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Impacts of the Form Design and Operational Factors on the Energy Consumption of a Solar-Powered Boat: A System Dynamics Approach

Güneş Enerjili Bir Teknenin Enerji Tüketimi Üzerinde Form Tasarımı ve İşletme Faktörlerinin Etkileri: Bir Sistem Dinamiği Yaklaşımı

Türk Denizcilik ve Deniz Bilimleri Dergisi

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ABSTRACT

This research paper aims to design a solar-powered boat and analyze the effects of environmental and form-related factors on power consumption and battery duration by utilizing a system dynamics approach-based simulation. The boat form is designed as the planing hull and its hull resistance analysis was ensured in Maxsurf package program. PV panels with 548 W power output and two battery packs with 4660 Wh capacity were placed on the hull body to employ an electric motor with a 10-kW nominal power output. Two MPPTs were implemented in the system to increase solar system efficiency. The relationships between all system components were modelled in Vensim software to observe battery endurance changes under different conditions. Results demonstrated that the ideal vessel speed is calculated to be around 7 knots with roughly 8 hours of battery duration for the designed boat. A critical stage of charge for sailing is 40% since 1.63 hours of cruising time may be achieved while maintaining a speed of 5 m/s (9.72 knots). Indeed, the boat's rising trim angle shortens the battery discharge time; thus, navigation by no trim angle is the most effective usage for the vessel.

Keywords: Solar-powered boat, System dynamics, Photovoltaic system, Renewable energy

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ÖZET

Bu araştırma makalesi, güneş enerjisiyle çalışan bir tekne tasarlamayı ve çevresel ve biçimle ilgili faktörlerin güç tüketimi ve batarya süresi üzerindeki etkilerini sistem dinamiği yaklaşımına dayalı bir simülasyon kullanarak analiz etmeyi amaçlamaktadır. Tekne formu, kayma gövdesi olarak tasarlanmış ve gövde direnci analizi Maxsurf paket programında yapılmıştır. 548 W güç çıkışına sahip PV paneller ve 4660 Wh kapasiteli iki adet pil paketi, 10 kW nominal güç çıkışına sahip bir elektrik motorunu çalıştırmak için gövde gövdesine yerleştirilmiştir. Güneş enerjisi sistemi verimliliğini artırmak için sistemde iki adet MPPT kullanılmıştır. Tüm sistem bileşenleri arasındaki ilişkiler, farklı koşullar altında pil dayanıklılık değişikliklerini gözlemlemek için Vensim yazılımında modellenmiştir. Sonuçlar, tasarlanan tekne için ideal tekne hızının yaklaşık 8 saat batarya kullanım süresi ile 7 knot hesaplandığını göstermiştir. %40 şarj durumu seyir için kritik bir olarak belirlenmiştir, çünkü hız 5 m/s (9,72 knot) sabit tutularak %40 seviyesinde 1,63 saat seyir süresi sağlanabilmektedir. Teknenin artan trim açısı akünün deşarj süresini kısaltmaktadır ve trim açısı olmadan seyir tekne için en etkili kullanım olarak belirlenmiştir.

Anahtar sözcükler: Güneş enerjili tekne, Sistem dinamikleri, Fotovoltaik sistem, Yenilenebilir enerji

1. INTRODUCTION

Technological improvements and the growth of population yield a remarkable increase in the energy demand around the Globe (Kannan and Vakeesan, 2016). Fossil fuels have met the raised energy demand since the 1800s; however, the world has faced crucial environmental issues because of exploiting fossil fuels. The emerging problems can be classified as major environmental accidents, water pollution, marine pollution, land use and sitting impact, solid waste disposal, hazardous air pollutants, poor air quality, acid rain, stratospheric ozone depletion, and global climate change. In addition, fossil fuel reserves have been depleted since they are non-renewable sources. That's why the utilization of Renewable Energy Sources (RESs) in every industry becomes a more significant issue considering the current environmental and economic situation in the World (Dincer, 2000; Kannan and Vakeesan, 2016; Mueller and Wallace, 2008).

The maritime transportation industry unquestionably harms environmental factors (Eyring *et al.*, 2005). A 2021 analysis from the International Energy Agency noted that international maritime freight transit accounts for around 2% of energy-based CO_2 emissions. (Connelly and Idini, 2022). Over the past ten years, the International Maritime Organization (IMO) has established ambitious objectives to reduce greenhouse gas emissions from maritime traffic. The IMO has set a target of at least a 40% decrease in carbon emissions from 2008 to 2030 (Ivanova, 2021). The Energy Efficiency Existing Ship Index (EEXI), released on June 17, 2021, replaced the Energy Efficiency Design Index (EEDI) to lower carbon emissions from existing ships. Using the weight of the cargo carried and the distance travelled, EEXI determines the ship's energy efficiency and displays its carbon emissions (Spinelli *et al.*, 2022). The EEXI-linked Carbon Intensity Indicator (CII) reduction factor measures how much operation-based carbon intensity has been reduced. If a marine vessel has 5000 gross tons (GT) or more, its CII performance must be monitored annually, and the CII and EEXI documentation has to be completed by January 1, 2023. Passenger ships and oceangoing freight boats with 400 GT or more must compute their EEXI. The approaching, brief deadline prompts the vessel's crew to use and improve energy-efficient technology and alternative energy sources (Konur *et al.*, 2023; S. Wang *et al.*, 2021).

Some significant challenges and issues exist in the field of RESs. The most crucial ones can be listed as survivability, reliability, and affordability. The decided system's resource selection must consider precise projected effective operating circumstances. A well-integrated renewable energy system results in fewer interactions between the parts. The design parameters of the system will be assessed and chosen using numerical modelling tests and calculations (Mueller and Wallace, 2008). Different types of energy sources and their potentials are considered when determining a renewable energy source for a system. In the literature, the potentials of alternative energy sources are examined under the following five different aspects (Hoogwijk and Graus, 2008):

- Theoretical potential is the highest level of potential. This only accounts for natural and climate parameter constraints.
- The geographical potential is a theoretical potential reducing factor that most renewable energy sources have geographical restrictions, e.g., land use and land cover. The geographical potential is the theoretical potential constrained by the resources in geographical regions.
- The technical potential is further reduced geographical potential due to technical limitations in conversion efficiency.
- Economic potential is the technical potential for cost levels considered competitive.
- Market potential refers to the total amount of renewable energy that can be applied on the market, considering market potential, energy demand, competing technologies, costs and subsidies of renewable energy sources, and obstacles. The market potential, including opportunities, may be greater than theoretically the economic potential, but it will turn into potential market potential due to potential hindrances.

Solar-powered boats are becoming increasingly popular for recreational and daily use since they are quiet, reliable, maintenance-free, and simple to operate. The case boat in this study, which will be used for both transportation and pleasure without polluting the environment, is constantly charged by the sun throughout daytime hours, eliminating the need for fossil fuel replenishment. This single-passenger capacity concept vessel can transfer energy from the main line during the time it is moored to the dock on cloudy days or is heavily utilized. This design, which enables personal use, is intended for use in touristic areas such as Izmir and regions with year-round long sunlight hours.

2. LITERATURE REVIEW

Considering the information given before in this research and the goals set by IMO, solar energy utilization is a reasonable choice for marine vessels. Especially for small ships, the electric motor, battery, and photovoltaic (PV) combination can provide decent propulsion. Small marine vessels can now use battery and electric motor propulsion due to technological enhancements to guarantee zero-emission ships (Solangi *et al.*, 2011). The all-electric ship (AES) and hybrid-powered ship concepts have been the subject of some research papers published in the previous decade. Nóbrega and Rössling, (2012) presented a design for a pleasure ship having a hybrid propulsion unit. The calculations and analyses have been carried out for the PV panel and diesel engine. Rivera-Solorio *et al.* (2013) designed and constructed an AES by utilizing computational fluid dynamics (CFD) within the scope of a student project. Cupelli *et al.* (2015) reviewed the technological progress of network architectures and approaches for AESs regarding network stability. Kabir *et al.* (2017) retrofitted a conventional ferry into a solar-powered boat with 1 kW solar panels and 9600 Wh energy storage units. Batteries that are fully charged can propel the vessel 60 kilometers at a speed of 3 knots. Balsamo *et al.* (2017) presented a novel energy management strategy (EMS) for a hybrid storage system involving batteries and supercapacitors for an AES using a simulation written in MATLAB/Simulink environment. Banjarnahor *et al.* (2017) designed a wind and solar energy harvester to supply energy for a refrigerator in a fishing boat. Solar panels provided daily 815-817 Wh of energy while wind turbines ensured 43-62 Wh that met the energy demand of the fishing boat. Nasirudin *et al.* (2017) introduced a methodology to optimize and determine the size of a PV system considering the minimum cost. The golden search algorithm is utilized to gather minimum propulsion power, and the Simplex algorithm is used to reduce battery and PV module costs. The optimal design is found as 32 PV modules (8.96 kW) and 32 batteries (34.56 kWh), while water line dimensions are 14.44 meters long, 4.37 meters wide, 0.852 meters deep, and 16.258 tons in total displacement. The PV system's annual capital cost is around $3557. Tamunodukobipi *et al.* (2018) analyzed the design of a solar-powered light weigh leisure AES. The ship had the catamaran form, and the resistance was calculated as 740 N at 5 knots using Savitsky and CAHI techniques. 3 HP of Electric motors and batteries having 235 Ah capacity were chosen, regarding the propulsion system the size of the PV module was determined. Kurniawan and Shintaku (2018) ensured a control strategy for PV power distribution in an AES. When the PV array voltage is kept above 95 V, the maximum power from the PV panel can be obtained with 99% efficiency. Chao *et al.* (2018) conducted research that involved a design for a PV power distribution of a marine vessel system having ten PV panels, a maximum power point tracker (MPPT), and a controller. The proposed system improved energy efficiency by approximately 28%, while the solar system met 40-50% of total power depending on sunlight exposure. Leung and Cheng, (2018) ensured an analysis based on various case studies for a solar-powered ship design. The results depicted that PV panel utilization can reduce up to 77.42% of CO_2, depending on the panel efficiency. Obaid *et al.* (2019) designed and simulated a hybrid electric-powered boat that includes a fuel cell, wind, and solar energies with an MPPT system. The simulation's outcomes can be used to indicate how the electric boat can keep going even when the wind and sun irradiance change. Pakhmode *et al.* (2019) provided a solar-powered water surface garbage gathering ship design to prevent water pollution and to assist with safety and security-related duties.

System Dynamics (SD) approach is one of the system thinking methodologies that avoids most jargon and complex explanations while operating in a whole-system approach (Hjorth and Bagheri, 2006). SD has been utilized to evaluate energy systems and their environmental sustainability in various fields. Anand *et al.* (2006) applied the SD approach to evaluate the reduction of CO_2 emissions from the cement industry. Results showed that based on an integrated reduction scenario introduced in the paper, a 42% reduction in CO_2 emissions can be ensured. Aslani *et al.* (2014) discussed and analyzed energy dependency and the impact of the policies in Finland. Despite Finland's projected 7% increase in power and heating demand by 2020, analysis indicates that import dependence will decline by 1% to 7%, depending on the scenarios used. Pizzitutti *et al.* (2017) carried out research that comprises a decision-support framework for tourism management in the Galapagos Islands of Ecuador using the SD method. The remarkable issues for the region to enlarge the human occupation are found as the unique natural ecosystem of the Islands is under threat from an increasing number of invasive species, and the capacity of the Galapagos National Park to receive tourists is quickly being reached. Esmaieli and Ahmadian (2018) conducted a simulation of the long-term electricity market using the SD method to observe the impact of the current and proposed research and development encouragements on wind energy investments. The outcomes showed that the suggested incentive was more successful than other well-known encouragements. Gravelsins *et al.* (2018) modelled the flexibility of energy generation using the SD method. Findings demonstrated that the limitations of intermittent power generation from renewable sources that can be integrated into the power system are raised by the consequences of technological disruption in the model. Jia *et al.* (2019) investigated the impact of the air pollution charging fee (APCF) policy to lower haze pollution in China using a dynamic simulation based on the SD approach. The simulation results demonstrated that the APCF policy successfully achieved the beneficial scenario of pollution reduction and congestion release. Liu *et al.* (2019) assessed the energy performance gaps of green offices in China using an SD methodology. The findings suggest that building managers should focus more on interactions with regular tenants and less on messages with austerity inhabitants to raise occupant awareness of energy conservation.

Pereira *et al.* (2020) analyzed the effects of energy change in medium-sized industries on the sustainability of small and medium industries using the combination of the fuzzy cognitive mapping and SD method. The experts validated the model's performance, and the authors also examined their constructivist, process-oriented framework's benefits, drawbacks, and implications for both study and practice. Pan *et al.* (2021) provided an SD simulation to evaluate the effectiveness of trading policies related to carbon emission reduction. Results indicated that a successful emission reduction could be achieved with the utilization of multiple policies. Joshi *et al.* (2021) ensured an SD-based simulation to assess the effect of the policies on recycling lead-acid batteries. Although a very high subsidy can result in the closure of regulated and unregulated recycling businesses, the authors' findings show that subsidizing formal batteries can minimize the amount of lead excretion. Baskoro *et al.* (2021) evaluated the coal utilization scenarios in Indonesia using the SD methodology. The findings indicate that Indonesia's coal production will rise in the future. Among these scenarios, an environmentally oriented scenario can lead to 33.5% of coal, 19.4% of oil, 7.8% of gas, and 39.3% of RES usage. Mobaseri *et al.* (2021) investigated waste reduction in the food industry and its environmental impact using the SD methodology. Based on the findings, annual food demand and energy consumption increases will be 1.35% percent and 3.31%, respectively. In these conditions, pollution emissions increase by 4% annually, reaching 1.13 million tons in 2031. Sheheryar *et al.* (2021) estimated CO_2 emission reduction through the utilization of ultrahigh-performance concrete instead of ordinary Portland cement concrete using the SD method. Results indicated that the usage of mentioned concrete can reduce CO_2 emission by 17%. Stasinopoulos *et al.* (2021) conducted an SD approach-based analysis of the GHG emission reduction potential using an autonomous vehicle fleet. The findings revealed that the greenhouse gas intensity of the energy supply and fuel efficiency of internal combustion engine vehicles have the greatest impact on reducing greenhouse gas emissions. Although the benefits may be offset by autonomous vehicles' inefficiency and increased demand. Ye *et al.* (2021) analyzed the efficiency of a certified emission reduction scheme in China and its impacts on CO_2 emissions through case scenarios using the SD approach. Findings depicted that the double trading market scenario compared to the baseline scenario can produce much extra cost savings over time. Daneshgar and Zahedi (2022) assessed the probability and generation capacity of hydropower plants using the data gathered from Karun 1 and SD approach. Different scenarios were tried regarding water release methods and cost limits. The findings depicted that the most profited scenario provided 3047 $/MW for two years and was the discharging of 15% of the dam. Francis and Thomas (2022) presented a methodology named dynamic life cycle sustainability assessment based on SD methodology. The case study findings demonstrate that underestimating general sustainability impacts by around 50% and specific environmental impacts by about 12% when time-dependent dynamic factors are ignored in building sustainability assessments. Kong *et al.* (2022) examined the impact of carbon reduction amendments on the maritime supply chain using a case-based SD approach. The outcomes demonstrate that shore power has a huge potential for lowering emissions. Shadman *et al.* (2022) investigated the implementation, future, and role of RES in Malaysia by utilizing the SD approach in terms of aspects of energy security. The results indicated that Malaysia's total environmental sustainability can be improved, and its reliance on energy imports can be decreased. Eftekhari Shahabad *et al.* (2022) explored the impacts of the incentives for solar panels utilized in houses using SD methodology through a case study in Iran. Results highlighted that it is vital to implement additional policies in addition to subsidies, such as building sizable renewable power plants or deconstructing outdated inefficient fossil fuel power plants.

The first part of the literature review involved the RES-powered ship and illustrated that the AES concept was analyzed majorly in terms of ship design, EMS optimization, microgrid enhancements, economic analysis, route optimization, and component sizing. The second part of the review was about SD approach-based simulations about energy modelling, energy dependency analysis, and PV panel utilization in various fields such as cement and automotive industries. Studies also investigated emission reduction strategies and predictions of energy source distribution by using the SD approach. The review depicted that there has been a research gap in the evaluation and enhancement of the solar-powered marine vessel's performance by utilizing SD methodology. This study's objectives include designing a solar-powered boat and using an SD approach-based simulation to examine how environmental and form-related elements affect power consumption and battery life. The SD technique is a well-known and practical methodology that can successfully simulate this kind of dynamic system. The boat form is designed as the planing hull type and its analysis were ensured in Maxsurf software. Boats with planing hulls are made to rise up and glide over the water when enough power is applied (Savitsky, 1964). PV panels with 548 W power output and two battery packs with 4660 Wh capacity were placed on the hull body to employ an electric motor with a 10-kW nominal power output. Two MPPTs were implemented in the system to increase efficiency. Vensim software was used to simulate the relationships between every system component to track variations in battery endurance under various circumstances. The main motivation is to optimize the energy demand for components of PV-powered boats and to attain increased battery discharge time.

3. SYSTEM DESCRIPTION

The investigated system configuration involves PV panels, MPPT, battery sets, an electric motor and propeller, and the hull. The specifications of the system components shown in the diagram are presented in Table 1.

Four of SP-137 model solar panels were selected to produce energy to be used in the system. Two pairs of panels are connected in series, and then both are connected in parallel to obtain 48 volts and keep the panel output amperage value low. The output voltage of the solar panels varies according to the amount of irradiation on the panel surfaces. Hence, a device, which restricts the flow direction, must be added to the system after each panel pair. Diodes direct electric current in one direction and are the most compatible items for this purpose (Ellenbogen and Christopher Love, 2000). Two high-performance lithium-ion batteries are connected in series and each battery is fed by one MPPT to obtain the voltage that will fill the batteries from the solar panels. A battery has a 25.9 V nominal output voltage and due to the series connection of the batteries, approximately 50 V output voltage will be attained. This connection is needed for the 48 V electric motor input value. The required power of the electric motor is adjusted with Torqeedo remote throttle. The setting will change the angular velocity of the propeller to reach the desired speed of the boat. In Figure 1, the schematic of the system is illustrated.

Table 1. Selected components of the system

PV panels	MPPT	Battery	MCU	Electric motor and propeller	Hull
Solbian SP-137 137 Watt 24 V 5.7 A Eff.%22.5 Monocristal silicon cells	Outback Flexmax 80 12-60 VDC battery charge voltage Eff. %98	Torqeedo Power 26-104 High-performance lithium battery 25.9 nominal voltage 180 A max discharge	Torqeedo top mounting throttle	Torqeedo Cruise 10.0 R electric motor 48 V nominal voltage 10kW input power Eff.%56 and v32/p10k propeller	4900 mm overall length, 700 mm molded beam, and 800 mm depth fiberglass planing hull

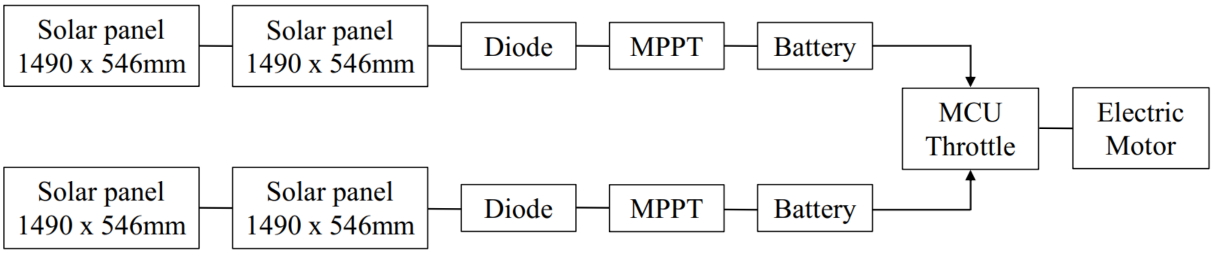

Figure 1. Diagram of system components

Each solar panel consists of 44 PV cells, and a PV cell has an area of 165 cm^2. Thus, a solar panel has a total area of 0.726 m^2. Four solar panels will be used in the system so that the total PV cell area will reach 2.9 m^2. The total theoretical power output is calculated as 548 watts. The selected Flexmax80 model MPPT can work up to 60 VDC and has an 80-amperage maximum output current. Each lithium battery has 4660 W maximum discharge power, so the designed system will have 9320 W power. This total capacity will be controlled by the motor control unit (MCU) (Torqeedo top mounting throttle) to provide power to the motor from batteries. Torqeedo Charger Power 26-104 model battery chargers will fill the batteries when the irradiation is insufficient. During the boat hull design phase, the total weight of the system's equipment and the driver's weight were evaluated, and the hull was formed regarding the weights given in Table 2.

Table 2. Weights of the system components

Component	Weight (kg)
4 x Solar panel	8
2 x MPPT	11
2 x Lithium battery	48.6
Electric motor	61.3
Driver	75
Miscellaneous	25
Hull	50
Total	278.9

The total weight of the solar-powered boat has reached 278.9 kg. Hence, the displacement of the boat must be this value. Moreover, when the boat's draft is at 165 mm, it gives 278.4 kg displacement weight. To calculate the power output from the PV panels, solar radiation data of the Izmir Gulf, where the boat is designed to operate, are used. The mean of monthly irradiation values is used in the calculations. Figure 2 indicates the monthly irradiation data for the Izmir region.

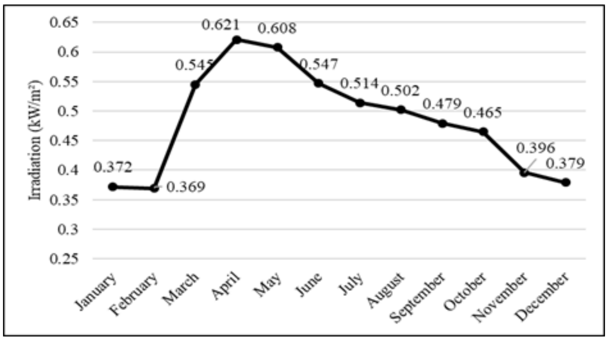

Figure 2. Irradiation values of Izmir (Cedar Lake Ventures, 2022)

4. MODELING

Hull design calculations have been provided using Maxsurf software which is a commonly used naval architecture program in similar projects and academic studies (Bentley, 2022). The designed hull is considered a chined hull form when the boat reaches the required planing speed, and hydrodynamic forces can lift the total boat weight (Lindbergh and Ahlstrand, 2020). To optimize a photovoltaic system, it is necessary to determine the functions and locations of the components in the system. Also, the relationship between the components of the system must be defined. The whole system from where the energy is produced to where it is consumed is shown in Figure 3.

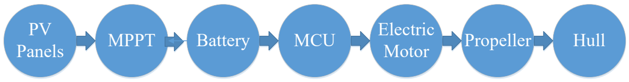

Figure 3. Solar-powered boat energy flow

The power of the PV system is generated as voltage in solar cells, which is converted by MPPT to the maximum power point at the highest voltage value. An MPPT is a DC-DC converter attached between the solar panels and their load to obtain optimum matching. The output power characteristics of the PV system as functions of solar irradiation and temperature curves are not linear and are influenced by irradiation and temperature. These continuous fluctuations affect the PV operating point; therefore, it must be fixed at the best voltage. The required energy for the electric motor is provided from batteries with the help of MCU that adjust the battery output voltage regarding the power by the electric motor. Depending on the desired speed, the interaction between hull and water varies, and consequently, electric motor needs various power consumption values. The trim angle and the propeller velocity are also affected by boat speed, and due to the change in ship resistance, the total power needed is altered by direct or indirect factors of the whole PV-powered boat (Walker, 2001).

The relationship between power consumption, battery discharge, and PV Panel battery charge has been explained by using the SD approach. The system model is developed in Vensim which provides a dynamic SD-based simulation environment (Ventana Systems, 2015). SD is a strategy for analyzing and handling dynamic issues in intricate feedback. The following steps make up the approach for system dynamics modelling (Gravelsins *et al.*, 2018):

- Specifying the dynamic problem's definition and the modelling's objective,
- Developing the dynamic hypothesis based on the researched system's structure,
- Establishing the fundamental elements of the model as a set of parameters, feedback loops, and ticks (which accumulate flows and govern stock level),
- Validation of the model,
- Testing the policies to identify the most important variables that can be altered to improve the system's undesirable behavior.

The electric motor consumes power while the batteries are being charged by the panels. Battery endurance time stands out in this system. When all irradiation values are suitable, all batteries can be charged from 0% to 100% in approximately 17 hours with PV panels. At this point, effective usage of the solar-powered boat becomes prominent. Relationships among boat hull resistance at various speeds, total panel power, propulsion efficiency, and total battery capacity must be well adjusted to attain long battery durations for usage. For this purpose, all variables in the system were mapped in Figure 4 with Vensim software. To observe battery endurance time according to alterations of all parameters.

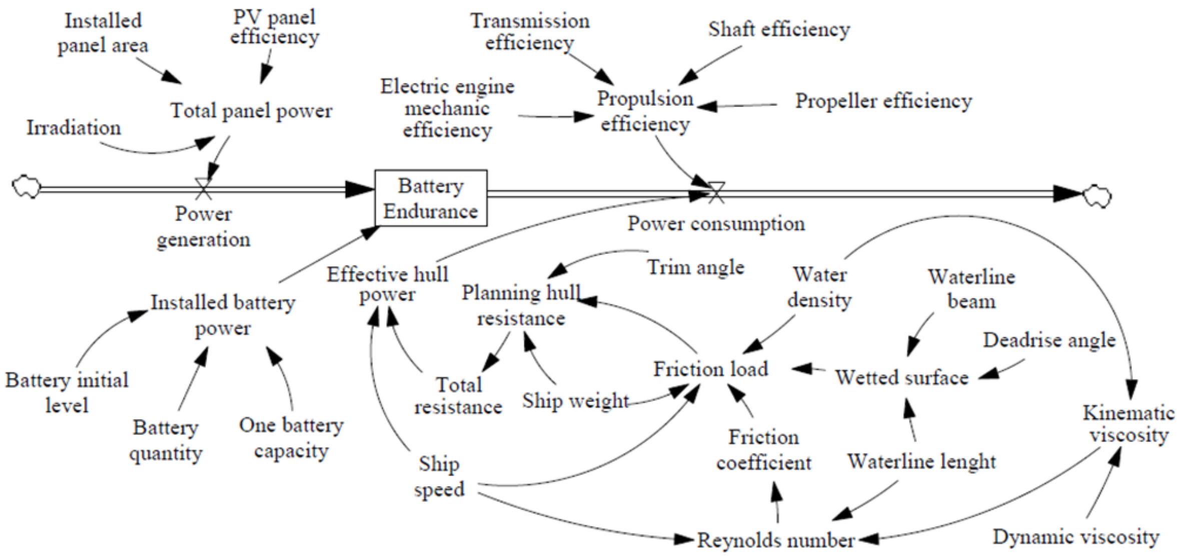

Figure 4. System dynamics model of the solar boat

The resistance of a ship at a given speed is the towing force at that velocity in smooth water. If there are no appendages on the boat, this value is named bare hull resistance. The required power to overcome this resistance is calculated using Equation 1.

$$P_E = R_T \times V \quad (1)$$

where P_E is effective power (kW), R_T represents total resistance (kN), and V is the velocity in m/s (Lewis, 1998). R_T has some components, generally R_H (bare hull drug), R_{AP} (appendages drag), R_A (air drag) and R_{PAR} (parasitic drag) are considered to calculate ship resistance (Lindbergh and Ahlstrand, 2020). The bare hull resistance value equals the addition of pressure and frictional resistance. Appendage drag includes shaft bosses and brackets, rudders, stern frames, etc. Air drag is affected by the above-water part of the main hull and superstructures because of the movement of the boat through the air (Saral and Köse, 2020). The calculation of R_T is shown in Equation 2 (Lewis, 1998).

$$R_T = R_H + R_{AP} + R_A + R_{PAR} \quad (2)$$

In this study, the R_A air drag value is considered zero because of the lack of above-water area and superstructure body. Also, due to the type of selected electric motor, there is no rudder, and the total electric motor efficiency calculated from the producer R_{AP} is ignored. R_{PAR} is neglected not only because it has a lower effect but also because the technology implementation has improved (Lewis, 1998). Since these neglected resistance components, the calculation has been ensured under the assumption of R_T= R_H. All the used formulas belong to the Savitsky method, which is one of the methods of calculating the bare hull resistance of planing hulls (Lindbergh and Ahlstrand, 2020). According to the Izmir Gulf's annual mean sea water temperature (18.5ºC), kinematic viscosity will be used v=1.055 m^2/s. The water density of the seawater in Izmir Gulf is taken as 1025 kg/m^3 (Eronat, 2017; Pazi and Ozturk, 2012).
Equation 3 illustrates the formula for calculating the energy produced by PV panels (Aijjou *et al.*, 2019).

$$E = A_p * \eta * H_a * P_r \quad (3)$$

where the energy in kWh is referenced as E, A_p is the solar panel area (m^2), η represents the efficiency of the panel, and P_r is the performance ratio that involves all losses on the system (accepted as 0.75), and average solar radiation is represented as H_a.
The Coulomb counting method is used to estimate the battery's state of charge (SoC).

Equation 4 shows how the SoC calculation is mathematically formulated over time. (Saxena *et al.*, 2016; Sepasi *et al.*, 2015).

$$SoC(t) = SoC(0) - \left(\int_0^t \eta \cdot I(t)/C_{av}\right) \quad (4)$$

where $SoC(0)$ represents the initial charge SoC, $SoC(t)$ is the SoC at time t, C_{av} is the available battery capacity, $I(t)$ is the charge/discharge current at the time t, and the Coulumbic efficiency is accepted as 1.

5. RESULTS AND DISCUSSION

Impacts of the initial battery level, trim angle, and boat speed variations have been investigated through an SD simulation formed in Vensim software. Table 3 and Figure 5 indicate the variation of power consumption in kW and battery duration in hours regarding boat speed changed from 4 m/s to 8 m/s (7.78 knots to 15.55 knots). The initial speed value is selected as 4 m/s since the Savitsky planing hull calculations don't involve the lower speed values. The maximum output power of the electric motor (10 kW) limits the peak speed at 8 m/s which met the desired velocity.

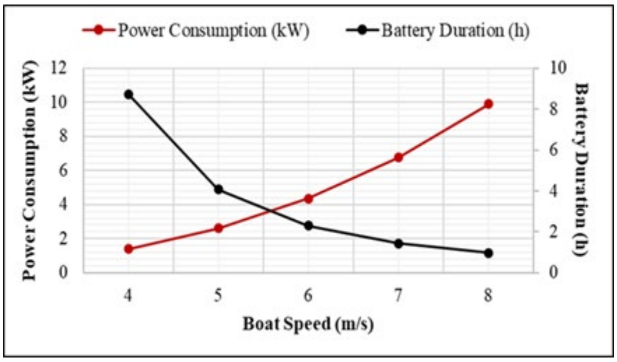

Figure 5. Relation between boat speed, power consumption, and battery duration

Table 3. Required power and battery duration change regarding boat speed

Boat speed (m/s)	Boat speed (knot)	Power consumption (kW)	Battery duration (hours)
4	7.78	1.38	8.73
5	9.72	2.60	4.07
6	11.66	4.36	2.30
7	13.61	6.77	1.44
8	15.55	9.90	0.97

The battery duration is found satisfactory at lower speeds. At 7.78 knots, the boat provides an acceptable usage time for achieving daily duties. The planing form chosen for this vessel helped to ensure these convincing outcomes. For the latter analysis, the boat speed was kept constant at 5 m/s, and it is accepted that the boat has no trim angle. Relationship between initial battery levels and durations were examined for the SoC of 40% to 100% of battery level and illustrated in Figure 6.

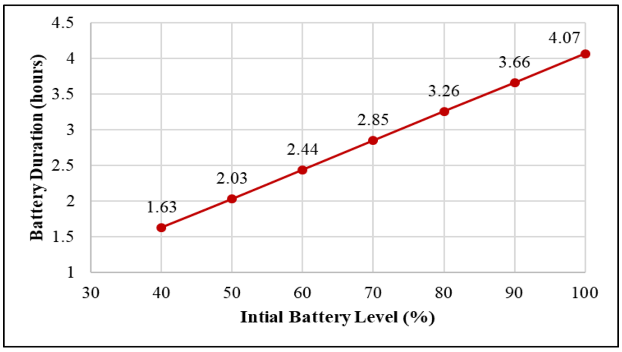

Figure 6. The relation between initial battery level and battery duration at 5 m/s boat speed

The four-hour cruise time is likely to be used near the shore when starting with full batteries. It is calculated that even at the 40% level, the batteries run for over an hour and a half. This is a very promising result for this boat design. In the following analysis, boat speed has been taken to a constant value of 5 m/s and the battery charge level has been 80%. Also, at 5 m/s speed and with no trim angle condition, power consumption has been obtained as 2.60 kW. Besides, in the same conditions with an 80% battery level, the battery duration was 3.26 hours. Moreover, when the effect of increased trim angle on battery endurance and power consumption analysis has been conducted, approximately up to 4% battery duration could be lost at a 10-degree trim angle. Indeed, the trim angle effect on navigation time, with an 80% charged battery pack, is shown in Figure 7. The findings related to the trim angle are in line with the experimental study conducted by Giraldo-Pérez *et al.*, (2022) for various hull types including planing hull. The optimum vessel speed was found at 7.78 knots which also complies with the studies using similar boat designs for all-electric ships. Ozden and Demir, (2009) determined the speed of the optimal speed at around 5-7 knots for small solar boats utilized in a solar boat contest while Yüksel *et al.*, (2023) depicted the optimal speed at around 8-11 knots for a solar boat having similar design aspects considering the hull resistance calculations.

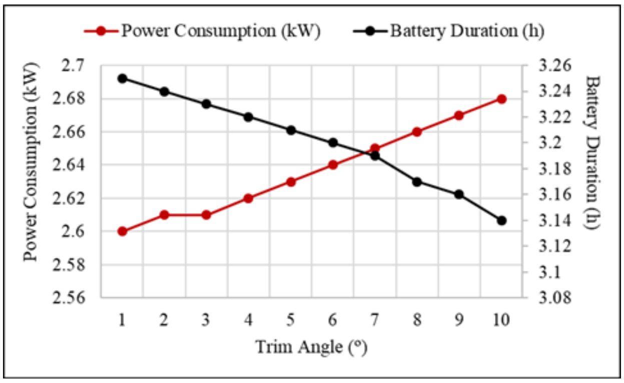

Figure 7. The relation among a trim angle, power consumption, and battery duration

As seen in Figure 7, the increased trim angle affects the power consumption negatively and reduces the battery duration. These results show that using the boat without a trim angle will reduce power consumption and will affect the navigation time positively. When the effect of an increase in trim value on battery duration is analyzed, a continuous decline in the boat's operational time is determined. Particularly when the 7-degree trim angle is surpassed, it is difficult to perform reliable estimates due to the uncertainties resulting from fluctuations in the curve.

6. CONCLUSION

The research paper aimed to design a solar-powered boat and analyze the effects of environmental and form-related factors on power consumption and battery duration by utilizing a system dynamics approach-based simulation. The boat design had the planing hull form, and its analysis was ensured in Maxsurf software. PV panels with 548 W power output and two battery packs with 4660 Wh capacity were placed on the hull body to employ an electric motor with a 10-kW nominal power output. Two MPPTs were implemented in the system to increase efficiency. The relationships between all system components were modelled in Vensim software to observe battery endurance changes under different conditions.

The main findings driven from the study can be listed as:

- The vessel speed is at 4 m/s (7.78 knots) for no trim condition with approximately 8.73 hours of maximum battery duration.
- The optimum boat speed is suggested at the intersection point of Battery duration and Power consumption curves in Figure 5.
- At 40% battery level and with 5 m/s (9.72 knots), 1.63 hours cruising time was obtained, and it can be said that below 40% battery level becomes a critical level for cruising.
- Start with a battery charge of more than 80% whenever possible.
- The rising trim angle decreases the battery duration thus, the most efficient trim angle to navigate the boat is zero.
- If it is obligatory to operate the vessel with any trim angle, the 7-degree limit should not be exceeded.

The research presented a simulation of battery charging and discharging of a solar boat using the system dynamics methodology. In this way, an interface was created that dynamically calculates how long the battery will last regarding the boat speed, charge rate, and trim angle. The utilization of the system dynamics-based approach is a divergent aspect of the paper. The study can be beneficial for naval architects and marine engineers working for shipyards, academic institutions, and investors interested in solar-powered leisure boats. Future research might include calculations that involve more detailed irradiation computations, usage of larger battery cells to extend the vessel's operating period, the economic evaluation of system design, real-time installation of the designed vessel configuration, and benchmarking of the study's results.

Nomenclature

Notation	Parameter	Unit
A_p	Total PV panel area	m^2
C_{av}	Available battery capacity	Ah
E	Produced energy by PV panels	kWh
H_a	Average solar radiation value	kW/m^2
$I(t)$	Charge/discharge current at any time	A
P_E	Effective power	kW
P_r	PV system performance ratio	-
R_A	Boat upper structure wind resistance	kN
R_{AP}	Boat underwater appendages resistance	kN
R_H	Bare boat hull resistance	kN
R_{PAR}	Boat hull fouling resistance	kN
R_T	Total resistance	kN
v	Kinematic viscosity	m^2/s
V	Boat velocity	m/s
t	Time	s
η	Efficiency ratio of PV panels	-

AUTHORSHIP CONTRIBUTION STATEMENT

Burak GÖKSU: Conceptualization, Methodology, Validation, Formal Analysis, Writing - Original Draft, Writing-Review and Editing, Data Curation, Software. **Onur YÜKSEL:** Conceptualization, Methodology, Writing - Original Draft, Writing-Review and Editing, Visualization.

CONFLICT OF INTERESTS

The authors declare that for this article they have no actual, potential, or perceived conflict of interests.

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