Word count: 12251.

Life Cycle and Economic Assessment of a Solar Panel Array Applied to a Short Route Ferry

Haibin Wang[a*], Elif Oguz[b], Byongug Jeong[a], Peilin Zhou[a,c]

a- Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, G4 0LZ, Glasgow, UK

b- Department of Civil Engineering, Middle East Technical University, 06800 Ankara, Turkey

c- Zhejiang University, 1 Zheda Road, Zhoushan, Zhejiang Province, 316021, China

Corresponding author: E-mail address: haibin.wang.100@strath.ac.uk (H. Wang).

Abstract

This paper was to investigate the potential benefits of solar panel systems if applied for obtaining propulsion power of a short route ferry operating in the Marmara Sea. The life cycle assessment was applied to evaluate the long-term environmental impact of the solar power systems on-board in replace of conventional diesel engine systems. The cost and benefit of such systems were evaluated through the economic assessment where the life cycle cost relative to installation, operation and recycling of the solar panels, fuel savings and payback time were considered. Research findings revealed the payback time would be around three years, whereas the accumulative fuel cost saving would be over $300,000 by the end of vessel life. The sensitivity analysis using two varying parameters - energy efficiency and investment cost - implied, that the longer payback time would be positively associated with lower energy efficiencies and higher investment costs. It was also suggested that the marginal cost of the carbon credit should be \$ 190 per tonne or higher to make the shipping business successful.

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

Abbreviation

AFV	Annual Future Value
AP	Acidification Potential
B	Breadth
C	Cost
Ce	Central Level
CF	Characterization Factor
CML	Institute of Environmental Sciences
CO_2	Carbon Dioxide
D	Distance
DFC	Daily Fuel Consumption
EEDI	Energy Efficiency Design Index
EI	Environmental Impact
EL	Engine Load
EP	Eutrophication Potential
eq.	Equivalent
ETA	Event Tree Analysis
FC	Fuel Consumption

FMEA	Failure Mode And Effects Analysis
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
FV	Future Value
GHG	Greenhouse Gas
GWP	Global Warming Potential
H	Hours
HAZOP	Hazard and Operability Study
HFO	Heavy Fuel Oil
Hi	Higher Level
i	Stage Number
IMO	International Maritime Organization
ISO	International Organization for Standardization
j	Year Number
k	Emission Category Number
kW	Kilowatts
L	Length
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Analysis
LHV	Low Heating Value
Lo	Lower Level
LOA	Length Overall

LOC	*Lubricating* Oil Consumption
LS	Lifespan
n	Number Of Years
P	Price
Pe	Power
PO_4^{3-}	Phosphate
PV	Present Value
r	Interest Rate
S	Scenario
SDOC	Specific Diesel Consumption
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption
SO_2	Sulphur Dioxide
TPV	Total Present Value
W	Weight

Table of contents

1. Introduction

At present, greener shipping is one of the hottest topics across the world with an adverse anticipation that the reserves of fossil fuel would be used up in the-not-too distance future as well as the climate change is at an alarming level. European Union has set up a goal to cut the greenhouse gas emissions by 80-95% by 2050 which will be an extremely heavy task facing by all the transportation sectors (Euroupean Union, 2012). An economic model developed by Shafiee and Topal (Shafiee and Topal, 2009) predicted that oil, gas and coal would diminish in approximately 35, 37 and 107 years from 2008 respectively. In this context, the research and development for applying feasible renewable systems for various industrial fields are attracting more and more attention. Moreover, considering the global warming effect on human beings, the use of renewable energy is regarded an urgent task (Kavli et al., 2017). An IPCC report (Rogner et al., 2007) revealed that the current concentration of CO_2 in the atmosphere had been increased by 100 ppm which is around 34% higher than the pre-industrial level. According to the data from the Carbon Dioxide Information Analysis Centre (CDIAC) in 2013, the annual global fossil-fuel carbon emissions had reached up to 35.9 billion metric tonnes of CO_2 which was only 15.4 billion metric tonnes of CO_2 in 1971 (Boden et al., 2017). Therefore, the replacement of conventional marine fuels - major contributors for Global Warming - with renewable energy sources may be essential to enhance global sustainability.

To contribute to global efforts by addressing the marine pollution from various emission types, IMO (International Maritime Organization) has developed a series of stringent environmental regulations. The mandatory application of the EEDI (Energy Efficiency Design Index) for new ships and the SEEMP (Ship Energy Efficiency Management Plan) for all ships over 400 gross tonnages are good examples (Smith et al., 2014).

Many shipyards, ship operators and owners are striving to find solutions to use cleaner energies as marine fuel sources. Given that the solar energy is widely renowned as a much cleaner energy than conventional fossil fuels, the solar energy has emerged as one of the most promising sources of future marine fuel. On the other hand, despite the strong popularity of solar systems at inland residential and industrial levels, the application of such energy has been very limited in the marine field due to the constraints of weather conditions and low energy efficiencies.

However, comprehensive research into the costs and benefits of replacing petroleum products with solar power is still lacking. In this context, this paper was designed to evaluate the effectiveness of the application of solar panel arrays on a short route ferry by means of LCA (Life Cycle Assessment). The authors also aimed to investigate the availability, feasibility, comprehensiveness and fineness of the LCA method.

To supplement the limited application of solar energy and LCA to the marine industry, this paper began with a thorough review of their usage in onshore and offshore fields (on ships and platforms) first. The application of LCA in different industries was also reviewed to determine the availability of the method.

1.1.Review of Solar Panel Applications

Solar panels, a well-known system to capture solar energy for generating electricity, have been widely used across countries and their environmental records have proven their cleanness. Eskew and his team evaluated the environmental impacts of installing rooftop photovoltaic solar panels in Bangkok, Thailand (Eskew et al., 2018). They adopted LCA for evaluation, while offering useful recommendations on purchase of the solar panel system. Smith's research investigated the effectiveness of a renewable energy island considering environmental impacts of hybrid micro grid where several types of energy sources (diesel, solar and wind) were combined (Smith et al., 2015). They determined an optimal micro grid system with lowest GWP (Global Warming Potential) by comparing a number of scenarios using LCA. Jacobson's team illustrated a renewable energy plan for Washington State, USA, including the conversion of wind, water and sunlight to electricity, which indicated solar photovoltaics would be one of the most cleaner and feasible technologies for contemporary electricity generation (Jacobson et al., 2016).

Solar energy is also attractive to the marine industry. To replace the conventional propulsion system driven by oil products, several types of hybrid systems have been introduced, which would utilise both oils and alternative energy sources. Researchers have revealed the excellence of hybrid ships which run on diesel engines and on board battery packs that could be charged from cleaner energy sources (Jeong et al., 2018; J. Ling-Chin and Roskilly, 2016). Their research findings highlighted the benefits of using battery packs in terms of CO_2 reduction. Apart from battery applications, there has been a need for research focusing on application of renewable energy systems on ships. The use of on-board solar panel systems has been very limitedly reported but photovoltaic solar systems were installed in the USA under extreme offshore environment. Two types of solar systems (crystalline and thin film) were compared to other renewable energy systems (wind, tidal and wave energy). Their findings showed that thin film solar system would be more cost effective than the crystalline one (Trapani et al., 2013). To present the existing hybrid vessels, Table 1indicates the latest hybrid vessels using different propulsion system: 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 (Transatlantic21, 2018)	Yacht	2006			x	
Viking lady (Ship Technology, 2018a)	Supply Vessel	2009	x	x		
Planet Solar (Ship Technology, 2018b)	Yacht	2010	x	x	x	
Aquarius Eco Ship (Eco, 2012)	Bulk carrier	2011	x	x	x	x
Hallaig (CMAL, 2018a)	Ferry	2012	x	x		
Catriona (CMAL, 2018b)	Ferry	2013	x	x		
Lochinvarl (CMAL, 2018c)	Ferry	2013	x	x		
Viking Grace (Viking Line, 2018)	Cruise ship	2013	x			x
Solar Voyager (Solar Voyage, 2018)	Autonomous Kayak	2016			x	
Victoria of Wight (Wight Link, 2018)	Ferry	2018	x	x		
Roald Amundsen (Hurtigeruten, 2018)	Ferry	2019	x	x		
Color Line (Poland@Sea, 2018)	Cruise ship	2019	x	x		
Duffy London (Inhabitat, 2018)	Yacht	2020		x	x	
Greenline (Greenline, 2018)	Yacht	Manufacturer	x	x	x	
Soel Yachts (Yachts Soel, 2018)	Yacht	Manufacturer		x	x	

In 1980, a wind-powered 2100-ton cargo ship, namely Aitoku Maru, was built by Japanese naval architects. They aimed to cut its energy consumption by half compared to the most fuel-efficient conventional ships (Shipspotting, 2016).

Due to the significant developments in solar energy, solar power started using as a cost effective fuel reduction alternative on pleasure boats, ferries and tourist ships. On the other hand, fuel saving by using solar power alone is relatively small on large ships compared to small ferries. After this finding, researchers and technology developers focused on hybrid systems to reduce fuel consumption. In 1990s a patent was obtained in the United States to combine the energy of wind and solar. Although ideas and different concepts for hybrid systems started to develop before 1990s, to date there is no operating large commercial ocean going ship.

Newman and Schaffrin's team started to develop solar energy conversion systems (Newman, 1992; Schaffrin and Fed. Rep. of Germany, 1993). Diab et al. (Diab et al., 2016) investigated the benefits of the hybrid system using diesel engines, battery packs connected with solar panels both for inland and on-board usages. Their study concluded that the application of solar panel systems and battery packs to a ship would reduce GHGs of about 10,000 tonnes over a typical ship life of 25 years. However, their consideration is mainly the evaluation of the environmental impact of operation phase while applying solar panel system and battery packs on a ship. An extensive view covering all ship life stages to determine the potential benefits of maritime solar system is not under investigation. Glykas et al. (Glykas et al., 2010) carried out a study on application and cost-benefit analysis of solar hybrid power installation on merchant marine vessels. Their findings showed a strong relation between the payback period time and the fuel prices. They indicate another interesting point as "contrary to the annual increase rate of the fuel prices, the payback period converges to a minimum of about 10 years". Several studies were also focused on energy storage system, determining how it could help solar panel systems to reduce the fuel consumption and the emissions from vessels' service period (Liu et al., 2017). Yu's team (Yu et al., 2018) evaluated the energy efficiency and the emissions reduction, taking advantage of the hybrid systems consisting of solar panel systems, battery packs and diesel generators. The results showed that the application of the hybrid systems could meet local emission reduction requirements and gain profits at the end of ship lifespan.

There are also many other researches carried out all over the world. Branker et al. (Branker et al., 2011) reviewed the economic feasibility studies of solar panels and argued that the power of solar energy would be increasingly beneficial to the economy in geographical areas. They also provided an appropriate insight to the cost estimation of solar panels whereas addressing misunderstandings and false assumptions laid on the cost analysis.

As one of the recent research on the economic feasibility on the solar panel, Imteaz and Ahsan (Imteaz and Ahsan, 2018) presented real efficiencies achieved from four houses in two Australian cities. Their findings were positive for solar energy applications, but the efficiency of the solar panels varied depending on a variety of factors, including current costs and size of the solar system.

These papers provided a valuable implication on the importance of appropriate design and selection of solar panels as well as proper assumptions in cost estimation.

In addition, some of previous research attempted to investigate the environmental impacts of solar systems using life cycle assessment. Some of the valuable examples are summarised below:

Kannan et al. (Kannan et al., 2006) analysed the performance of PV systems compared to oil steam turbine systems. Research shows that photovoltaic systems are good at reducing greenhouse gas emissions but can still be a burden due to high costs.

Beccali et al. (Beccali et al., 2016) applied a simplified LCA method to investigate the global warming potentials of solar heating and cooling systems, compared to conventional systems with PV technology. It pointed out the solar heating and cooling systems are superior in the scope of analysis.

Lunardi et al. (M. Lunardi et al., 2018) presented a comparison of two types of solar panel technology: screen printed aluminium back field (AL-BSF) and passivated emitter and back cell (PERC). The study noted that current standards using AL-BSF could be improved by replacing PERC in terms of environmental impact.

The previous application of LCA to the solar system was fairly limited in the calculation of emissions. However, a comprehensive survey of the life cycle of the solar system is still lacking. Moreover, LCA for marine solar systems was rarely applied.

1.2.Review on LCA

According to previous research stated in Section 1.1, it has been pointed out that the application of hybrid power systems to marine vessels would be attractive in both economic and environmental aspects. Nevertheless, there is still need for research associated with their on-board applications; most of research appeared overly focusing on the purchase and operation of renewable energy devices. For a comprehensive evaluation with the environmental and economic impacts of on-board solar systems, LCA and LCCA could be introduced. This chapter reviews the feasibility and capability to carry out comprehensive evaluations.

LCA is a cutting-edge technique to evaluate the holistic environmental impact of a system or a product by considering the whole life stages from cradle to grave. Taking the flows of emission, cash and energy into account, LCA could estimate the emission release, capital and operational expenditures and energy consumptions within the assessment scope.

LCA has drawn a considerable attention in the different industry. For instance, LCA was applied to quantify the willow growth on river buffer zones to find out the benefits of willow cultivation (Styles et al., 2016). To evaluate the energy consumption and environmental impact of edible protein energy return on investment (ep-EROI) for fishing industry, LCA was used by a research group in Spain. Research findings and recommendations were presented and contributed to the EU Common Fisheries Policy (Vázquez-Rowe et al., 2014). Fredga and Maler also established a full scope of LCA model to assess the state-of-art and under-developed biofuel application considering energy, material and emission flows. Such a comprehensive analysis led to enhancing the precision for results (Fredga and Mäler, 2010). There are many other applications in different industries to prove the feasibility of the method, relating to ship design, operation and recycle, automotive manufacturing, yacht industry and assessments on transportation sectors. Raugei's research applied LCA to determine the potential environmental benefits of innovative automotive manufacturing process (Raugei et al., 2014). They also evaluated several light weighting options of compact vehicles to determine the most robust method with lowest environmental impact (Raugei et al., 2015). In yacht industry, LCA method was applied to compare and evaluate the two different infusion methods which help to quantify the reduction of environmental impact during the life span of the vessel (Cucinotta et al., 2017). The research team from Italy investigated the economic and environmental impacts of applying two different composite materials in automotive manufacturing and they determined the preferred material from the perspective of environmental impact (Delogu et al., 2016). Duan's team quantified the CO_2 emission from different transportation sectors in China using LCA method which indicated the rapid growth of the carbon emission in China was mainly led by the freight transportation rather than passenger transportations. The trend of the growing in carbon emission was also presented in their research (Duan et al., 2015). In marine field, Gilbert assessed different types of fuel oils (such as biofuel, hydrogen) consumed by the vessel considering the environmental impact through full life cycle stages to meet the national or international regulations and to mitigate the climate change by reducing carbon emission (Gilbert et al., 2018). Another LCA application in marine sector was carried out by Obrecht and Knez. They compared three container configurations (new designs) for container vessels to determine the optimal design with low carbon emission and to resource consumptions in their study. Their findings indicated the usage of material will be increased by 15% when applying the design with lowest environmental impacts (Obrecht and Knez, 2017). The recycling process of steel was analysed by Rahman's research team by carrying out LCA analysis which considered GWP, resource use, human health and ecosystem quality (Rahman et al., 2016). These researches indicate not only the widely uses of LCA method in different industries but also its feasibility to evaluate and compare alternative options to determine optimal solutions.

LCA has also been used to evaluate the environmental impacts of marine activities to investigate and assess the performances of different alternatives such as selection of various retrofitting options and propulsion systems. Alkaner and Zhou investigated the fuel cell using LCA to evaluate the performance of application on board (Alkaner and Zhou, 2006). Some of the important projects in this area can be summarised as in the following. Eco-REFITEC is an European Union project focus on the developments of green power, on board system and retrofitting options with the consideration of LCA and LCCA of vessels (Blanco-Davis et al., 2014; Blanco-Davis and Zhou, 2014). The SHIPLYS project is another EU project, developing LCA software considering the hybrid propulsion system selection, ship design and retrofitting options (Wang et al., 2017). One of the outputs of the SHIPLYS project was suggested an effective framework for LCA and LCCA for marine vessels aiming to select optimal propulsion systems by modularisation (Jeong et al.,2017). With the help of LCA, the overall environment protection performance could be achieved by optimization of raw material and energy consumption, and recycle processes (Nicolae et al., 2014).

1.3.Research Objectives

The main objective of this paper is to investigate the benefits of solar panel applications to a marine vessel using LCA and LCCA. The proposed method is used to evaluate whether on-board solar panel systems would be a feasible solution, economically and environmentally. For this purpose, this paper introduces a framework of LCA and governs relevant equations and models in Section 2. Following this, an established LCA model is presented including a specific case vessel and then the economic assessment is presented in Section 3. In Section 4, data sensitivity is carried out in consideration of operational hours and weather conditions (sunny hours). Using the model established, their impacts on the fuel saving, emission reduction and payback time are determined, converted and compared in monetary value. Finally, the research findings are highlighted, summarised and concluded in Section 5.

2. Method

This section will introduce the method of life cycle assessment including the framework and associate activities. The formula related to the LCA calculation/estimation are also presented to fundamentally indicate the evaluation of LCA.

2.1.Introduction to Life Cycle Assessment

According to the ISO standards, LCA consists of four processes: the definition of research/analysis objectives and boundaries; life cycle inventory analysis (LCI); life cycle impact analysis (LCIA); and life cycle interpretation (ISO, 2006a, 2006b). The framework of LCA analysis is presented in Figure 1.

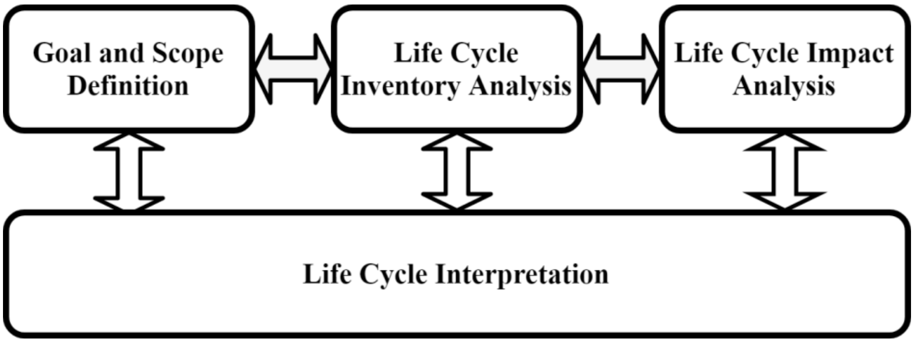

Figure 1 The schematic chart of LCA

The first step of an LCA is to define the objectives and boundaries of analysis. Since typical research could evaluate the performance of systems or products, the focus of LCA study is placed on estimating their environmental impacts. Meanwhile, there are a number of different categories of environmental impacts; GWP, AP (acidification potential) and EP (eutrophication potential) can be considered as major environmental potentials. Once the objective, the scope and boundary of the LCA are determined, certain types of potentials (GWP, AP or EP) can be selected and considered according to the research purpose. Then, based on the selected potentials, a functional unit should be set up as a standard to evaluate and compare one another across various scenarios. A normalization process is performed to convert different emissions into a single representative emission type. For instance, according to the CML database (CML, 2016), the emissions contributing to global warming are normalized and converted into an equivalent quantity of CO_2 represented by the unit of *kg* CO_2 *equivalent*. The same process is carried out for AP and EP of which the fundamental pollutions are sulphur dioxide and phosphate (SO_2 and PO_4^{3-}). Despite such a general guidance, functional units can also be set up freely by end users depending on their own objectives. Another important part in the goal and scope definition is to establish 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, while disregarding the repeated, redundant and less effective parts of the system or product. Therefore, reasonable scope should be made to neglect these unnecessary parts. Furthermore, assumptions based on experts' knowledge may need to be made where real data cannot be retrieved or provided.

After the definition of goal and scope, life cycle inventory analysis can be conducted as shown in the schematic diagram in Figure 2. The figure starts with the defined goal and scope where an initial LCA plan has been selected and determined as mentioned in previous paragraph.

With this plan, the data involved in the plan could be collected, normalized and aggregated so that initial outcomes could be determined. However, the scope of the LCA will be expanded or trimmed depending on the availability of the relevant data. After adjusting the scope based on data availability, similar processes of data collection, normalization and aggregation will be conducted so that a modified but a complete inventory of an LCA can be obtained.

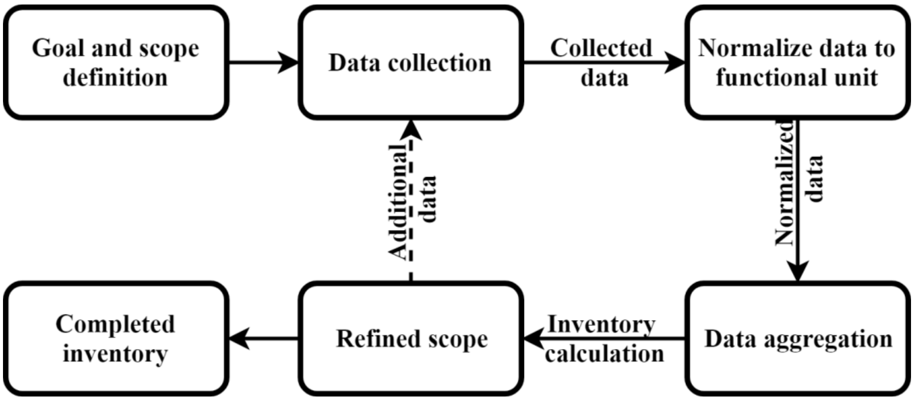

Figure 2 Schematic chart of life cycle inventory analysis

The LCI can be used as a fundamental input for LCIA which consists of three main steps:

a. Selection: impact categories chosen including indicators and characterization models;
b. Classification: LCI results assigned to the selected impact categories;
c. Characterization: calculation using LCI results as input and characterization models to determine results based on category indicator.

In the life cycle interpretation phase, the sensitivity analysis will be carried out to evaluate the influence of varying input parameters on results, i.e. midterm and final results. Through LCI and LCIA, critical parameters or elements can be identified, thereby providing end users with proper views on the cost-benefit of various scenarios. Furthermore, the conclusions, limitations and recommendations of LCA are to be included in this interpretation processes to make sure of illustrating not only the final decisions but also the constraints of the analysis.

The calculation processes of LCA are: 1) to identify the activity; 2) to calculate the cost of investments; 3) to calculate related fuel cost; 4) to calculate related emission released; 5) to calculate the cost due to emission release; 6) to calculate the present value of the costs (due to activity). The formulas involved in the calculation processes will be shown and explained in the following section.

2.2.Formulation for LCA calculation process

The equations required to establish an LCA model will be presented in this section.

The fuel oil consumption during operation phase of vessels is considered as four different operational loads: a) engine mode for sailing; b) engine mode for manoeuvring; c) solar and engine mode for sailing; d) solar and engine mode for manoeuvring. A general equation could be used to calculate the fuel oil consumption under both conditions(Equation (1)):

$$FC_i = Pe_i \times SFOC_i \times H_i \times LS \qquad (1)$$

Where,

FC is the annual fuel consumptions [g];

Pe is the power requirement during vessel operation [kW];

SFOC is the specific fuel oil consumptions of the engine under specific engine output [g/kWh];

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

LS is the years of vessel life span [years];

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

Due to the engine load variation under different operating conditions, the SFOC adjustment of the engine will be considered based on the engine project guide data shown in Figure 3 (MAN Diesel & Turbo, 2015). Equation (2) gives the interpolation curve of this figure.

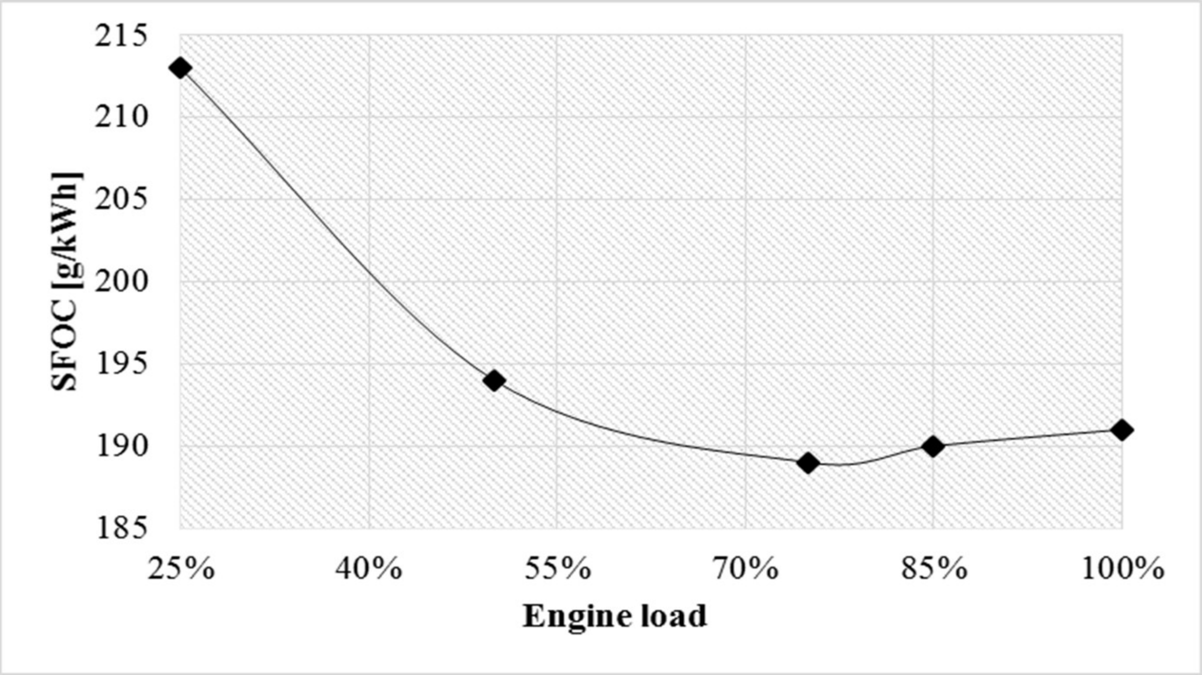

Figure 3 SFOC changes due to engine load variations

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

Where,

$SFOC_y$ is the adjusted specific fuel consumption under a certain engine load [g/kWh];

EL_y is the engine load under a certain operation conditions [%];

$SFOC_{x1}$ and $SFOC_{x2}$ are the specific fuel consumptions retrieved from the engine project guide when the engine loads are EL_{x1} and EL_{x2} [g/kWh];

EL_{x1} and EL_{x2} are engine loads [%].

Similar to fuel oil consumption, the lubricating oil consumptions could be determined using the following equation (3):

$$LOC_i = Pe_i \times SLOC_i \times H_i \times LS \qquad (3)$$

Where,

LOC is the annual lubricating oil consumptions [g];

SLOC is the specific lubricating oil consumptions under specific engine output [g/kWh] (the SLOC of the selected engine provided by engine manufacturer has a range from 0.4 g/kWh to 0.8g/kWh; hence, the realistic lubricating oil consumptions according to the operators' records are used to determine the SLOC so that the results are more reliable).

To consider the cost of a vessel from cradle to grave, the present value is applied to determine the value of future costs before or at the beginning of a project. The following equation (4) is used to determine a cost at a specific year (Žižlavský, 2014):

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

Where,

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

FV is the future value of which will be invested or earned in the nth year [$]; during the operation phase (from year 1 to year 24), the FV covers the operation cost and relative environmental impact in monetary form; at the end of vessel life (year 25), the FV covers the scrapping cost and relative environmental impact in monetary form;

r is the interest rate [%];

n is the number of years.

While the annual operation cost is constant, the present value of the total cost during the vessel life span can be determined as Equation (5):

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

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 [\$] (the determination of AFV is similar to that of FV in Equation 4);

j represents a specific year of life span.

The characterization process is designed to convert different emissions into a common indicator in specific impact categories based on the characterization database, such as CML2001, ReCiPe and TRACI (IERE , 2014; RIVM , 2011). The converting process is shown in the following equation (6):

$$EI_k = FC \times C_k \times CF_k \tag{6}$$

Where,

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

C is the conversion factor from fuel to emission [kg emission /kg fuel consumed] (Smith et al., 2015);

CF is the characterization factor to convert emissions to the indicator [kg emission indicator eq./kg] (CML, 2016);

k represents different emissions in specific impact categories.

While the solar energy is utilized, the minimum quantity of fuel oil saved can be estimated with the following equation (7):

$$FC_s = Pe_s \times H_s \times 3600/LHV \tag{7}$$

Where,

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

Pe_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 cost presents the fuel cost of different materials and machinery transportation from the manufacturers or suppliers to the shipyards or ship operators (Equation (8)):

$$C_{trans} = W \times D \times SDOC \times P_{diesel} \quad (8)$$

Where,

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

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

D is the distance of the transportation [km];

SDOC is the specific diesel oil consumption of the transportation (e.g. trucks) [kg/(km×kg cargo)] (this value can be determined from GaBi truck transportation database);

P_{diesel} is the price of the diesel oil [$/tonne] (Ship and bunker, 2018).

3. Life Cycle and Cost Assessment

The structure of LCA is presented and described in Section 2.1. This chapter presents the LCA procedures ranging from the goal definition to the sensitivity analysis. The benchmark study is carried out for a selected ferry operated in the Sea of Marmara, Turkey; Figure 4 overviews the study procedures. This figure shows data sources and types to be considered in different life stages and the outcome of the analysis. It can be seen from this figure that there are three main stages under investigation: construction, operation and scrapping, which covers most significant activities from the perspective of cost and emission release. There are three main activities in construction phase: purchase, transportation and installation of solar panel arrays considering the price (fuel, electricity, system etc.), fuel consumption, electricity consumption, transportation details to determine the cost and emission release from construction phase. Same as construction phase, operation phase mainly considers the purchase of and emission from fuels (fuel oil, lubricating oil and diesel oil) and their transportation and quantity estimations. Therefore, the operation phase can be assessed based on these economic and environmental factors. At the end of ship life, the scrapping process is evaluated by assessing the transportation, dismantling and recycling of the propulsion systems at the end of vessel life. The cost and emission details are derived from these activity models and will be summed up together with these results from two other phase to determine the overall LCCA and LCA results.

In the following sections, the details of this LCA study will be presented.

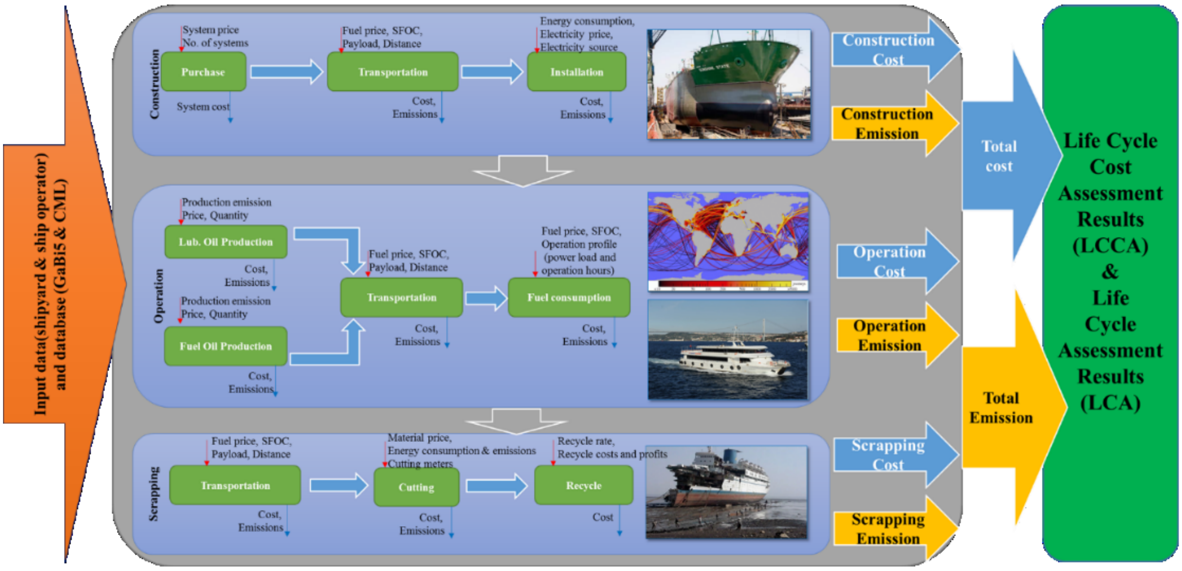

Figure 4 Overview procedure of LCA study

3.1.Goal and Scope Definition

In this section, the purpose of this study is emphasised to define the goal and the scope of the life cycle assessment. The objective and the related information are gathered and presented as well as the assumptions made to complete the assessment.

3.1.1. Goal and Scope of study

The main objective of this LCA is to determine the effectiveness of the on-board solar panels in ways of reducing the global warming impact. 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 Bosphorus Strait, located in the Sea of Marmara (Figure 5). “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” (Sansal, 2018). It has a length of nearly 30 km and widths varying from 0.7 to 3.5 km. Given the geometrical reason, the Bosporus Strait has been subjected heavy shipping traffic which causes significant levels of air pollution.

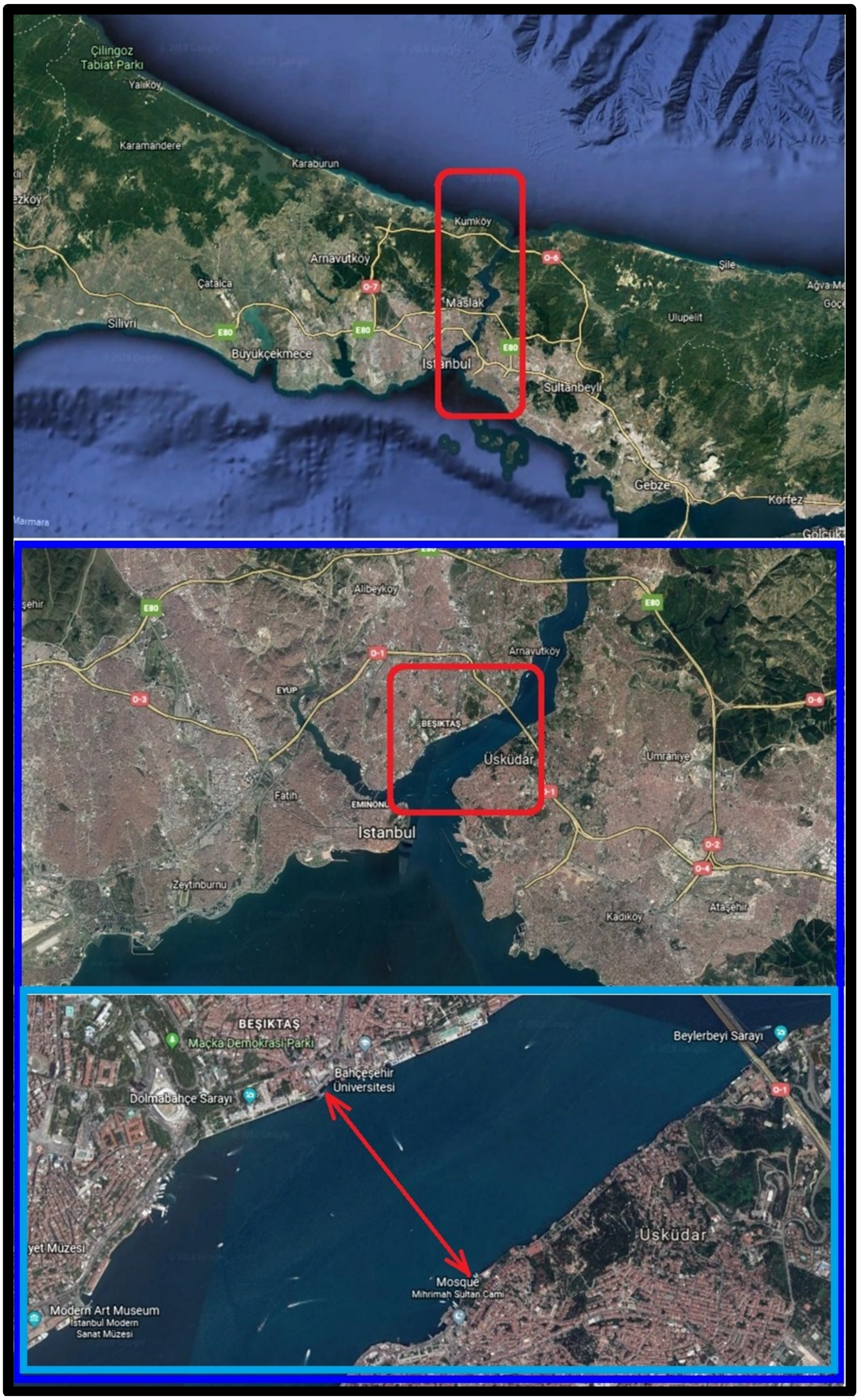

Figure 5 Operation route of the vessel

Considering relevant activities in four life stages of the vessel, the release of emissions can be derived for two different scenarios: Scenario 1 (S1) without solar panels; Scenario 2 (S2) with solar panels. The activities in four life stages of two considered scenarios are listed in Table 2.

Table 2 Activities of two scenarios in four life stages of the vessel

Life stages	**Activities**	
	Scenario 1 (S1)	**Scenario 2 (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
Operation	*Fuel oil consumption*	*Fuel oil consumption*
	Lubricating oil consumption	*Lubricating 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, the scope of the study can be modified by omitting the similar ones. However, as described in Section 2.2, the application of solar panel will change the power requirement and the specific fuel oil consumption. Due to a long period of operation, the reduced fuel consumption accumulates and becomes considerable which also reduces the operation costs significantly. It is also essential to include the operation activities to determine the payback time of the solar panels.

This study aims to determine the impact of solar panels on its contributions to GWP. To consider GHGs, the emissions from CML database and from engine project guide (from MAN Diesel) are compared and included. The functional unit is the 'kg CO_2 eq.' which is commonly used in emission databases. The unit is used while all the emissions which contribute to GWP are converted into equivalent quantity of CO_2.

3.1.2. Assumptions

As discussed earlier, reasonable assumptions are necessary to perform an LCA once the goal and scope are set up. Assumptions were inevitable part of this study because there are a number of feasible application options and conditions but they have yet to be practically decided by the ship-owner. The authors are actively engaged in fundamental and industry focused research on the effect of hybrid ships. All the assumptions were made as a result of discussions with the experts who are actively working in the marine industry. Thus, the assumption is believed not to jeopardize the reliability of our analysis. For the benchmark study, the following assumptions are made:

a. The LCA model takes into account the practical operations by the Turkish ship operator (Dentur);
b. LCA modelling is established and assessed by using GaBi 5;
c. Emissions due to engine fuel consumption are calculated based on emission factors provided by IMO (Smith et al., 2015);
d. The scrapping processes use the data presented and methodology developed by Ling-Chin and Roskilly (J Ling-Chin and Roskilly, 2016);

e. Manufacturing processes for the solar panel from raw materials are not considered because the focus of the LCA and LCCA analysis is on the vessel life span and the solar panel manufacturing is out of scope of this study; furthermore, the investment of solar panels have been considered in the purchasing activities;

f. The SFOC adjustment is considered as linear locally;

g. Properties of solar panel systems are determined based on the information provided by manufacturer and supplier (Alibaba, 2018);

h. It is assumed that all power outputs from solar panel systems 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 panel systems are neglected; the maintenances of the engine in both scenarios are 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 spare changing will be decreased; it will be considered in the future studies;

j. The transportation processes of solar panels are modelled by using GaBi built-in module (GaBi, 2018);

k. The electrical power used in construction and scrapping is supplied from hydro power which is one of the commonly used power generations in Turkey and the fuels supplies are selected from GaBi database by considering locations of the suppliers; the selection of power generation source only impacts the construction and scrapping phases, which are insignificant parts of the results from life cycle inventory assessment;

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 vessel is L42m×B10m.

3.2.Life Cycle Inventory Assessment

According to the goal and scope defined, an LCA model is established within GaBi with consideration of four life stages of the case study ferry. Table 3 presents the characteristics of the ferry and its operational profiles. The installation area of solar panel systems is based on the geometry of the vessel and is assumed as 400m^2. According to the manufacturer's data, the size of one Monocrystalline Silicon solar panel is 1,956mm×991mm×40mm, so maximally 206 solar panels can be installed. The power output of one panel is provided as 0.35 kW so the total power output for the whole solar panel system could reach about 72kW. Figure 6 outlines the proposed power distribution for the vessel. Based on all the information and equations, Figure 7 shows the established LCA model which is designed and developed based on the overview procedure of LCA study (Figure 4). The activities are modelled and the results are processed from one activity to another and also connected to share models for similar activities, such as diesel oil supplied to transportation is similar to the models included in all three phases. Different materials and energy are distinguished using the colour code in this figure so that it is clearly describing the quantities of these flows as well as identifying the shared models in the established LCA model. In Scenario 1, there is no solar energy used in the propulsion system.

Table 3 Case study vessel information

Vessel specification		**Operational profile**		
Name	Hizir Reis	**Category**	**Sailing**	**Manoeuvring**
Flag	Turkey	Operation profile (hours)	9	1
LOA (m)	41.98	Engine Load (%)	85%	50%
B (m)	10	Power required (kW)	1078	634

Gross tonnage (tonne)	327	SFOC (g/kWh)	190	194
		SLOC (g/kWh)	2.85	4.85
Fuel type	HFO	**Solar panel installations**		
Annual operation days (days)	325	Available area	400	m^2
		Area per panel	1.94	m^2
Engine power (kW)	634×2	Number of panels used	206	
Life span (years)	25	Power output per panel	0.35	kW
Year built	2012	Total output power	72.1	kW

Figure 6 Case vessel and outline of power distributions

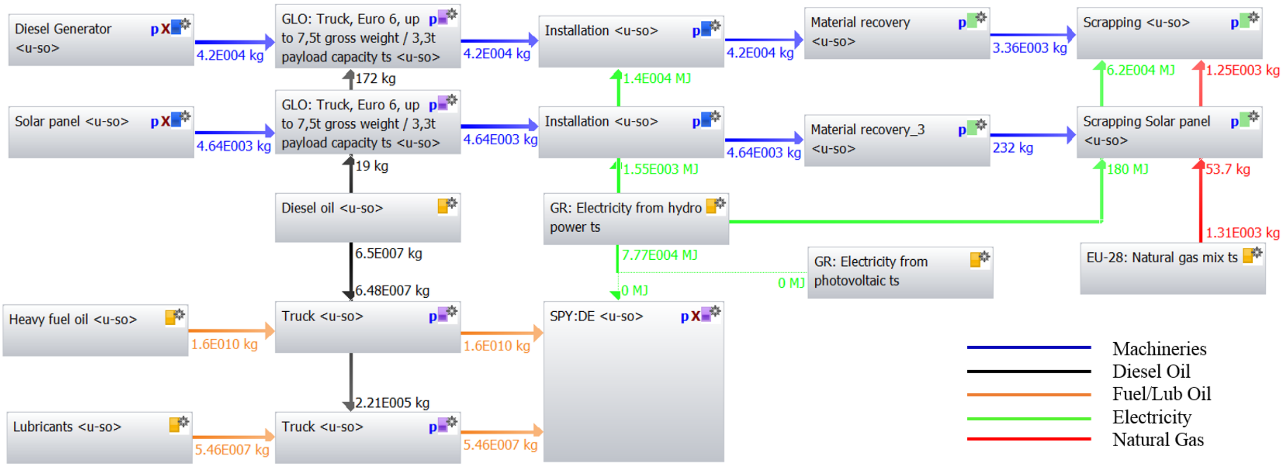

Figure 7 Flowchart of LCA processes and established model in GaBi

With the established LCA model and data/information provided by the ship operator, the emission inventory of the LCA is determined for the vessel in service with only engine running for 325 days a year in 25 years as shown in Table 3.

Table 4 indicates that the ship operation would contribute the most to increase the GWP due to considerable fuel consumptions during operation. The production of fuel oil was also identified to generate large amount of GHGs. On the other hand, the emission levels for other activities, such as production of lubricating oil and diesel oil and the transportation, were revealed relatively insignificant amount.

Table 4 Emission inventory of life cycle assessment

Module name	**Emission Quantity**	**Unit**
Transportation	1.96×10^5	kg CO_2 eq.
Heavy Fuel Oil production	7.36×10^6	kg CO_2 eq.
Lubricating oil production	5.88×10^4	kg CO_2 eq.
Diesel oil production	3.19×10^4	kg CO_2 eq.
Operation: fuel consumption	4.99×10^7	kg CO_2 eq.
Other activities	6.70×10^2	kg CO_2 eq.
Total	5.75×10^7	kg CO_2 eq.

3.3.Life Cycle Impact Assessment

To compare the levels of GWP across two different scenarios, one additional analysis with solar panel application is conducted; the flowchart of this analysis is presented in Figure 8 and the results of the analysis are revealed in Figure 9, indicating that the level of GWP can be reduced if applying Scenario 2 (based on the calculation processes 1-4-5-6 in Section 2.1.) . Such results can be a good reference of describing the potential benefits of on-board solar panel system applications.

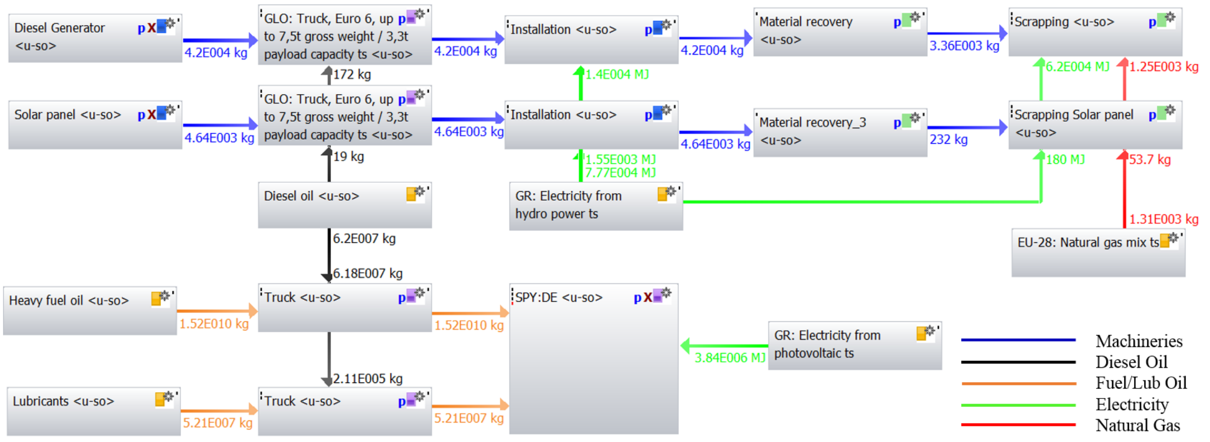

Figure 8 LCA flowchart of Scenario 2: with solar panel application

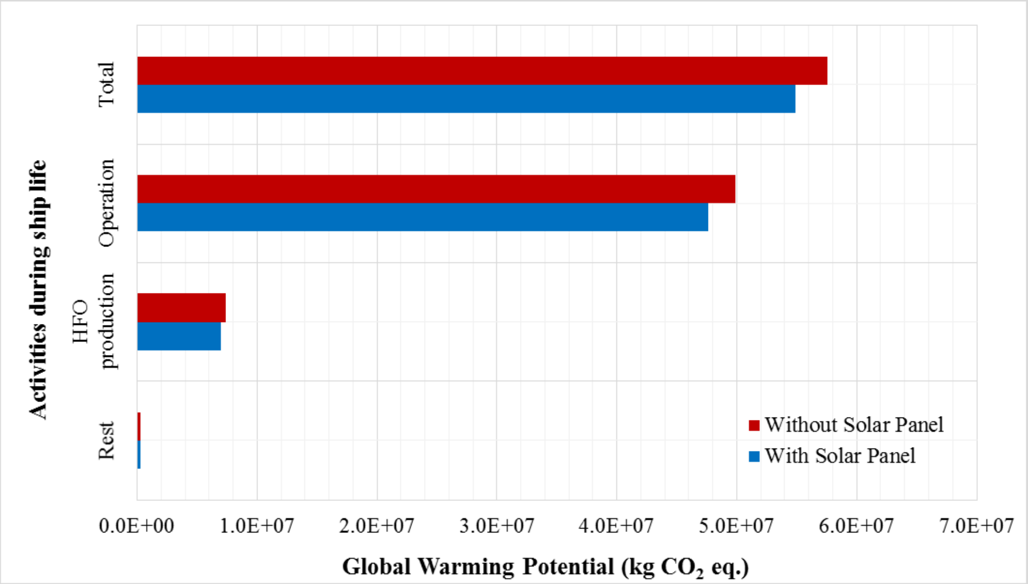

Figure 9 Comparison of GWP of two scenarios

3.4.Sensitivity Analysis 1: Operation days and sunny hours

Since the operational days and weather conditions (such as sunny hours per day) are not certain during the operation of the vessel, two sensitivity analyses are conducted to determine how operation conditions could impact the LCA results in terms of equivalent CO_2 emissions release.

Table 5 presents three different operation conditions with varying annual operation days: 325 days, 217 days and 108 days. This table illustrates the relationships between the operation days and the life cycle equivalent CO_2 emission. As it is expected, a reduction during operating days results in a decrease in the quantity of emission released. According to the LCIA, the operation phase contributes the most of the emission release among all the life stages considered, which are also presented in these three operation conditions in the table.

The table also presents another three operation conditions with varying sunny hours per day: 6 hours, 4 hours and 2 hours. It indicates that while the weather condition is different from the benchmark scenario, the life cycle equivalent CO_2 emission will be impacted. When the sunny hours per day is less, there will be more quantity of emission release. The emission releases from operation phase are also presented in the table under these three operation conditions.

Table 5 Results of sensitivity analyses

Sensitivity analysis of the operation days per year on the GWP				
Category	Operation days per year			Unit
	325 days	217 days	108 days	
Operation	4.75×10^7	3.17×10^7	1.58×10^7	kg CO_2 eq.
Total	5.48×10^7	3.66×10^7	1.82×10^7	kg CO_2 eq.

Sensitivity analysis of the sunny hours per day on the GWP				
Category	Sunny hours per day			Unit
	2 hours	4 hours	6 hours	
Operation	4.92×10^7	4.84×10^7	4.77×10^7	kg CO_2 eq.
Total	5.67×10^7	5.59×10^7	5.50×10^7	kg CO_2 eq.

3.5.Economic Assessment

After the estimating of life cycle environmental impact, the economic assessment is carried out in this section, covering the costs associating with the investment, operation and decommissioning. A sensitivity analysis is conducted to examine the impact of uncertain parameters to the cost-effectiveness of this application.

3.5.1. Life Cycle Cost Assessment

The objective of this section is to investigate the cost effectiveness and payback time period of the solar panel system investment. Basically, the LCCA is applied to investigate either cash flows or a cost comparison between alternatives (ISO, 2017). Since most of the activities for benchmark and contrast scenarios are the same, the LCCA of the case study will only focus on fuel costs and carbon credits. Present value will be calculated in consideration of monetary value of time passage.

According to Section 2.2, the fuel consumption is based on the power requirement, operational hours and SFOC. 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 6 (Holiday Weather, 2018; Meteoroloji Genel Müdürlüğü, 2018).

Table 6 Daily average sunny hours for different months (1929-2017)

Month	Daily sunny hours	Total sunny hours
January	2.9	89.9
February	3.6	100.8
March	4.6	142.6
April	6.5	195.0
May	8.8	272.8
June	10.6	318.0
July	11.5	356.5
August	10.6	328.6
September	8.2	246.0
October	5.7	176.7
November	4.0	120.0
December	2.7	83.7

The new SFOC could be determined using the SFOC adjustment equation after the power output from solar panel system is derived. Table 7 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 7 Engine SFOC under different power loads

Condition No.	Loads (%)	SFOC (g/kWh)
1	85.0	190.0
2	81.2	189.6
3	50.0	194.0
4	44.3	195.1

After determination of adjusted SFOCs, the fuel consumption can be obtained; together with fuel price in Istanbul (Ship and bunker, 2018), the annual fuel cost and fuel saved can be derived and are presented in Table 8. Considering the present value under condition of 25 years life span and 8% interest rate (Trading Economics, 2018) the saved life cycle cost is adjusted to be $130275.

Table 8 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 obtained from the manufacturer, the cost of a single solar panel ranges from $0.35 to $0.4 per watt so the total cost of purchasing solar panels can be estimated as maximum $25,235 (based on the calculation processes 1-2-3-6 in Section 2.1.). Therefore, the payback time period of the investigation would be less than 3 years, even while without considering the present value.

According to the third GHG report from IMO, the carbon conversion factor of HFO is 3.114g/g fuel so the quantity of carbon emission reduction for 25 years' operation can be determined as 2,372 tonnes. Since there is no active policy or regulation on carbon emissions, based on the report from Maibach et al., the lower (Lo), central (Ce) and higher (Hi) carbon credits value for one tonne of CO_2 emission in 2020 will be equivalent to \$21, \$50 and \$87 (Maibach et al., 2007). The respective saved carbon credit costs are \$44,886, \$106,871 and \$185,956. Therefore, with the consideration of carbon credits in LCCA, the payback time period 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.

3.5.2. Sensitivity Analysis 2: Sunny hours

To assess the impact of daily average sunny hours on the fuel cost saving, carbon credits and payback time period, three different scenarios are considered in this section: 6 hours, 4 hours and 2 hours. The results are presented in Table 9. It is also determined that the investment of solar panel system could be paid back at the end of the lifespan in condition that a minimum daily average sunny hour of 0.56 hours (about 34 minutes) with the lower level carbon credit. Given this worst case scenario, the fuel cost saving is estimated at \$25,785; the saved carbon credit costs are estimated at \$3,391.

Table 9 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 (Lo) (year)	3	4	7
Payback year (Ce) (year)	2	3	6

Payback year (Hi) (year)	2	3	5

4. Results and Discussion

This part will illustrate the results derived from the assessment of this paper including the evaluation results of LCA and LCCA and the impact of some significant parameters on the results. Some further discussions are made to expand the analysis to a broader vision in the shipping industry. Recommendations of LCA method are also made to shipping industry to help shipyard, ship owner, operator and policy makers to evaluate different alternatives, both technologies and strategies. Some further discussions are mentioned to be considered as the weak points of this study and possible future works.

4.1.Impact of energy efficiency of solar panel system on LCA and LCCA

Indeed, it is not practically credible to use 100% of solar power from the panels for vessel propulsion, because of energy transmission and combination losses between engines and solar panels. This section discusses the influence of varying efficiencies of the solar panels on the estimation of the life cycle fuel cost. Since there is no practical system available, this approach is worthy to provide to ship operator with an insight of the performance of solar panel system application. Considering the energy losses, four different energy efficiencies are considered as: 90%, 80%, 70% and 52%. The last scenario with 52% of energy efficiency is referred to RETScreen (Natural Resources Canada, 2018). Table 10 presents how the energy efficiencies impact the life total cost. Not surprisingly, it is obvious that high energy efficiency has a high level of cost savings. Although the daily change in fuel consumption is minor, when it is accumulated through the vessel’s life, the total fuel cost difference is considerable. The payback time period is, more or less, fixed around 3 years when the energy efficiency is changed from 100% to 90%. The payback time periods for 80% and 70% energy efficiencies are 4 and 5 years respectively. The payback time period is also derived when energy efficiency is 52% referring to RETScreen software which is 9 years.

Table 10 Comparison of fuel cost saved under different energy efficiencies

Scenarios	Full Load	90%	80%	70%	52%	Unit
Engine Load	79.31%	79.88	80.91	82.13	83.49	
Daily Fuel Consumption (DFC)	1,966	1,966	1,966	1,966	1,966	kg/day
New DFC (6.7 hours sunny)	1,270	1,278	1,295	1,316	1,338	kg/day
New DFC (3.3 hours not sunny)	602	602	602	602	602	kg/day
New DFC (total)	1,872	1,880	1,898	1,918	1,941	kg/day
Annual FC (Benchmark)	638,961	638,961	638,961	638,961	638,961	kg
Annual FC (New)	608,489	611,156	616,706	623,373	630,753	kg
Annual fuel saved	30.47	27.80	22.26	15.59	8.21	tonne
Fuel price	401	401	401	401	401	$/tonne
Annual fuel cost saved	12,204	11,136	8,913	6,243	3,287	$
Life cycle fuel cost saved	305,101	278,396	222,832	156,079	82,185	$

4.2.Impact of solar panel system price on the payback time period

Based on the manufacturer’s quotation, the price of selected solar panel is $0.4/W. However, the price may be varied in the future or not available at certain circumstances so three more scenarios are presented and investigated to determine the impact of solar panel system cost on the payback time period. Three scenarios are $0.6/W, $0.8/W and $1.2/W. Applying the same LCCA processes, the payback time periods are determined to be 4 years, 5 years and 8 years. Therefore, even if the price of solar panels is tripled, the investment could be paid back during the vessel’s life span.

Considering the data provided by RETScreen, the price for solar panel system with 52% of energy conversion efficiency is $3.3/W (which is about 7 times of the price from the manufacturer's quotation), hence, it requires an investment of $201,009 and also an operation and maintenance cost of $2,682. Under this circumstance, when only considering the fuel cost saving during the operation stage, the payback of investment will not be possible during the vessel's life span (payback time period is 62 years). Therefore, it makes the carbon policy to play an important role to proactively urge ship owners to turn their attention to green shipping technologies. To ensure the investment can be paid back during or at the end of life, the carbon credit should be over $190 per tonne.

4.3.Application on Fleet

The LCA and LCCA have been carried out for one ferry and the performances of solar array application from perspectives of environmental protection and cost effectiveness are significant. To extent the investigation from one single target to a fleet will provide a deeper indication on the benefits of solar array application. Table 11 lists the vessels information of the ferry fleet retrieved from the ship operator, Bodrum. With the consideration of the vessels' specifications, the maximum deck areas are considered to be solar panel installation areas. The lowest energy efficiency, 52%, is applied for this fleet analysis. The fuel consumptions are estimated using the same SFOC and engine load. Since the HFO consumption will be reduced due to the usage of energy provided from solar array, the reduction amount of HFO consumed can be estimated through dividing the energy from solar array by the LHV of HFO. Therefore, the fuel oil saved and carbon emission reduction from the fleet due to the application of solar panel array is derived and presented in Table 12. It indicates that the application of solar arrays to a fleet will bring considerable benefits from both environmental and economic aspects due to the increasing usage of solar energy during vessels operation.

Table 11 Fleet information from ship operator

	LOA (m)	**B (m)**	**DWT (tonne)**	**Engine Output (kW)**

Hizir Reis	42.0	10.0	327	1268
Fahri Kaptan 3	33.0	5.7	122	432.5
Fahri Kaptan 2	34.0	8.0	135	650
Kemal Reis 3	38.0	8.0	134	866
Fahri Kaptan 1	17.8	5.7	35.4	418
Sunny Express	39.0	7.0	228	1342

Source: *http://www.bodrumferibot.com/tr/ourfleet.asp*

Table 12 Fuel saved and carbon emission reduction of fleet

	Area	**Energy efficiency**	**Power output**	**Hours**	**Energy saved**	**Fuel saved**	**LS fuel saved**	**LS carbon reduction**
Unit	m^2	100%	kW		kJ	kg	tonne	tonne
Hizir Reis	400	52%	72.1	6.6	2.9E+08	7369	184	574
Fahri Kaptan 3	179	52%	32.2	6.6	1.3E+08	3291	82	256
Fahri Kaptan 2	259	52%	46.6	6.6	1.9E+08	4758	119	370
Kemal Reis 3	290	52%	52.2	6.6	2.1E+08	5330	133	415
Fahri Kaptan 1	97	52%	17.2	6.6	6.8E+07	1753	44	136
Sunny Express	260	52%	46.9	6.6	1.9E+08	4793	120	373
Total						27293	682	2125

4.4.Risk identification and mitigation

The risk identification process helps to foresee possible hazard while applying solar panel arrays on marine vessels as there are a few practical applications and related regulations all over the world. There are many different risk assessment methods available such as HAZOP, FMEA, FMECA, FTA ETA and FSA (Chen et al., 2018; Gul and Ak, 2018; IMO, 2002). This paper focuses on the identification and mitigation of possible hazards and comprehensive risk assessment will be carried out in future studies. There are four different types of hazards under consideration: installations, operations, environments and technical risks (Table 13). These hazards can be avoided before they occur and also can be controlled while they occur. Table 13 shows the mitigations for different hazards.

Table 13 Hazard identifications and mitigations

	Hazards	**Mitigations**
No.	**Installation**	
1	Fire caused by welding	Increase fire awareness of workers; Remove flammable from welding working place; Prepare fire extinguisher
2	Fire caused by cutting	Increase fire awareness of workers; Remove flammable from cutting working place; Prepare fire extinguisher
3	Faulty installation due to unskilled worker	Training arrangement; Inspection after installation
	Operation	
4	Solar panel not working	Training arrangement before operation; Use diesel generator; Inspection and repair
5	Solar system disconnected from switchboard	Training arrangement before operation; Use diesel generator
6	Disoperation	Training arrangement before operation; Use diesel generator
	Environment	
7	Damaged by severe weather	Use diesel generator; Forecast to avoid severe weather; Repair damaged part
8	Corrosion due to rain accumulated	Use diesel generator; Clean up stagnant water; Repair damaged part
9	Animal collision	Use diesel generator; Repair damaged part
	Technology	
10	Control system faulty	Use diesel generator; Repair or replace control system with new one
11	Invertor faulty	Use diesel generator; Repair or replace invertor
12	Distributor faulty	Use diesel generator; Repair or replace distributor

4.5.A general evaluation method

LCA could work as a tool for selection of green technologies and as an evaluation method for policy makers to investigate the *'environmental friendliness'* of a vessel. With the LCA model established based on specific cases, the environmental impact of green technologies could be determined and compared. Following the economic assessment processes, the life cycle cost will be derived and together with the initial investment information, the payback time period will be obtained. For any unavailable details, operators or end users can carry out sensitivity analysis to determine their environmental and economic impacts so that a reasonable assessment could be conducted and help users to make their decisions.

4.6.Further discussion

This paper assessed the performance and payback time period for on-board application of solar panels under different energy efficiencies. It is clear that current applications of solar panel system have been highly limited due to low energy efficiency but relatively high investment costs. Moreover, due to limited space utilisation, the power provided by solar panel system can only manage to contribute to covering a small portion of total power loads. Therefore, their energy efficiencies need to be enhanced.

Since the electricity generation from a solar panel is sensitive to real time weather conditions, i.e. sunny hours, having a stable energy provision for propulsion system is another issue. Electrical fluctuations are always harmful to the stability of the vessel. Although the average annual sunny hours are applied and the results suggest reasonable solutions in this paper, it is still necessary to consider the fluctuations of the solar power output. It is recommended to store the solar energy in battery packs so that continuous and stable electricity supply will be achieved. However, the additional equipment also increases the initial investment, thereby prolonging the payback time period. While in this situation, further analysis on the modified system could be carried out using LCA to determine the impact of the new system to the vessel in the perspective of environmental friendliness and cost effectiveness.

The risk issue has also a significant importance for solar panel system applications. While applying solar panel arrays, there are many possible hazards which may affect their performance and life span. Therefore, a future study should also consider the life cycle impacts of risks to determine a more detailed and comprehensive LCA study for the evaluations of green shipping technologies.

5. Conclusions

This paper presents the impact of the application of a solar panel system on a short route ferry operating in Turkey. The LCA method is applied considering from cradle to grave costs of the vessel by establishing an LCA model as well as evaluating the environmental impact and assessing the sensitivities of important parameters. The research results from the LCA analysis indicate that the reduction of GHG emissions release after the application of solar array is around 3×10^6 kg CO_2 eq. during the lifespan of the ferry. It indicates that applying solar power system on a vessel as a future marine power is a promising technique which could make one of the best uses of solar energy as it is a greener energy than fossil fuels. To expand the application from one case ferry to all possible target vessel, no matter it has a short route or is an ocean going vessel, the mitigation effect on the global warming will become significant. However, the sensitivity analysis shows that the relationship between the ferry working hours and emission release is nearly linear. It means that the longer ferry under working condition, the more GHG emission will be generated because the reduction effect from solar array application is incomparable with the emission generated from ferry operation. To effectively improve the reduction effect, it is essential to increase the energy conversion efficiency of the solar array. Due to the limitation of solar conversion technology, the energy conversion efficiency is currently low. Even though the theoretical analysis presents the advantages of solar array application, the benefits of the application will be hardly realized without the development and improvement in advanced solar conversion technology.

From the perspective of cost, with consideration of SFOC adjustment, the fuel cost saved after 25 years' operation could reach approximate $300,000 and about $130,000 in present value. The payback time period of investing in the solar panel system was estimated at only 3 years. It indicates the application of solar array will not only bring benefits from the perspective of environmental protection, but also save the operation costs of the ferry. Furthermore, as there is no carbon credit currently in force in Turkey, three different levels of carbon credit values from the EU are applied to find out the carbon credit saving from the solar panel application. It is a promising investment that about $45,000 carbon credits will be saved no matter which level of carbon credits is applied. Since there is a lack of policy on carbon emission release in Turkey, this study will help policy makers to have a deeper insight of green technologies from the perspective of environment and economic friendliness. The worst scenario with 52% energy efficiency and price of $3.3/W indicates: with a carbon credit over $190 per tonne, the investment of solar panel system could be paid back during the life of the vessel. The sensitivity analysis on energy efficiency also illustrates that increasing the energy conversion efficiency of solar panel system is highly demanding which is restricting its development and application, especially on short route ferries.

This paper eventually provides a guide of evaluation processes using LCA and LCCA method to assess the performance of green technologies so that policy makers and ship operators could make decisions on the technology selections based on the LCA results.

6. Acknowledgement

The authors wish to thank the Dentur Avrasya for providing the data used in this paper. The authors also gratefully acknowledge that the research presented in this paper was partially generated as part of the HORIZON 2020 SHIPLYS (Ship Life Cycle Software Solutions) Project, Grant agreement number 690770.

7. References

Alibaba, 2018. High Efficiency Oem 48v Monocrystalline 72 Cell 350w Solar Panel - Buy Solar Panel,350w Solar Panel,Solar Panel 350w Product on Alibaba.com [WWW Document]. URL https://www.alibaba.com/product-detail/High-Efficiency-OEM-48V-Monocrystalline-72_60735581346.html?spm=a2700.7724838.2017115.15.59f06f6f3BW8Xm (accessed 7.18.18).

Alkaner, S., Zhou, P., 2006. A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application. J. Power Sources 158, 188–199. https://doi.org/10.1016/J.JPOWSOUR.2005.07.076

Beccali, M., Cellura, M., Longo, S., Guarino, F., 2016. Solar heating and cooling systems versus conventional systems assisted by photovoltaic: Application of a simplified LCA tool. Sol. Energy Mater. Sol. Cells 156, 92–100. https://doi.org/10.1016/j.solmat.2016.03.025

Blanco-Davis, E., del Castillo, F., Zhou, P., 2014. Fouling release coating application as an environmentally efficient retrofit: a case study of a ferry-type ship. Int. J. Life Cycle

Assess. 19, 1705–1715. https://doi.org/10.1007/s11367-014-0780-8

Blanco-Davis, E., Zhou, P., 2014. LCA as a tool to aid in the selection of retrofitting alternatives. Ocean Eng. 77, 33–41. https://doi.org/10.1016/J.OCEANENG.2013.12.010

Boden, T.A., Marland, G., Andres, R.J., 2017. Global, Regional, and National Fossil-Fuel CO2 Emissions. Oak Ridge, Tenn., U.S.A. . https://doi.org/10.3334/CDIAC/00001_V2017.

Branker, K., Pathak, M., Pearce, J.M., 2011. A Review of Solar Photovoltaic Levelized Cost of Electricity. Renew. Sustain. Energy Rev. 15, 4470–4482. https://doi.org/10.1016/j.rser.2011.07.104

Chen, J., Zhang, W., Li, S., Zhang, F., Zhu, Y., Huang, X., 2018. Identifying critical factors of oil spill in the tanker shipping industry worldwide. J. Clean. Prod. 180, 1–10. https://doi.org/10.1016/J.JCLEPRO.2017.12.238

CMAL, 2018a. CMAL [WWW Document]. URL http://www.cmassets.co.uk/ferry/mv-hallaig-2/ (accessed 5.18.18).

CMAL, 2018b. CMAL [WWW Document]. URL http://www.cmassets.co.uk/ferry/mv-catriona/ (accessed 5.18.18).

CMAL, 2018c. CMAL [WWW Document]. URL http://www.cmassets.co.uk/ferry/mv-lochinvar-2/ (accessed 5.18.18).

CML, 2016. CML-IA Characterisation Factors - Leiden University [WWW Document]. Inst. Environ. Sci. URL https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors (accessed 7.18.18).

Cucinotta, F., Guglielmino, E., Sfravara, F., 2017. Life cycle assessment in yacht industry: A case study of comparison between hand lay-up and vacuum infusion. J. Clean. Prod. 142, 3822–3833. https://doi.org/10.1016/J.JCLEPRO.2016.10.080

Delogu, M., Zanchi, L., Maltese, S., Bonoli, A., Pierini, M., 2016. Environmental and economic life cycle assessment of a lightweight solution for an automotive component: A comparison between talc-filled and hollow glass microspheres-reinforced polymer composites. J. Clean. Prod. 139, 548–560. https://doi.org/10.1016/J.JCLEPRO.2016.08.079

Diab, F., Lan, H., Ali, S., 2016. Novel comparison study between the hybrid renewable energy systems on land and on ship. Renew. Sustain. Energy Rev. 63, 452–463. https://doi.org/10.1016/J.RSER.2016.05.053

Duan, H., Hu, M., Zhang, Y., Wang, J., Jiang, W., Huang, Q., Li, J., 2015. Quantification of carbon emissions of the transport service sector in China by using streamlined life cycle assessment. J. Clean. Prod. 95, 109–116. https://doi.org/10.1016/J.JCLEPRO.2015.02.029

Eco, M.P., 2012. Aquarius Eco Ship | Eco Marine Power [WWW Document]. Eco Mar. Power. URL https://www.ecomarinepower.com/en/aquarius-eco-ship (accessed 11.22.18).

Eskew, J., Ratledge, M., Wallace, M., Gheewala, S.H., Rakkwamsuk, P., 2018. An environmental Life Cycle Assessment of rooftop solar in Bangkok, Thailand. Renew. Energy 123, 781–792. https://doi.org/10.1016/J.RENENE.2018.02.045

Euroupean Union, 2012. Energy roadmap 2050 Energy. https://doi.org/10.2833/10759

Fredga, K., Mäler, K.G., 2010. Life cycle analyses and resource assessments. Ambio 39, 36–41. https://doi.org/10.1007/s13280-010-0063-y

GaBi, 2018. Software: GaBi Software [WWW Document]. URL http://www.gabi-software.com/uk-ireland/software/ (accessed 7.18.18).

Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., Murphy, A., 2018. Assessment of full life-cycle air emissions of alternative shipping fuels. J. Clean. Prod. 172, 855–866. https://doi.org/10.1016/J.JCLEPRO.2017.10.165

Glykas, A., Papaioannou, G., Perissakis, S., 2010. Application and cost–benefit analysis of solar hybrid power installation on merchant marine vessels. Ocean Eng. 37, 592–602. https://doi.org/10.1016/J.OCEANENG.2010.01.019

Greenline, 2018. Greenline [WWW Document]. URL https://www.greenlinehybrid.si/#ourfleet (accessed 5.18.18).

Gul, M., Ak, M.F., 2018. A comparative outline for quantifying risk ratings in occupational health and safety risk assessment. J. Clean. Prod. 196, 653–664. https://doi.org/10.1016/J.JCLEPRO.2018.06.106

Holiday Weather, 2018. Istanbul Average Annual Weather - Holiday Weather [WWW Document]. URL https://www.holiday-weather.com/istanbul/averages/ (accessed 7.18.18).

Hurtigeruten, 2018. Hurtigeruten [WWW Document]. URL https://www.hurtigruten.co.uk/our-ships/ms-roald-amundsen/ (accessed 5.18.18).

IERE (The Institute for Environmental Research and Education), 2014. TRACI

Characterization Factors [WWW Document]. IERE (The Inst. Environ. Res. Educ. URL https://iere.org/programs/earthsure/TRACI-factors.htm

IMO, 2002. Formal Safety Assessment [WWW Document]. Int. Marit. Organ. URL http://www.imo.org/en/OurWork/safety/safetytopics/pages/formalsafetyassessment.aspx (accessed 8.10.18).

Imteaz, M.A., Ahsan, A., 2018. Solar panels: Real efficiencies, potential productions and payback periods for major Australian cities. Sustain. Energy Technol. Assessments 25, 119–125. https://doi.org/10.1016/J.SETA.2017.12.007

Inhabitat, 2018. Inhabitat [WWW Document]. URL https://inhabitat.com/solaris-is-the-33m-solar-powered-super-yacht-of-the-future/ (accessed 5.18.18).

ISO, 2017. ISO 15686-5:2017 - Buildings and constructed assets -- Service life planning -- Part 5: Life-cycle costing [WWW Document]. URL https://www.iso.org/standard/61148.html (accessed 7.18.18).

ISO, 2006a. ISO 14040:2006 - Environmental management -- Life cycle assessment -- Principles and framework [WWW Document]. Int. Organ. Stand. Geneva, Switz. URL https://www.iso.org/standard/37456.html (accessed 7.18.18).

ISO, 2006b. ISO 14044:2006 - Environmental management -- Life cycle assessment -- Requirements and guidelines [WWW Document]. Int. Organ. Stand. Geneva, Switz. URL https://www.iso.org/standard/38498.html (accessed 7.18.18).

Jacobson, M.Z., Delucchi, M.A., Bazouin, G., Dvorak, M.J., Arghandeh, R., Bauer, Z.A.F., Cotte, A., de Moor, G.M.T.H., Goldner, E.G., Heier, C., Holmes, R.T., Hughes, S.A., Jin, L., Kapadia, M., Menon, C., Mullendore, S.A., Paris, E.M., Provost, G.A., Romano, A.R., Srivastava, C., Vencill, T.A., Whitney, N.S., Yeskoo, T.W., 2016. A 100% wind, water, sunlight (WWS) all-sector energy plan for Washington State. Renew. Energy 86, 75–88. https://doi.org/10.1016/J.RENENE.2015.08.003

Jeong, B., Wang, H., Oguz, E., Zhou, P., 2018. An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems. J. Clean. Prod. 187, 111–130. https://doi.org/10.1016/J.JCLEPRO.2018.03.184

Kannan, R., Leong, K.C., Osman, R., Ho, H.K., Tso, C.P., 2006. Life cycle assessment study of solar PV systems: An example of a 2.7 kWp distributed solar PV system in Singapore. Sol. Energy 80, 555–563. https://doi.org/10.1016/J.SOLENER.2005.04.008

Kavli, H., Oguz, E., Tezdogan, T., 2017. A comparative study on the design of an environmentally friendly RoPax ferry using CFD. Ocean Eng. 137, 22–37. https://doi.org/10.1016/J.OCEANENG.2017.03.043

Ling-Chin, J., Roskilly, A.P., 2016. Investigating a conventional and retrofit power plant on-board a Roll-on/Roll-off cargo ship from a sustainability perspective – A life cycle assessment case study. Energy Convers. Manag. 117, 305–318. https://doi.org/10.1016/J.ENCONMAN.2016.03.032

Ling-Chin, J., Roskilly, A.P., 2016. Investigating the implications of a new-build hybrid power system for Roll-on/Roll-off cargo ships from a sustainability perspective – A life cycle assessment case study. Appl. Energy 181, 416–434. https://doi.org/10.1016/J.APENERGY.2016.08.065

Liu, H., Zhang, Q., Qi, X., Han, Y., Lu, F., 2017. Estimation of PV output power in moving and rocking hybrid energy marine ships. Appl. Energy 204, 362–372. https://doi.org/10.1016/J.APENERGY.2017.07.014

M. Lunardi, M., Alvarez-Gaitan, J.P., Chang, N.L., Corkish, R., 2018. Life cycle assessment on PERC solar modules. Sol. Energy Mater. Sol. Cells 187, 154–159. https://doi.org/10.1016/J.SOLMAT.2018.08.004

Maibach, M., Schreyer, C., Sutter, D., Van Essen, H.P., Boon, B.H., Smokers, R., Schroten, A., Doll, C., Pawlowska, B., 2007. Handbook on Estimation of External Cost in the Transport Sector. Produced within the Study Internalisation Measures and Policies for All external Cost of Transport (IMPACT) version 1.0.

MAN Diesel & Turbo, 2015. L16/24 Project Guide-Marine Four-stroke GenSet compliant with IMO Tier II.

Meteoroloji Genel Müdürlüğü, 2018. Turkish weather database - Ministry of Forest and Water Management [WWW Document]. URL https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?m=ISTANBUL (accessed 7.18.18).

Natural Resources Canada, 2018. RETScreen | Data Analysis Software and Modelling Tools [WWW Document]. URL http://www.nrcan.gc.ca/energy/software-tools/7465 (accessed 7.18.18).

Newman, E., 1992. Solar Powered Electric Ship System. 5,131,341.

Nicolae, F., Popa, C., Beizadea, H., 2014. APPLICATIONS OF LIFE CYCLE ASSESSMENT (LCA) IN SHIPPING INDUSTRY, in: GEOCONFERENCE ON ENERGY AND CLEAN TECHNOLOGIES, VOL II. STEF92 Technology Ltd, Albena, BULGARIA, pp.

289–296.

Obrecht, M., Knez, M., 2017. Carbon and resource savings of different cargo container designs. J. Clean. Prod. 155, 151–156. https://doi.org/10.1016/J.JCLEPRO.2016.11.076

Poland@Sea, 2018. Poland@Sea [WWW Document]. URL http://www.polandatsea.com/the-worlds-largest-plug-in-hybrid-ship-begins-to-take-form/ (accessed 5.18.18).

Rahman, S.M.M., Handler, R.M., Mayer, A.L., 2016. Life cycle assessment of steel in the ship recycling industry in Bangladesh. J. Clean. Prod. 135, 963–971. https://doi.org/10.1016/J.JCLEPRO.2016.07.014

Raugei, M., El Fakir, O., Wang, L., Lin, J., Morrey, D., 2014. Life cycle assessment of the potential environmental benefits of a novel hot forming process in automotive manufacturing. J. Clean. Prod. 83, 80–86. https://doi.org/10.1016/J.JCLEPRO.2014.07.037

Raugei, M., Morrey, D., Hutchinson, A., Winfield, P., 2015. A coherent life cycle assessment of a range of lightweighting strategies for compact vehicles. J. Clean. Prod. 108, 1168–1176. https://doi.org/10.1016/J.JCLEPRO.2015.05.100

RIVM (The Dutch National Institute for Public Health and the Environment), 2011. LCIA: the ReCiPe model - RIVM [WWW Document]. RIVM (The Dutch Natl. Inst. Public Heal. Environ. URL https://www.rivm.nl/en/Topics/L/Life_Cycle_Assessment_LCA/ReCiPe (accessed 7.18.18).

Rogner, H.-H., Zhou, D., R. Bradley., Crabbé, P., Edenhofer, O., Hare, B., Kuijpers, L., Yamaguchi, M., 2007. Introduction. In Climate Change 2007: Mitigation. Contribution of

Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA.

Sansal, B.H., 2018. Seas of Turkey - All About Turkey [WWW Document]. URL http://www.allaboutturkey.com/sea.htm (accessed 7.18.18).

Schaffrin, C., Fed. Rep. of Germany, K., 1993. Energy-generating Plant, Particularly Propeller-type Ships Propulsion Plant, including a Solar Generator. 5,235,266.

Shafiee, S., Topal, E., 2009. When will fossil fuel reserves be diminished? Energy Policy 37, 181–189. https://doi.org/10.1016/j.enpol.2008.08.016

Ship and bunker, 2018. Istanbul Bunker Prices - Ship & Bunker [WWW Document]. URL https://shipandbunker.com/prices/emea/medabs/tr-ist-istanbul (accessed 7.18.18).

Ship Technology, 2018a. Ship Technology [WWW Document]. URL https://www.ship-technology.com/projects/viking-lady/ (accessed 5.18.18).

Ship Technology, 2018b. Ship Technology [WWW Document]. URL https://www.ship-technology.com/projects/planetsolar/ (accessed 5.18.18).

Shipspotting, 2016. YUE YOU 129 - IMO 8010879 - ShipSpotting.com - Ship Photos and Ship Tracker [WWW Document]. Shipspotting.com. URL http://www.shipspotting.com/gallery/photo.php?lid=2514454 (accessed 11.22.18).

Smith, C., Burrows, J., Scheier, E., Young, A., Smith, J., Young, T., Gheewala, S.H., 2015. Comparative Life Cycle Assessment of a Thai Island's diesel/PV/wind hybrid microgrid. Renew. Energy 80, 85–100. https://doi.org/10.1016/J.RENENE.2015.01.003

Smith, T.W.P., Jalkanen, J.P., Anderson, B.A., Corbett, J.J., Faber, J., Hanayama, S., O'Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D.S., Ng, S., Agrawal, A., Winebrake, J.J., M., A.H., 2014. A new scenario framework for climate change research: Background, process, and future directions, Climatic Change. London, UK. https://doi.org/10.1007/s10584-013-0912-3

Solar Voyage, 2018. Solar Voyage [WWW Document]. URL http://www.solar-voyager.com/ (accessed 5.18.18).

Styles, D., Börjesson, P., D'Hertefeldt, T., Birkhofer, K., Dauber, J., Adams, P., Patil, S., Pagella, T., Pettersson, L.B., Peck, P., Vaneeckhaute, C., Rosenqvist, H., 2016. Climate regulation, energy provisioning and water purification: Quantifying ecosystem service delivery of bioenergy willow grown on riparian buffer zones using life cycle assessment. Ambio 45, 872–884. https://doi.org/10.1007/s13280-016-0790-9

Trading Economics, 2018. Turkey Interest Rate | 1990-2018 | Data | Chart | Calendar | Forecast [WWW Document]. URL https://tradingeconomics.com/turkey/interest-rate (accessed 7.18.18).

Transatlantic21, 2018. Transatlantic21 [WWW Document]. URL http://www.transatlantic21.org/ (accessed 5.18.18).

Trapani, K., Millar, D.L., Smith, H.C.M., 2013. Novel offshore application of photovoltaics in comparison to conventional marine renewable energy technologies. Renew. Energy 50, 879–888. https://doi.org/10.1016/J.RENENE.2012.08.043

Vázquez-Rowe, I., Villanueva-Rey, P., Moreira, M.T., Feijoo, G., 2014. Edible Protein Energy Return on Investment Ratio (ep-EROI) for Spanish Seafood Products. Ambio 43, 381–

394. https://doi.org/10.1007/s13280-013-0426-2

Viking Line, 2018. Viking Line [WWW Document]. URL https://www.sales.vikingline.com/find-cruise-trip/our-ships/ms-viking-grace/ (accessed 5.18.18).

Wang, H., Oguz, E., Jeong, B., Zhou, P., 2017. Optimisation of operational modes of short-route ferry, in: 17th International Congress of the International Maritime Association of the Mediterranean, Lisbon, Portugal, 9-11 October 2017, Lisbon, Portugal, 9/10/17.

Wight Link, 2018. Wight Link [WWW Document]. URL http://www.wightlink.co.uk/pressrelease/wightlinks-new-flagship-victoria-of-wight-is-launched/ (accessed 5.18.18).

Yachts Soel, 2018. Soel Yachts [WWW Document]. URL http://soelyachts.com/soelcat12-solar-electric-catamaran/ (accessed 5.18.18).

Yu, W., Zhou, P., Wang, H., 2018. Evaluation on the energy efficiency and emissions reduction of a short-route hybrid sightseeing ship. Ocean Eng. 162, 34–42. https://doi.org/10.1016/J.OCEANENG.2018.05.016

Žižlavský, O., 2014. Net Present Value Approach: Method for Economic Assessment of Innovation Projects. Procedia - Soc. Behav. Sci. 156, 506–512. https://doi.org/10.1016/J.SBSPRO.2014.11.230