, the loan amount with the same annual repayment rate and the profit rate at which the project is cost-effective from a private sector perspective if the policymaker is interested in using photovoltaic propulsion by granting loans to ship owners as presented in Equations 24 and 25.

$$L_{Fuel\ oil} = \frac{3925747 \times S}{1 - \left(\frac{A}{P}, i\%, 30\right) \times (\frac{P}{A}, 25\%, 30)} \tag{24}$$

$$L_{Gas\ oil} = \frac{4131595 \times S}{1 - \left(\frac{A}{P}, i\%, 30\right) \times (\frac{P}{A}, 25\%, 30)} \tag{25}$$

In the above equation, $L_{\text{Fuel oil}}$ and $L_{\text{Gas oil}}$ represent the loan with a profit rate of i% to the owners of ships that use fuel oil and gas oil, respectively. Parameter S is the available area of the ship deck used to equip the photovoltaic propulsion system.

The amount of the loan with the same annual repayment (L) for low bank profit rates by the type of fuel, justifying the project from the private sector perspective, is shown in Figure 14.

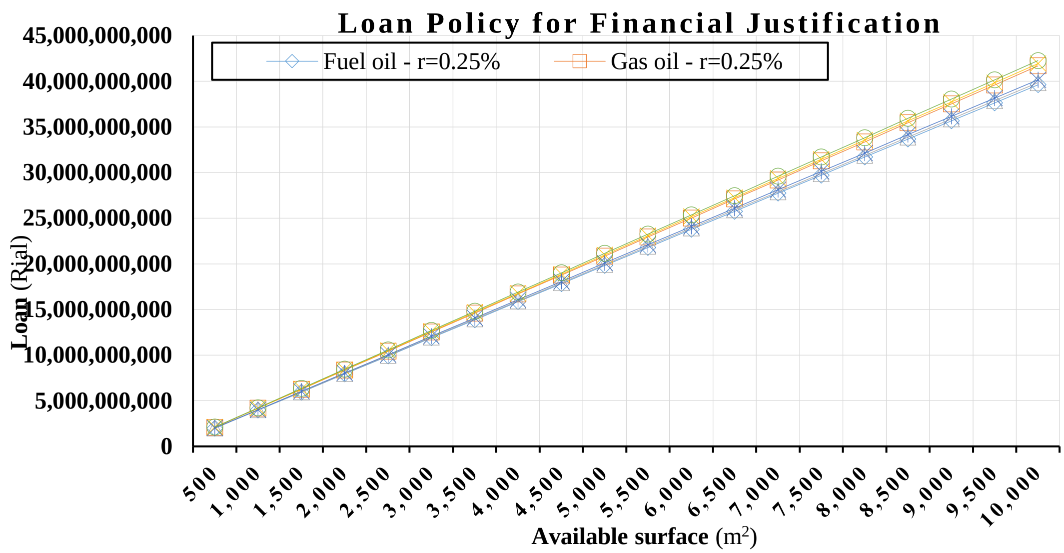

Figure 14. The Amount of the Loan with the Same Repayment, so That the Project is Justified from the Private Sector Perspective

Source: Research finding.

The results of Figure 14 indicate that the government should provide a loan of approximately 40 billion rials at a profit rate of 4% with the same 30-year repayment to make the project cost-effective when the private owner of a merchant ship wants to equip 10000 square meters of deck with photovoltaic propulsion system.

5. Conclusion

The high potential of the Persian Gulf and the Sea of Oman in using solar energy makes it possible to equip about 5.2% of the energy consumption of a large merchant ship and annually save 3253 tons of pollutants and 366 tons of fossil fuels.

Evaluating technical, economic, and environmental parameters of photovoltaic propulsion technologies for merchant ships in southern Iran under economic indicators indicated that this project is economically viable from a social and governmental perspective and has a high level of attractiveness. Due to the high discount rate and low fuel prices of ships in the current situation in Iran, implementing this project is not cost-effective from the private sector perspective.

In this study, the policy proposals such as reducing the discount rate or financing below 5%, increasing the growth of fuel prices to twice the current situation, combining the reduction of the discount rate, and increasing fuel prices were presented in Equation 23. In addition, granting low-profit facilities as Equations 24 and 25, and

Figure 14 for the economic viability of the project were presented from the private sector perspective, which can be considered by the government to support the private sector.

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