Application of Solar Panel Array on a Short Route Ferry: A Life Cycle and Economic Assessment

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Abstract

Green technologies are considered to be one of the most significant way to mitigate the severe global warming effect and have been drawing attentions from researchers all over the world. Solar energy is a type of renewable energy and solar panel array can capture and convert solar energy to electricity for domestic and industry uses. This paper considers the application of solar panel array to propulsion system of a short route ferry operating in the Marmara Sea where currently no environment protection policy is active to guide marine activities. The evaluation of the application is carried out using life cycle assessment from the aspect of cost effective and environment friendly. To take the payback time of the system into account, this study investigate the difference due to different average daily sunny hours in the operating area considering three levels of carbon credits. The results indicates both average daily sunny hours and carbon credits have an impact on the payback time. With the highest average daily sunny hours and carbon credits, the payback time of the application is only 2 years.

Keywords Solar Power, Life Cycle Assessment, Life Cycle Cost Assessment, Hybrid Propulsion, Green Technologies

Introduction

Due to the limited reserves of fossil fuel and the climate changing, green shipping has become one of the most popular topics all over the world. Based on Shafiee and Topal's study [1], an economic model was established to predict the diminishment of oil, gas and coal will be in approximately 35, 37 and 107 years from 2008. Due to the severe situation, more and more attention are paid to the research and development of renewable energy systems by researchers, industries and countries. It is also because of the rapidly growing interest in the application of renewable energy to mitigate the human impact of global warming [2]. IPCC report indicates the current carbon dioxide (CO_2) concentration has been increased by 100 ppm in the atmosphere which is around 34% more than the pre-industrial level [3]. Data from the Carbon Dioxide Information Analysis Centre also indicates that the annual global fossil-fuel carbon emissions had increase from 2995 to 9,855 million metric tonnes in 2014, [4]. CO_2 is considered to be a greenhouse gas and also a main contributor to Global Warming, mainly coming from

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fossil fuel consumption so that it is significant for the mitigation of Global Warming by replacing traditional fossil fuel systems with renewable energy systems in terms of global sustainability.

Solar Panel Applications

As solar panels are widely used, it is an environment friendly way to convert solar energy to electricity for onshore application. A study carried out by Eskew et al. evaluated the environmental impact of rooftop photovoltaic solar installation in Bangkok, Thailand. Recommendations were provided based on LCA result to the purchase of the solar panel syste [5]. A renewable energy island were investigated by Smith et al. considering the impacts of combinations of different energy sources (diesel, solar and wind) in hybrid micro grid. An optimal micro grid system under LCA was determined with lowest global warming potential compared with a number of scenarios [6]. Jacobson's team illustrated a renewable energy plan for Washington State, USA, including the conversion of wind, water and sunlight to electricity. One of the most significant technologies for electricity generation is the solar photovoltaics [7].

Apart from onshore applications, it is also attractive to marine industry. Currently, a hybrid system is usually preferred which utilises energy from engines and gen-sets together with that from other sources for propulsion. Investigations on the application of battery packs on board ferries were carried out to evaluate the impact of operation modes on environmentally friendly and cost effective[8, 9, 10, 11, 12]. This research presented the advantages of the battery packs application on carbon emission reduction in the marine industry. Unfortunately there is only a limited number of research about renewable energy applied on ships. There is one solar panel system application from the USA utilizing photovoltaic solar system under extreme offshore environment comparing solar systems (thin film and crystalline) with other renewable systems, (wind, tidal and wave energy). It is showed that thin film system has the lowest cost [13]. The latest hybrid vessels are listed in Table 1 with different systems: generators, battery packs, solar panel system and wind (kite) system.

Table 1 A list of latest hybrid vessels and their propulsion system

General information			**Hybrid methods**			
Name	Ship type	Year	Generator	Battery	Solar	Wind
Sun21 [14]	Yacht	2006			x	
Viking lady [15]	Supply Vessel	2009	x	x		
PlanetSolar [16]	Yacht	2010	x	x	x	
Hallaig [17]	Ferry	2012	x	x		
Catriona [18]	Ferry	2013	x	x		
Lochinvarl [19]	Ferry	2013	x	x		
Viking Grace [20]	Cruise ship	2013	x			x
Solar Voyager [21]	Autonomous Kayak	2016			x	
Victoria of Wight [22]	Ferry	2018	x	x		
Roald Amundsen [23]	Ferry	2019	x	x		
Color Line [24]	Cruise ship	2019	x	x		
Duffy London [25]	Yacht	2020		x	x	
Greenline [26]	Yacht	N?A	x	x	x	

SoelYachts[27]	Yacht	N/A		x	x	

Some patents from 1990s indicated the feasibility of solar power usage on ships [28, 29]. Diab et al. [30] found that with the applications of solar panels system, around 10,000 tonnes of GHG emissions could be eliminated with a ship life span of 25 years. The solar panels have also been applied on an ocean-going vessel to evaluate the financial feasibility [31]. The research indicated the minimum payback time for the investment on solar panel system was 10 years but maximally it took 27 years. Studies focus on energy storage system helped to determine how it could to reduce the fuel consumption and the emission of a vessel in its route [32]. Yu's team evaluated a hybrid system comprising solar panel system, battery pack and diesel generators from the angle of energy efficiency and emission reduction. It indicated the hybrid system could meet the regional regulation of emission reduction and also be profitable after ship life [33].

Life Cycle Assessment

This paper is to investigate the impact of solar panel array applications to a marine vessel from the perspective of environmental and economic. As stated in Section 1.1, hybrid power systems is an interesting topic for marine vessels considered and investigated in many studies. Therefore, Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) will be introduced to comprehensively investigate the environmental and economic impact of a system or device application. To evaluate the environmental impact of a system or a product, the whole life stages should be considered (construction, operation, maintenance and scrapping). LCA could determine the life cycle emission released, cash and energy required within the scope. LCA has drawn a considerable attention in the marine industry. [34, 35, 36, 37, 38, 39, 40].

For marine activities, there are also a great number of research works [41, 42, 43, 44, 45, 46]. Supporting by LCA, the life cycle environment protection performance could be optimized considering of raw material and energy consumption, and recycle processes [47].

Methodology

Life Cycle Assessment Introduction

Based on ISO standard, a LCA analysis should fundamentally include the definition of research/analysis objectives and boundaries, life cycle inventory analysis (LCI), life cycle impact analysis (LCIA) and life cycle interpretation [48, 49]. The framework of LCA analysis is presented in Figure 1.

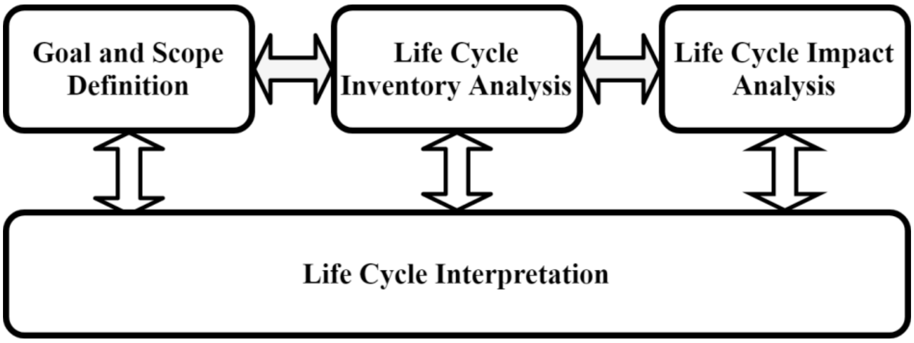

Figure 1 The schematic chart of life cycle assessment

The first procedure in LCA is the objectives and boundaries definitions. The goal or objective is set up based on a certain performance and a LCA study is to obtain the environmental impact. However, many different types of environmental impacts exist (global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP)), hence a key indicator of the study is necessary. Then the scope or the boundary of the study should be considered. If certain types of potential (e.g. GWP, AP or EP) are selected to be key indicator, there will be many emissions and pollutions under evaluation and many others will neglected as minor impact. Then based on the potentials selected, a functional unit should be set up as a standard to carry out the evaluation and comparisons of different scenarios. A normalization process will be conducted to convert different emissions which have contributions to different potentials into one type of emissions. According to the CML database [50], all the emissions which make contributions to global warming will be normalized and converted in to an equivalent quantity of CO_2 and the unit is kg CO_2 equivalent. For AP and EP, the fundamental pollutions are sulphur dioxide and phosphate (SO_2 and PO_4^{3-}). Although the functional unit could be these equivalent units, they can also be set up by the end users based on their objective. The normalization processes help to simplify the set up process which usually is based on or an extension of the normalized units. Another important part in goal and scope definition is to define the system boundary. Apart from constraining the scope by the relevant emissions, the differences between alternatives could also help reduce the LCA scope so that a compact but comprehensive LCA model can be established without considering repeated, redundant and less effective parts of the system or product. Therefore, reasonable scope should be made in order to neglect these unnecessary parts. Furthermore, assumptions should be made to progress the analysis because sometimes real data cannot be retrieved or provided. Usually assumptions should be made or advised by the system or product owners, manufacturers and operators.

After the definition of goal and scope, life cycle inventory analysis (Figure 2) can be conducted. With the goal and scope, the selection of the LCA plan will be determined and with this plan, data involved will be collected, normalized and aggregated in order to determine the initial outcomes. However, the relevant data maybe unavailable sometimes so that the study scope will be trimmed. After adjusting the scope based on data availability, similar processes will be carried out to modify and complete the assessment.

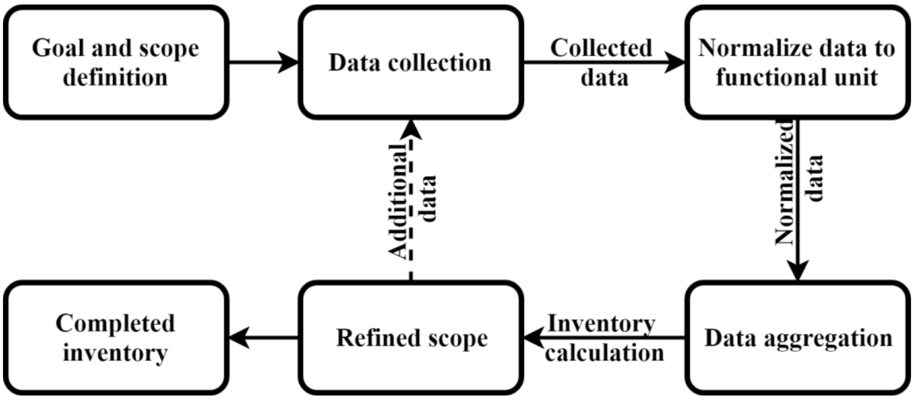

Figure 2 Schematic chart of life cycle inventory analysis

Based on the LCI analysis, LCIA consists of three main steps:

a. Selection of impact categories;
b. Classification of the selected impact categories;
c. Characterization of determined results based on category indicator.

After these phases, life cycle interpretation phase will carry out sensitivity analysis in order to evaluate impacts of key factors on the established LCA processes and results. It provides end users recommendations on the selections of different alternatives. Furthermore, the conclusions, limitations and recommendations of the LCA analysis should be provided in this process to illustrate both the decision making and the analysis constraints.

Formulations

The equations required for a LCA model establishment will be presented in this section.

Under four different operational loads, the fuel oil consumption during ship operation is considered: a. engine mode for sailing; b. engine mode for manoeuvring; c. solar and engine combination mode for sailing; d. combination mode for manoeuvring. A general equation could present the relationships between the fuel oil consumption and other parameters under different conditions:

$$FO_i = P_i \times SFOC_i \times H_i \times LS \quad \text{(Equation 1)}$$

Where,

FO is the annual fuel consumed [tonne];

P is the power requirement [kW];

SFOC is the specific fuel oil consumptions [g/kWh];

H is the total hours of operation in a year [hours];

LS is the ship life span [years];

i represents four different ship operation conditions under different engine loads.

As engine load varied, the adjustment of the engine SFOC will be considered based on the engine project guide (Figure 3) [51]:

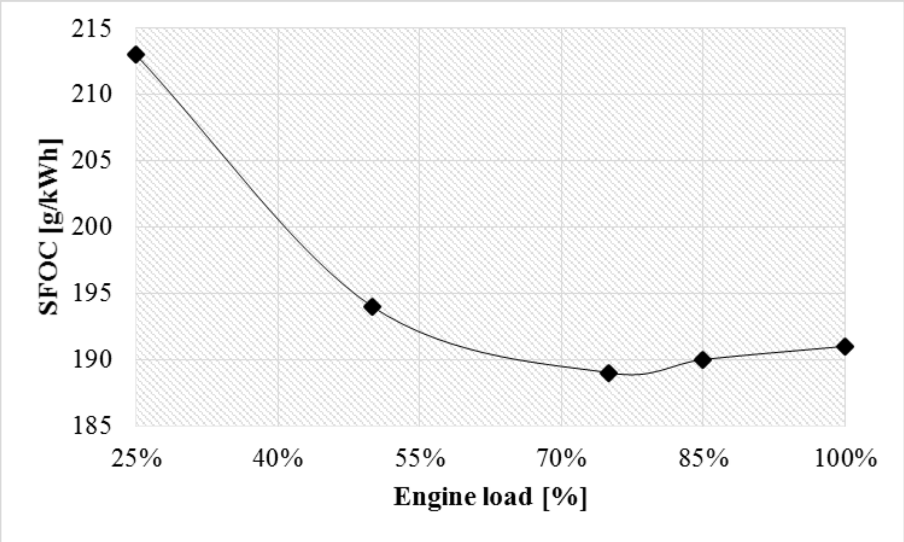

Figure 3 SFOC varied with engine loads

$SFOC_y = SFOC_{x1}-(SFOC_{x1}-SFOC_{x2})/(EL_{x1}-EL_{x2})\times(EL_{x1}-EL_y)$ (Equation 2)

Where,

$SFOC_y$, $SFOC_{x1}$ and $SFOC_{x2}$ are the specific fuel oil consumption [g/kWh];

EL_y, EL_{x1} and EL_{x2} are the engine loads [%];

Similarly, the lubrication oil consumptions could be determined:

$LO_i = P_i\times SLOC_i\times H_i\times LS$ (Equation 3)

Where,

LO is the annual lubrication oil consumptions [tonne];

SLOC is the specific lubrication oil consumptions [g/kWh].

If considering the ship costs fom the cradle to the grave, present value is applied to determine the value of future costs before or at the beginning of a project. The following equation is used to determine a cost at specific year [52]:

$PV = FV/(1+r)^n$ (Equation 4)

Where,

PV is the present value for a future investment [$];

FV is the future value of which will be invested or earned in the n^{th} year [$];

r is the interest rate [%];

n is the number of years.

For a constant annual operation cost, the present value of the total cost during the ship life span can be determined:

$$TPV = \sum_{j=1}^{LS} AFV/(1+r)^{LS} \quad \text{(Equation 5)}$$

Where,

TPV is the total present value for a period of constant investment or income [$];

AFV is the future value of annual investment or income [$];

j represents a specific year of life span.

The characterization process is to convert different emissions to the indicator in specific impact categories based on the characterization database, such as CML2001, ReCiPe and TRACI [53, 54]. The converting process is shown in the following equation:

$$EI_k = FO \times C_k \times CF_k \quad \text{(Equation 6)}$$

Where,

EI is the impact of emissions equivalent to the indicator [kg indicator eq.];

C is the conversion factor from fuel to emission [kg emission /kg fuel consumed];

CF is the characterization factor to convert emissions to the indicator [kg indicator eq./kg];

k represents different emissions in specific impact categories.

The minimum quantity of fuel oil saved can be estimated for solar system application with the following equation:

$$FO_s = P_s \times H_s \times 3600/LHV \quad \text{(Equation 7)}$$

Where,

FO_s is the minimum quantity of saved fuel oil based on the solar energy used [tonne];

P_s is the power output of solar device/system [kW];

H_s is the daily average sunny time [hours];

LHV is the low heating value of fuel oil [kJ/tonne].

Transportation costs present the transportation fuel costs for different materials and machinery from the manufacturers or suppliers to the shipyards or ship operators. The following equation can be used to determine transportation costs:

$C\_{trans} = W \times D \times SDOC \times P\_{trans}$ (Equation 8)

Where,

C_{trans} is the transportation cost [$];

W is the weight of the transported materials or machineries [$];

D is the transportation distance [km];

SDOC is the specific diesel oil consumption of the transportation (e.g. trucks) [kg/(km×kg)];

P_{diesel} is the diesel oil price [$/tonne].

Life Cycle Assessment

Goal and Scope Definition

Goal and Scope of study

This LCA analysis is to determine the possible reduction in global warming impact of the application of solar panels on a short route ferry. This paper presents a study of life cycle and economic assessment of solar power system application on a short route ferry which regularly serves in the Bosporus Strait, located in the Sea of Marmara (Figure 4). “Sea of Marmara is an inland sea within the Marmara region connecting to the Black Sea with the Bosphorus Strait in the northeast, and to the Aegean with the Dardanelles Strait in the southwest”[55]. The length is nearly 30 km and widths varying from 0.7 to 3.5 km. Thus the Bosporus Strait is an especially critical area facing heavy shipping traffic which causes significant air pollution.

There are two different scenarios under consideration: Scenario 1 (S1) without solar panels; Scenario 2 (S2) with solar panels. The activities in two scenarios are listed in Table 2. Any the shadow cells in S2 present different activities from S1.

Table 2 Activities lists of two scenarios

Life stages	Activities	
	S1	S2
Construction	Engine purchase, transportation and installation	Engine purchase, transportation and installation
	Hull steel plate purchase, transportation and installation	Hull steel plate purchase, transportation and installation
	Hull cutting, blasting, bending, welding and coating	Hull cutting, blasting, bending, welding and coating
		Solar panel purchase, transportation and installation
	Fuel oil consumption	Fuel oil consumption

Operation	Lub. oil consumption	Lub. oil consumption
Maintenance	Engine maintenance	Engine maintenance
	Hull steel renewal and surface coating	Hull steel renewal and surface coating
Scrapping	Engine parts recycle and disposal	Engine parts recycle and disposal
	Hull steel recycle and disposal	Hull steel recycle and disposal
	Hull coating removal	Hull coating removal
		Solar panel recycle and disposal

Comparing the scenarios' activities and omitting the similar ones, the scope of the study can be simplified. However, the application of solar panel will change the power requirement and the specific fuel oil consumption. Due to a long period of operation, the accumulation of fuel saving becomes considerable so that the operation costs will be reduced significantly. Therefore, it is essential to include the operation activities in the comparison in order to determine the payback time of the solar panels.

Since the aim is to determine the impact of solar panels on ship's GWP, the GHG emissions from CML database and from engine project guide (from MAN Diesel) are included. The functional unit is the 'kg CO_2 eq.' commonly used in LCA analysis which indicates all the emissions in the GWP category will be converted into equivalent quantity of CO_2.

Assumptions for LCA

It is necessary to make reasonable assumptions before performing the LCA analysis in order to supplement the missing data and determine duplicated information. This study assumes:

a. The LCA model takes into account the practical operation by the Turkish ship operator;
b. LCA modelling is carried out using GaBi 5;
c. Emissions due to engine fuel consumption are calculated based on emission factors provided by the International Maritime Organization (IMO) [56];
d. The scrapping processes use the methodology developed by Ling-Chin and Roskilly's research;
e. Manufacturing processes for the solar panel from raw materials are not considered;
f. The SFOC adjustment is considered as linear;
g. Properties of solar panels are determined based on the information provided by manufacturer [57];

h. It is assumed that all power output from solar panels could be used for propulsion and more consideration on solar panel system efficiency will be discussed in the Section 5.1;

i. Maintenances of the solar panels are neglected; the maintenance of the engine in both scenarios is not considered because the relationship between the required maintenance and power variation is complex; however, the impact of using different sources is definitely beneficial to the ship operator because the usage of engines and the cycle of spares changing will be decreased;

j. The transportation processes of solar panels are modelled using GaBi built-in module [58];

k. The electrical power used in construction and scrapping is supplied from hydro power and the fuels supplies are selected from GaBi database by considering locations of the suppliers;

l. Environmental impact assessment is limited to evaluating the GWP which is directly impacting the global temperature;

m. The area available for solar panel installation is 400m^2 based on the overall length and the breadth of the ship is L42m×B10m.

Life Cycle Inventory Assessment

According to the goal and scope defined, with the ship particulars and operation profiles in Figure 3 and 4, a LCA model is established using GaBi. According to manufacturer's data, the size of one Monocrystalline Silicon solar panel is 1,956mm×991mm×40mm (Table 5) so a maximum 206 solar panels can be installed based on the area assumption in point "m". One panel can provide 0.35 kW power output so the total power output is about 72kW. In Figure 5 the proposed power distribution for the case ship is presented. Figure 6 shows the established LCA model.

Table 3 Case study ship specifications

Name	Hizir Reis
Flag	Turkey
LOA (m)	41.98
Breadth (m)	10
Gross tonnage (tonnes)	327
Engine power (kW)	634×2
Fuel type	Heavy fuel oil (HFO)
Annual operation days (days)	325
Ship life span (years)	25
Year built	2012

Çilingoz
Tabiat Parkı
Yalıköy
Karamandere
Karaburun
Kumköy
Arnavutköy
Çatalca
Silivri
E80
O-7
O-6
Maslak
Şile
Ulupelit
Büyükçekmece
İstanbul
Sultanbeyli
Gebze
Körfez
Alibeyköy
O-1
EYÜP
O-3
BEŞİKTAŞ
Üsküdar
Ümraniye
Fatih
EMİNÖNÜ
O-2
O-4
Zeytinburnu
Kadıköy
Ataşehir
Maçka Demokrasi Parkı
Bahçeşehir
Üniversitesi
Dolmabahçe Sarayı
Beylerbeyi Sarayı
Mosque
Mihrimah Sultan Cami
Modern Art Museum
İstanbul Modern
Sanat Müzesi

Figure 4 Operation route of the case study ship

Table 4 Operation profile of the case study ship

Category	Sailing	Manoeuvring
Operation profile (hours)	9	1
MCR (%)	85%	50%
Power required (kW)	1078	634
SFOC (g/kWh)	190	194
SLOC	2.85	4.85

Table 5 Solar panel installations

Available area	400	m^2
Area per panel	1.94	m^2
Number of panels used	206	
Power output per panel	0.35	kW
Total output power	72.1	kW

Table 6 Emission inventory

Module name	Emission Quantity	Unit
Transportation	1.96×10^{8}	kg CO_2 eq.
HFO production	7.36×10^{9}	kg CO_2 eq.
Lub. oil production	5.88×10^{7}	kg CO_2 eq.
Diesel oil production	3.19×10^{7}	kg CO_2 eq.
Operation: fuel consumption	4.99×10^{10}	kg CO_2 eq.
Other activities	6.70×10^{5}	kg CO_2 eq.
Total	5.75×10^{10}	kg CO_2 eq.

Figure 5 Case ship and outline of power distribution for case ship

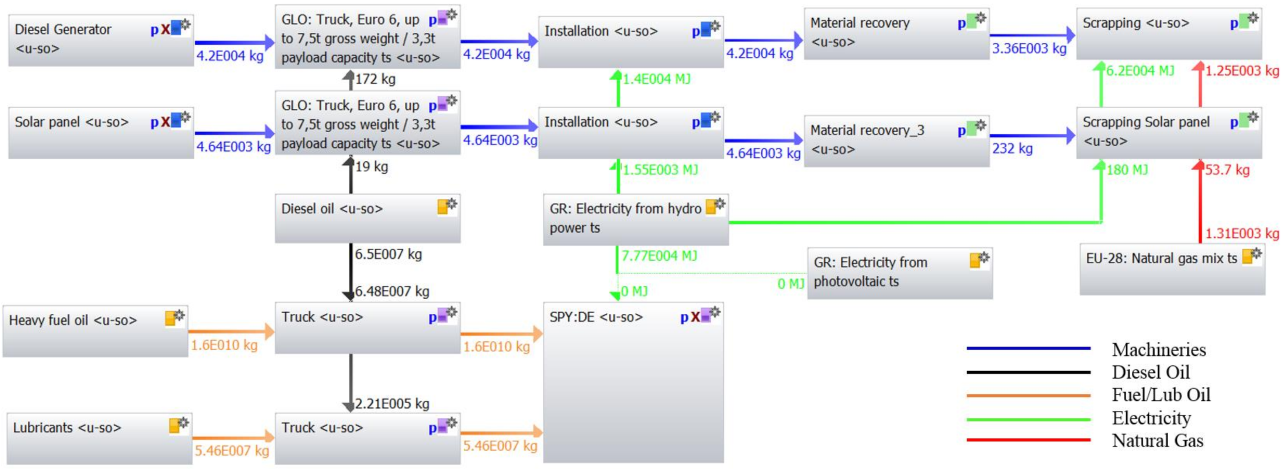

Figure 6 Flowchart of LCA processes in GaBi

With the established LCA model and data/information provided by ship operator, the emission inventory of the LCA analysis is determined for ship in service with only engine running for 325 days a year in 25 years as shown in Table 6. The table indicates most of the GWP impact is from ship operation because considerable of fuel oil are consumed. The production of fuel oil will generate significant amount of GWP but other activities, such as production of lubricating oil and diesel oil and the transportation, will have lower impact than these two activities.

Life Cycle Impact Assessment

To compare the GWP of two scenarios, one more analysis with solar panel application is conducted for S2 and the flowchart of this analysis is presented in Figure 7. The comparison of GWP results for two scenarios are presented in Figure 8 indicating that the GWP from Scenario 2 is less than Scenario 1. Therefore, the potential of solar panel application on reducing greenhouse emission is proven.

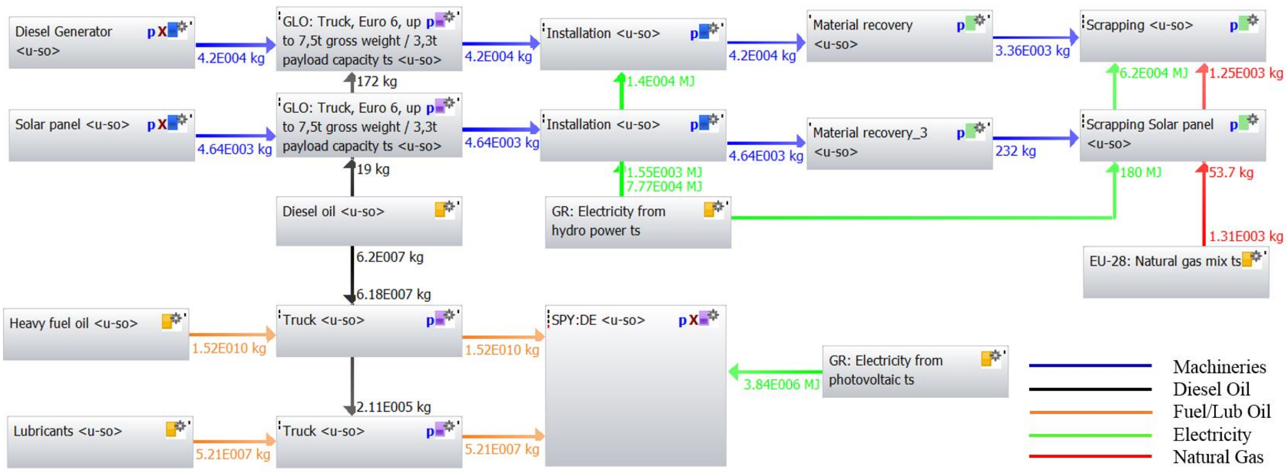

Figure 7 LCA analysis flowchart of Scenario 2: with solar panel application

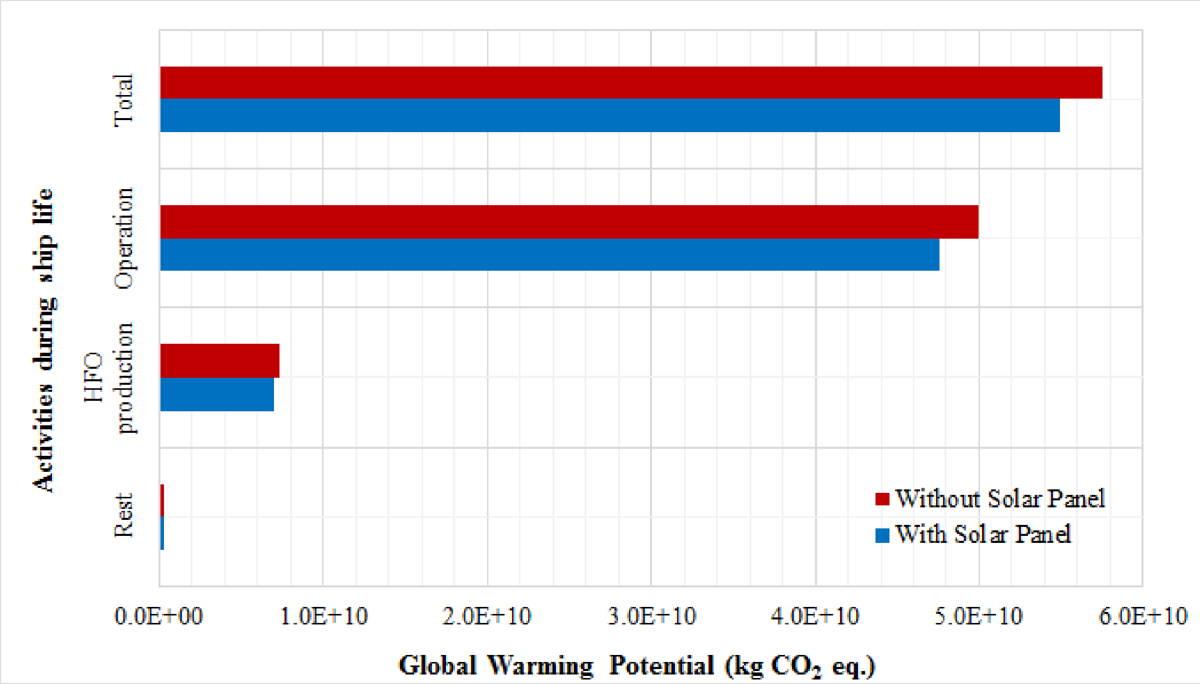

Figure 8 GWP Comparison for two scenarios

Sensitivity Analysis 1: Operation days and sunny hours

Sensitivity analyses are conducted in order to determine how different operation conditions could impact the LCA results in terms of equivalent CO_2 emissions, such as sunny hours per day and operation days per year.

Table 7 presents three different ship operation conditions with varied operation days per years: 325 days, 217 days and 108 days, which illustrates when reducing the operation days, the quantity of emission will be decreased. According to the LCIA analysis, the operation phase contributes the most of the emission release which are also presented in these three operation conditions in the table.

Table 8 presents another three ship operation conditions with varied sunny hours per days: 6 hours, 4 hours and 2 hours. It indicates the quantity of life cycle equivalent CO_2 emission will be impacted if the weather condition is changed. If there is shorter the sunny hours per day, more quantity of emission will be released. The emission release from operation phase are also presented in the table for three operation conditions.

Table 7 Sensitivity analysis of the operation days per year

Category	Operation days per year			Unit
	325 days	217 days	108 days	
Total	5.48×10^{10}	3.66×10^{10}	1.82×10^{10}	kg CO_2 eq.
Operation	4.75×10^{10}	3.17×10^{10}	1.58×10^{10}	kg CO_2 eq.

Table 8 Sensitivity analysis of the sunny hours per day

Category	Sunny hours per day			Unit
	2 hours	4 hours	6 hours	
Total	5.67×10^{10}	5.59×10^{10}	5.50×10^{10}	kg CO_2 eq.

Operation	4.92×10^{10}	4.84×10^{10}	4.77×10^{10}	kg CO_2 eq.

Economic Assessment

Life Cycle Cost Assessment

Although the LCA assessment presents the advantages of solar panel arrays application, it is not straightforward to end-users to make a decision. Therefore, the investigations on the cost effectiveness and payback time of the solar panel investment are carried out for two scenarios [59]. Similar to LCA assessment, the LCCA analysis of the case study will focus on fuel costs and carbon credits. Present value will be considered as the investments and profits in the future are considered as less valuable than current ones.

As the fuel consumption is based on the power requirement, operational hours and specific fuel oil consumption, to determine the amount of solar energy converted to electrical energy, the weather conditions will be significant so a database of daily average sunny hours in Istanbul from 1929 to 2017 is referred as shown in Table 9 [60, 61].

Table 9 Daily average sunny hours for different months (1929-2017)

Month	Daily sunny hours
January	2.9
February	3.6
March	4.6
April	6.5
May	8.8
June	10.6
July	11.5
August	10.6
September	8.2
October	5.7
November	4.0
December	2.7

The new specific fuel oil consumption could be determined using the SFOC adjustment equation after the power output from solar panel system is derived. Table 10 presents the SFOC under four different conditions: 1) sailing without solar panel system; 2) sailing with solar panel system; 3) manoeuvring without solar panel system; 4) manoeuvring with solar panel system.

Table 10 SFOC under different operation conditions

Operation conditions	Loads (%)	SFOC (g/kWh)
1	85	190.0
2	81.2	189.6
3	50	194.0
4	44.3	195.1

After determination of SFOC, the fuel price in Istanbul is also derived [62], so that the fuel consumption and the annual fuel cost and fuel saved can be derived (Table 11). With a 25-year life span and 8% interest rate [63] the adjusted life cycle cost saved is obtained to be $130275.

Table 11 Annual fuel consumptions and costs for two scenarios

Item	Quantity	Units
Daily fuel consumption (FC)	1,966	kg/day
FC1 (6.7 hours sunny)	1,270	kg/day
FC2 (3.3 hours not sunny)	602	kg/day
New daily FC (total)	1,872	kg/day
Annual fuel consumption (benchmark)	638,961	kg
Annual fuel consumption (Scenario 2)	608,489	kg
Annual fuel saved	30.5	tonne
Fuel price	401	$/tonne
Annual fuel cost saved	12,204	$
LC fuel cost saved	305,101	$
Present value	130,275	$

According to the price information from manufacturer, the cost of a single solar panel is $0.35-0.4 per watt so the cost of the solar panels is no more than $25,235. Therefore, the payback time of the investigation is less than 3 years no matter present value is considered or not.

IMO reports that the carbon conversion factor of HFO is 3.114g CO_2/g fuel burnt so the quantity of carbon emission reduction can be determined as 2,372 tonne for 25 years' operation. As there is no active policy or regulation on carbon emissions, the report from Maibach et al. is referred: the lower (L), central (C) and higher (H) carbon credits for every tonne of CO_2 emission will be equivalent to $21, $50 and $87 in 2020 [64]. The respective carbon credits saved are $44,886, $106,871 and $185,956. Therefore, with an overall consideration, the payback time of the solar panels investment under the lower, central and higher carbon credits conditions could be obtained as 3 years, 2 years and 2 years respectively.

Sensitivity Analysis 2: Sunny hours

To assess the impact of daily average sunny hours on the fuel costs saved, carbon credits saved and payback time, four different scenarios are considered in this section: 6 hours, 4 hours, 2 hours and a worst case with no sunny hours. The results are presented in Table 12. There is no policy or regulations about carbon emissions in Turkey but the trend of regional carbon emission reduction is imperative for the purpose of mitigation of global warming effect. The results under different carbon credits level are shown in the table. After considering both saving from fuel costs and carbon credits as well as the investment of solar panels, the payback years are also determined and presented in the table. It is also determined that with a minimum daily average sunny hour of 0.56 hours (about 34 minutes) under lower level carbon credit, the investment of solar panel system could be paid back at the end of the ship life. At this worst case scenario, the fuel cost saved is $25,785; the carbon credits saved is $3,391.

Table 12 Costs saved and payback years for different average daily sunny hours

Scenarios	A	B	C
Average daily sunny hours (hours)	6	4	2
Fuel cost saved (thousand $)	275	183	92
PV Fuel cost saved (thousand $)	242	161	81
Carbon credit saved (L) (thousand $)	45	30	15
Carbon credit saved (C) (thousand $)	107	71	36
Carbon credit saved (H) (thousand $)	186	124	62

Payback year (L) (year)	3	4	7
Payback year (C) (year)	2	3	6
Payback year (H) (year)	2	3	5

Conclusion

This paper presents the study of the application of a solar panel system on a short route ferry operating in Turkey on its environmental and economic impacts. From cradle to grave, the LCA method is applied considering costs of the ship by establishing a LCA model, evaluating the environmental impact and assessing the sensitivities of important parameters. It is suggested that with the solar panel system, the quantity of GHG emission release will be reduced by 20,000 tonnes over 25 years of ship life. With longer average daily sunny hours, the emission reduction will be increased. Similarly, there will be less emission release if the operation days per year are increased. From the perspective of cost, with consideration of SFOC adjustment, the fuel cost saved after 25 years operation could reach approximate $305,101 and about $130,275 in present value. The payback time of investing in the solar panel system is only 3 years. As there is no carbon credit currently in force in Turkey, three different levels of carbon credit values from EU in 2030 are applied to find out the carbon credit saved due to the solar panel application. It is a promising investment that at least $44,886 carbon credits will be saved. With the highest average daily sunny hours and carbon credits, the payback time of the solar panel array is only 2 years. This paper also provides an evaluation process using LCA and LCCA method to assess the performance of green technologies so that policy makers and ship operators could make decisions on the technologies selections based on the LCA results.

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