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ORIGINAL RESEARCH

Techno-financial analysis and design of on-board intelligent-assisting system for a hybrid solar–DEG-powered boat

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Abstract In this paper, we present a financial feasibility analysis and design of an on-board-assisting system for a hybrid solar–diesel-powered boat. The major components of this boat are solar panel, battery bank, speed and direction controller for dc motor, brushless dc motor, diesel engine generator (DEG), and intelligent-assisting system (IAS) to assist the sailor. A DEG is considered to maintain the ability to run the system even during night-time, cloudy, and partially cloudy days. The energy demand posed by the electrical system requires maintaining an appropriate balance between the energy sources-done by an on-board-processing element which facilitates the system to run automatically. The capacity of the battery bank is considered large enough to satisfy electrical power requirement of the system for a whole day during non-charging periods. The optimal configuration for the hybrid system is selected from HOMER simulation results, whereas a financial feasibility analysis of the proposed hybrid solar and DEG-powered boat is performed using a clean energy management software called RETScreen. The IAS also provides solutions to the common naval hazards, such as over-weight and inclement weather by employing depth of submergence detector and GSM network interface. Financial analysis reveals that the proposed system is financially feasible, while tests showed that IAS successfully provides navigational supports to sailors.

Keywords Solar · Boat · Diesel · Hybrid · Intelligent-assisting system · Depth of submergence · Over-weight · GPS · Weather information

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Introduction

Bangladesh is known as the country of river owing to the fact that she has about 800 rivers, including tributaries distributed throughout the main land, and constitutes a waterway having a total length of around 24,140 km [1]. A vast amount of transportation traffic is carried on boats using this waterway. The majority of these water boats are powered by human labor, sail power, and diesel and gasoline driven engines. Diesel and gasoline are fossil fuels, which are formed from geological deposits of organic materials on the earth surface over hundreds of millions of years [1–4].

The human-powered boats are very popular in countries, such as Bangladesh due to low cost of transportation. These convert human labor into displacement on the water surface causing the boat to move in any direction. A large number of sailors remain engaged in the occupation of sailing these boats. They are involved in strenuous physical activity which might be the main cause of DNA damage [4, 5]. Nowadays, most of these boats are replaced by engine boats and these engine boats are powered by the fossil fuels. The burning of fossil fuels for electricity and transportation is the largest source of Greenhouse Gas (GHG) emissions, which makes the earth warmer by trapping heat [2]. The residual fuel leakage and accidental fuel spill from the engines cause the water to be polluted. In addition, the noise of the engines contributes to the disruption of environmental and biological balance. A possible solution to the problems presented by the use of fossil fuels is to use electricity powered engines. The concept of electricity-powered boats goes back to 1880, and they were quite popular until 1920. The lack of suitability in application environment, such as high current in the river, strong wind, etc, aided by long period of low irradiance, and they soon lost the advantage over traditional boats. The modern electric boats, which are charged using shore-based power stations, take care of the air, water, and noise contamination problems. The drawback of centralized-charging station is lengthened-waiting time of the boats, imposed by the use of the traditional batteries for their long-charging times. To mitigate this drawback, distributed energy source would be a good choice as on-board energy storage charge continually from the roof top solar panels.

The interest in renewable energy resources, such as solar, wind, geo-thermal, bio-gas, and hydro-electric have drawn increased attention over the last decade following the rise in the awareness about global warming [2]. They are sustainable, clean, and renewable sources of alternative energy. Solar energy is one of the most promising candidates for future alternative energy source, due to the abundance of the solar radiation. Solar panels—the devise to harness the solar energy—do not rely on the earth's natural resources but on the energy from the sun to produce electrical energy. Due to the issues of energy crisis and global warming, the practical solar boat was probably developed in 1975 in England. The core requirement for using such boats is sufficient insolation throughout the year. Some researches have reported attempts to develop efficient solar boat systems until today. However, the majority of these works focus on the physical constructions of the boats with no detail electrical requirement analysis being discussed [6–8].

Bangladesh is positioned between 20°30′ to 26°45′ north latitude and receives an average of 5 kWh/m^2 solar radiation throughout the year [9, 10]. A study has found that bright sunshine hours in Bangladesh vary from 4 to 10 h daily and global radiation varies from 2.8 to 6.1 kWh/m^2/day [11]. In Bangladesh, only about 50 % population have access to the national grid and the demand of electrical energy is always higher than the generation [12, 13]. Thus, solar energy can be considered as one of the alternate source of energy which could be used to drive solar boats as well [14–18].

Electric engine boats are mainly run on electricity generated by petrol and diesel. Although the initial installation cost of solar photovoltaic (PV) systems is quite high, the consistent price hike of fossil fuels and increased generation of greenhouse gases have influenced us to conduct a research on performance evaluation and feasibility of solar-powered boats in Bangladesh [19, 21, 22]. Usually, solar boats include auxiliary source of energy to meet unsatisfied power demand during cloudy and partially cloudy days. This type of systems—known as hybrid systems—is feasible in terms of technical and economical point of views [10]. Most of the hybrid systems include a diesel engine generator (DEG) due to relatively low price [3].

In this work, we have proposed and developed a hybrid solar–DEG energy source driven boat, and analyzed the techno-financial feasibility of such a system. This analysis will enable designers to make decision on the best suited configuration of the hybrid energy source for a solar boat in a specific application environment. In addition, the parametric evaluation of the proposed solar boat discusses the relationship between the navigational and structural parameters of the boat. One additional contribution of this work is the design of an assisting system for the sailors. Due to inclement nature of weather around a particular time period of a year in Bangladesh, and also due to the lack of management and consciousness of people, many accidents take place—leading to loss of large number of lives. Considering the issues responsible for such catastrophic events, an Intelligent-Assisting System (IAS) is proposed. The concept of information management system (IMS) is already reported in some research works [7, 23]. IAS handles two major contributing issues towards accidents: bad weather condition and over-weight loading of the boat. Since most of the sailor do not have access to wireless communication module, GSM network is utilized to notify them of any update about declining weather. The over weight protection system lets the sailor know about the current weight status of the boat and warns if it is about to cross into unsafe state. In addition, to facilitate the rescue operation in the case of any accident, an emergency location notification system based on GPS is integrated into IAS.

System model

Figure 1 shows the block diagram of hybrid solar–DEG-powered boat. The main components are solar panel, DEG, microcontroller-based battery charge controller, battery bank, motor speed controller, clutch and gear, IAS, and propulsion system. Figure 2 shows the photo of the proposed hybrid solar–DEG-powered boat.

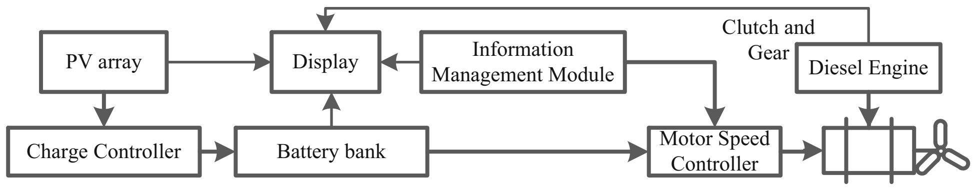


Fig. 1 *Block diagrammatic* representation of a solar PV–DEG hybrid-powered boat

Fig. 2 Photo of the proposed hybrid boat

Selection of motor

The selection of motor depends on required power and efficiency to convert motor power into actual thrust of the propeller. Propeller efficiency depends on both RPM rating and diameter of the propeller. The required motor power can then be calculated based on the hull speed (H) and displacement produced of the hull (D).

The required motor power, denoted by Pm, is given by

$$Pm = \frac{D}{150^2/H^2}. \quad (1)$$

Selection of battery bank

The selection of battery bank depends on nominal system voltage, required load current to run the boat at a particular speed and selected day of autonomy. There are different types of batteries available at the market—valve-regulated lead acid (VRLA) battery, Lithium ion battery, etc. VRLA batteries are maintenance-free battery bank, whereas the depth of discharge of lithium ion batteries is twice of that of VRLA batteries. VRLA battery is selected as the energy storage for our proposed system due to comparatively lesser cost. The batteries can be charged by its roof top solar panel or by national grid at a dock. The onboard automatic battery charger controls the correct charging rate and is always plugged-in.

The battery power, denoted by P_{batt}, can be expressed as [3]

$$P_{batt} = Pm + Lc + (Pm - Pp) \quad (2)$$

where Lc is the cable loss, and Pp is the power absorbed by propeller. Pm can also be expressed as

$$Pm = \frac{Pp}{\eta_p \times \eta_m} \quad (3)$$

where η_p and η_m are the efficiency of the propeller and motor, respectively.

Selection of propeller

A propeller converts rotational energy into thrust, and water is driven out behind the blades. Propeller dynamics can be modeled by both Bernoulli's principle and Newton's third law. The goal in propeller selection is to maximize the performance in terms of required RPM of a particular boat. The RPM is reduced by increasing the pitch of the propeller. If pitch is increased by 2 inch, the RPM of a propeller will drop by 200.

The thrust, denoted by T, is mathematically expressed as [3]

$$T = \frac{\pi}{4} \times \chi \times \left(v + \frac{\Delta v}{2}\right) \times \rho \times \Delta v \quad (4)$$

where χ is the diameter of propeller, v is the velocity of the propeller, and ρ is the density of the fluid (water).

Neglecting the rotational loss, the power absorbed by the propeller on a particular torque, T, can be expressed as [3]

$$Pp = T \times \left(v + \frac{\Delta v}{2}\right). \quad (5)$$

Modeling of hybrid energy system components

The hybrid system is comprised of PV-harnessing system, i.e., solar panel, DEG, and associated components. The configuration for maximum energy efficiency is dependent on the energy system modeling of the hybrid source. Under a particular application scenario, this model provides a design framework to the designers.

Sizing of PV modules and batteries

If solar efficiency is η_{pv}, hourly irradiance is $G(t)$, area of solar is A_{pv}, sailing period is H_s, parking hour is H_p, the average sun hour is H_{pv}, and ϵ is constant, then total energy available from PV, denoted by E_{pv}, is

$$E_{pv} = \eta_{pv} G(t) A_{pv} [(\epsilon \times H_p) + H_s \times (1 - \epsilon)] \quad (6)$$

where

$$\epsilon = \frac{H_p}{H_{pv}}. \quad (7)$$

The total Ampere-hour (Ah) required by motor, denoted by Γ_m, can be written as

$$\Gamma_m = \frac{L_{daily}}{0.8} \quad (8)$$

where L_{daily} is daily load demand in Ah and total system loss is 20 % [13].

The PV array sizing is calculated by

$$\text{No. of solar module in series} = \frac{V_s}{V_{pv}} \quad (9)$$

and

$$\text{No. of solar module in parallel} = \frac{\Gamma_m}{\Gamma_{pv}} \quad (10)$$

where Vs and V_{pv} are nominal system voltage and output voltage of PV, respectively, and Γ_{pv} is the Ah from the solar PV array. The battery capacity requirement depends on the number of reserved days–days with low insolation, and the percentage maximum usable limit denoted by u_{max}. It can be expressed as

$$\text{Battery capacity} = \frac{D_r \times L_{daily}}{u_{max}} \quad (11)$$

where Dr is the reserved day(s).

The number of required batteries in series and parallel, denoted by N_{BS} and N_{BP}, respectively, is calculated as

$$N_{BS} = \frac{Vs}{Vb} \quad (12)$$

where Vb is the battery bank voltage (nominal):

$$N_{BP} = \frac{L_{daily}}{V_{pv} \times \varrho \times \eta_{charge}} \quad (13)$$

where ϱ is the derating factor and η_{charge} is the charging efficiency.

Mathematical model of diesel generator

The hourly energy output of a DEG, denoted by E_{DEG}, is expressed as

$$E_{DEG} = P_{DEG}(t) \times \eta_{DEG} \quad (14)$$

where P_{DEG} is the rated power output, and η_{DEG} is the efficiency of DEG. For better performance and higher efficiency, optimum values of η_{DEG} range from 0.8 to 1.

Mathematical model of charge controller

A charge controller prevents overcharging of a battery bank and reduces the amount of energy flowing from the energy source to the battery when the battery is in the fully charged state. The model of the charge controller is presented as follows [3]:

$$E_{cc-out} = E_{cc-in} \times \eta_{cc} \quad (15)$$

$$E_{cc-in} = E_{rec-out} + E_{sur-dc} \quad (16)$$

where E_{cc-out} is the hourly energy output from charge controller, E_{cc-in} is the hourly energy input to charge controller, $E_{rec-out}$ is the hourly energy output from rectifier, E_{sur-dc} $(=E_{pv} + E_{DEG} - E_m)$ is the hourly surplus energy supplied to battery, and η_{cc} is the efficiency of charge controller.

Mathematical model of battery bank

The battery state of charge (SOC) is a cumulative function of the daily charge and discharge. At any hour t, the state of battery depends on the previous SOC and energy production and consumption situation of the system between time

$t-1$ and t. When the generation exceeds the load demand, the excess energy, denoted by E_{bat}, is stored in the battery bank which is given by

$$E_{\text{bat}}(t) = E_{\text{sur-dc}} = E_{\text{bat}}(t-1) - E_{\text{cc-out}}(t) \times \eta_{\text{ch}} \quad (17)$$

where E_{bat} is the energy stored in battery at hour t, and η_{ch} is the battery charging efficiency.

On the other hand, when the generation is less than the load demand, the battery bank is in discharging state. Therefore, the available battery bank energy at time t can be expressed as

$$E_{\text{bat}}(t) = E_{\text{bat}}(t-1) - E_{\text{m}}(t). \quad (18)$$

Let the ratio of minimum allowable SOC voltage limit, denoted by $SOC_{\min}$, to the maximum SOC be denoted by δ. Therefore, the Depth of Discharge (DOD) is expressed mathematically as

$$DOD = (1-\delta) \times 100. \quad (19)$$

DOD implies how much energy has been taken from a battery, expressed as a percentage of full capacity. The maximum value of SOC is 1, whereas SOC has a minimum value that is determined by maximum depth of discharge, denoted by $DOD_{\max}$, which can be expressed as

$$SOC_{\min} = 1 - \frac{DOD_{\max}}{100}. \quad (20)$$

Objective function

Total energy, i.e., E_{G}, generated by the PV, DEG, and Battery system can be expressed according to [24, 25] as

$$E_{\text{G}} = m \times E_{\text{pv}} + n \times E_{\text{DEG}} + o \times E_{\text{bat}} \quad (21)$$

where m, n, and o are the number of PV modules in array, DEG, and the number of batteries in battery bank, respectively. E_{pv} depends on sailing period, H_{s}, which has a linear relationship with E_{pv} and in turn, contributes to the total energy generated. The total capital cost, denoted by CC, for the proposed hybrid system is given by

$$CC = m \times C_{\text{pv}} + n \times C_{\text{DEG}} + o \times C_{\text{bat}} \quad (22)$$

where C_{pv}, C_{DEG}, and C_{bat} are the capital cost of PV generator, DEG, and Battery system, respectively.

The annual operating cost, denoted by CO, is computed based on the operating costs of all the installed units for the interval t in a day. The total annualized life cycle cost of the system, denoted by $C_{\text{ann,tot}}$, comprised of both capital and operating costs is expressed as

$$C_{\text{ann,tot}} = CC \times \text{CRF} + \text{CO} \quad (23)$$

where CRF is the capital recovery factor for the system with expected discount rate.

The main objective function of the hybrid solar–DEC-powered boat is to minimize the total life cycle cost by choosing the best combination of energy sources. The objective function of this optimization problem can be written as [3, 24, 25]

$$\begin{aligned} &\min \ CC \\ &\text{subject to} \ \ EG \geq E_{\text{m}}. \end{aligned} \quad (24)$$

Techno-financial feasibility analysis

In this section, the joint technical and financial analysis of the proposed boat using the micropower optimization model, called HOMER, is discussed. HOMER's optimization and sensitivity analysis evaluate the best system sizing—based on the energy resources available from many possible system configurations. It uses indicators, such as net present cost (NPC), renewable fraction, and the levelized cost of energy (COE). Based on NPC, HOMER ranks the system [24, 25].

Net present cost (NPC)

The total NPC is one of the economic indicators of HOMER. All the possible hybrid systems are ranked in regard of this. The NPC is mathematically calculated using the following equation [11]:

$$\text{NPC} = \frac{C_{\text{ann,tot}}}{\text{CRF(i, n)}} \quad (25)$$

where i is the interest rate in (%), and n is the lifetime in (year).

Renewable fraction

It indicates what percentage of energy is originated from renewable power source, which is another important parameter in sensitivity analysis. HOMER calculates the renewable fraction using the following equation:

$$f_{\text{ren}} = \frac{E_{\text{ren}}}{E_{\text{tot}}} \quad (26)$$

where E_{ren} = renewable electrical production and E_{tot} = total electrical production.

Levelized cost of energy (COE)

It specifies the average cost per kWh of useful electrical energy produced by the system. It can be evaluated by the following equation:

$$\text{COE} = \frac{C_{\text{ann,tot}}}{E_{\text{ann,m}}} \quad (27)$$

where $E_{ann,m}$ is the per annum energy absorbed by the motor.

Sensitivity analysis

The sensitivity analysis generates a large number of output data. In every sensitivity case, HOMER results several outputs, e.g., NPC, f_{ren}, annual fuel usage, the total capital cost, etc. The purpose of performing sensitivity analysis in HOMER is to generate the best combination of (m, n, o) through exhaustive search that requires minimum system cost [24].

HOMER simulation

The hybrid optimization of multiple energy resources (HOMER) model is used to select the optimized configuration of the hybrid system. Based on the end user demand and energy resources available at the site location, HOMER determines different conventional, renewable, and hybrid systems.

Energy resource

Figure 3 shows the monthly solar insolation received in Bangladesh. The maximum solar radiation is available from March to April, and the minimum insolation is experienced between December and January [13, 30]. The energy generated in the form of electricity is 105 times lower than that is due to the solar energy reaching Bangladesh—an enormous amount of 5.2×10^6 MWhr/year [16, 17]. The Hourly solar irradiation data for the last two decade have been collected from Bangladesh Meteorological Department. The sensitivity analysis is done for the values—0.5, 1.0, 1.5, and 2.0 kWh/m2/d.

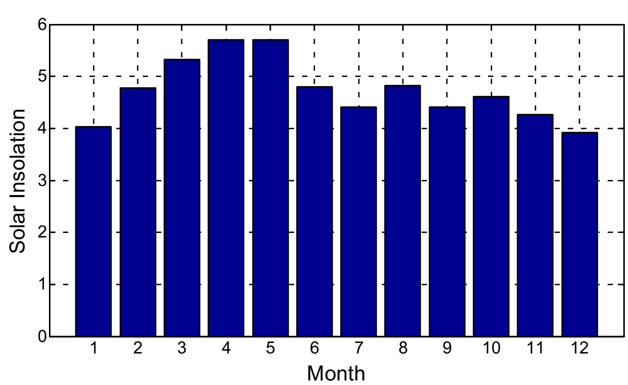


Fig. 3 Monthly solar insolation over Bangladesh

A research study found that the daily sunlight hours range from 10 to 7 h in Bangladesh, and the authors further reduced this by 54 % (to 4.6 h) to consider the effects of rainfall, cloud, fog, and dust on the solar panels [17–19].

PV model

The daily solar radiation on the horizontal surface data is considered for simulation. The capital cost of the PV array may vary from \$0.625 to \$0.8/W [14]. In the HOMER model, the three different sizes are inputted, which are 0 (no PV module), 0.01, 0.1, 0.2, 0.5, and 1 kW. HOMER found that the optimal PV array size is 0.45 kW. Since the nominal system voltage is $48V$, the proposed system requires four PV panels with each having capacity of 120 Wp. The lifetime of the PV array is considered 20 years. There is no automatic tracking option available in the system [15].

Battery model

Since the energy generation from PV is not constant and varies continually with time, the energy generation occasionally can not satisfy the demand. Thus a battery bank is required to smooth the time distribution mismatch between the generation and the load demand. The battery is considered as a major cost factor in small-scale stand-alone power systems. In HOMER model, battery of rating 12 V and 20 Ah are considered, The cost of each battery unit is 45 and the battery bank may contain 0, 2, 4, 8, 16 batteries. HOMER founds four battery module are needed to be considered. In this simulation, four battery module-rated 20 Ah have been chosen. The lifetime of the battery is less than 3 years. It means that the battery bank has to be replaced more than six times.

DEG model

The NPC and COE analyses are sensitive to the price of diesel fuel. The price is considered \$0.4/L, but based on the statistical data of last 5 years, the price should increase between 10 and 20 % in every half year. Thus, the price of diesel fuel is considered \$0.4/L, \$0.7/L, \$0.8/L, and \$0.9/L in the HOMER analysis. The diesel back-up system is operated when the generation from the PV systems fails to satisfy the load demand and also when the battery bank is depleted. The diesel price and the operating lifetime of the DEG are considered to be 0.7\$/L and 10,000h, respectively.

System economics and constraint

The lifetime of the system is considered to be 20 years, whereas the annual interest rate is considered to be 7.00 %

as per local bank [20]. As the speed of the boat is not constant during the operating hours, the electric boat uses a storage bank. The days of autonomy are considered as 1 day only. No subsidy given by the Bangladesh government is considered in this study.

Rectifier model

An electronic rectifier maintains the flow of energy between ac and dc components of the system. In the proposed system, a rectifier of size 1 kW is considered to convert the ac power from the DEG to dc power. In this analysis, the size of the rectifier is considered to be 0.5, 1.0, 1.5, and 2 kW. The lifetime of the rectifier is considered to be 15 years with an efficiency of 0.9. The installation and replacement costs are taken as \$90 and \$80, respectively, which could be visualized in Table 2.

Structure of boat

The boat has a dimension of $6.85\,\mathrm{m} \times 2.3\,\mathrm{m} \times 1.3\,\mathrm{m}$ and carries maximum of six passengers. Under normal load condition, a $400W$ dc motor is considered to run the hybrid source powered boat at the speed of 3–4 Knots. The capital cost of the motor is \$87.5, and the replacement cost is taken \$70. The lifetime of the motor is 5–10 years.

Numerical results and discussion

In the hybrid PV-DEG-powered boat, the sensitivity variables are considered to be solar irradiation, PV cost, and diesel price. To find the optimal hybrid system configuration for the boat, all possible system types and configurations are input which are discussed in the previous section. HOMER simulates system configurations with all possible combinations of components that were specified at the component inputs. Based on the energy resources and demand, HOMER performs an exhausted search to min the best possible combination which ensures lower COE. To ensure the best possible matching of demand and supply, HOMER performs many simulations, and offers a list of feasible configurations, which are ranked on the basis of the NPC analysis. HOMER also derives operational characteristics of any particular configuration.

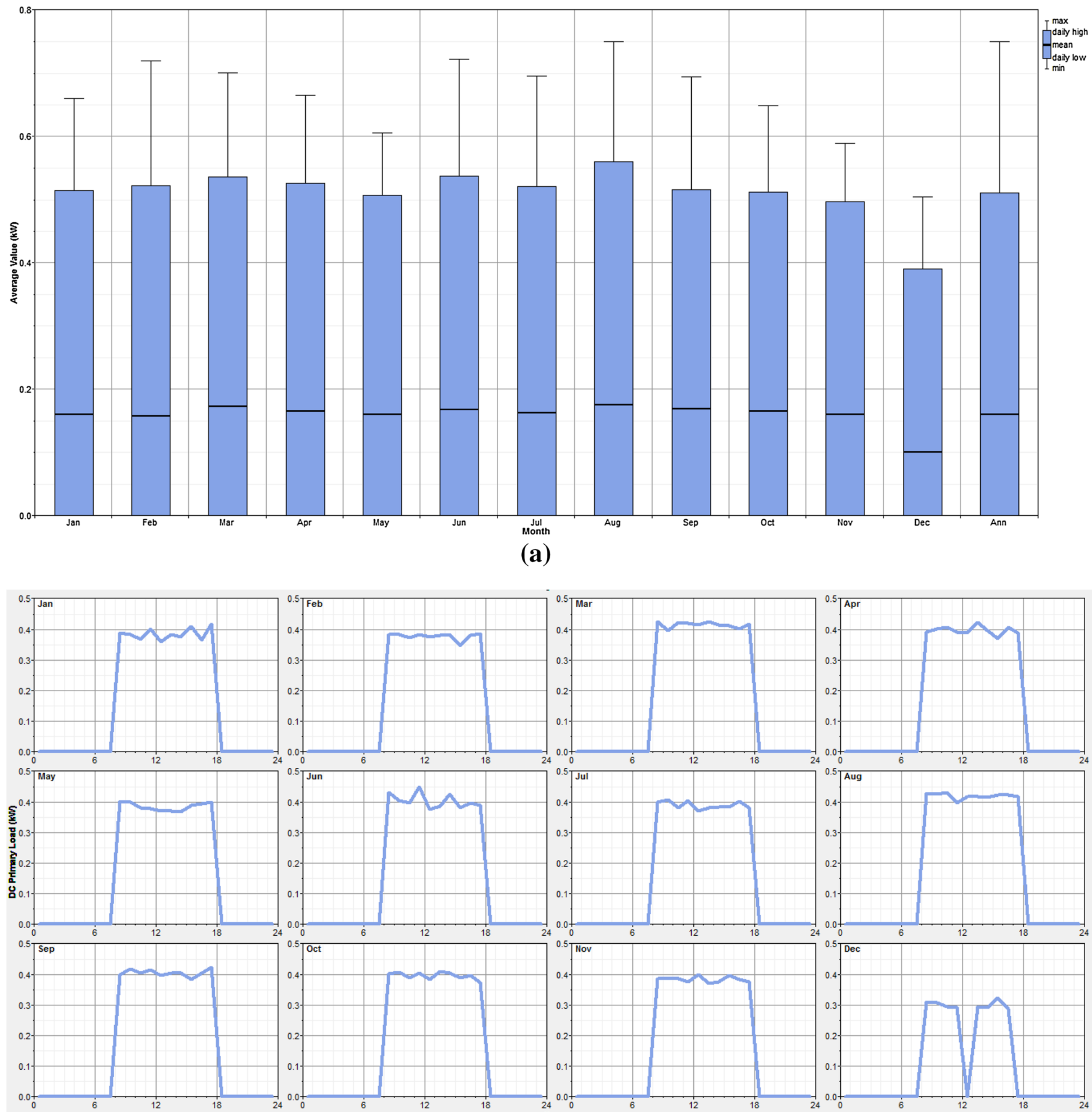
In Figs. 4a, 5a, 6a, and 7a, top whiskers in the box plots are longer and the bottom whiskers are very close to zero, which indicates that the plots are skewed upwards. The daily low and minimum values for the box plots are null. Figure 4 illustrates the monthly average power consumed by dc load and the corresponding load profile. The load profile is the hourly average of power consumed by load in KW for each month of a year. It could be observed from the load profile, in Fig. 4b, that the consumption of power is maximum in a particular time period throughout the year. The average output power generated by PV array is shown in Fig. 5. The average hourly power generation profile of PV array is illustrated in Fig. 5b. From the profile, it is clearly understood that the peak hour for generation floats around the middle of the day when the solar irradiance is expected to be greater than the average insolation, while the generation falls off on both the sides of the peak hour. In Fig. 6, the graphical information presents the average power of DEG and its monthly profile. The profile has peaks, where the power generation from the PV array is relatively low, indicating the DEG contributing more in the total generated power, to ensure the satisfaction of the load demand. The average excess power and its monthly profile are illustrated in Fig. 7. The excess power quantifies the amount of additional power generated by PV and DEG, which is stored in the battery bank. Figure 7b indicates a variable behavior of the excess energy generated at different months of the year. This behavior is directly results from the load demand at respective months.

Figure 8 shows monthly average electrical power generated by solar–DEG hybrid source. It is found that during the months of June, July, and August, DEG is required to generate more power, as the solar insolation is low during these months.

Tables 1 and 2 show optimized configuration obtained by HOMER model and annualized cost of all individual components of the proposed system, respectively. Figure 9 shows the cash flow analysis of the proposed system. The effect of cost escalation rate on the cumulative cash flow analysis is understood from this illustration. The increasing cost escalation rate has a decreasing effect on net present value. It is evident from this illustration that this system is feasible, since the internal rate of return is less than around 2 years for all the cases. Table 3 shows simulation parameters for the cumulative cash flow analysis.

The use of renewable energy reduces the emission of GHG, such as CO_2, SO_2, and NO_x, into the atmosphere. Table 4 shows the comparison among annual emissions (kg/yr) of pollutants from the proposed system (Case A) and only diesel engine powered boat (Case B). It it found that the generation of pollutants is reduced to more than 70 % for Case A.

Table 5 shows the effect of fuel price on the NPC and COE. If the fuel price increases 2.25 times, the NPC and COE increase by 1.65 times and 1.645 times, respectively. The required electrical power calculations is shown in Table 6. Figures 10 and 11 illustrate the relationships of required motor power with hull length and motor speed,



(a)

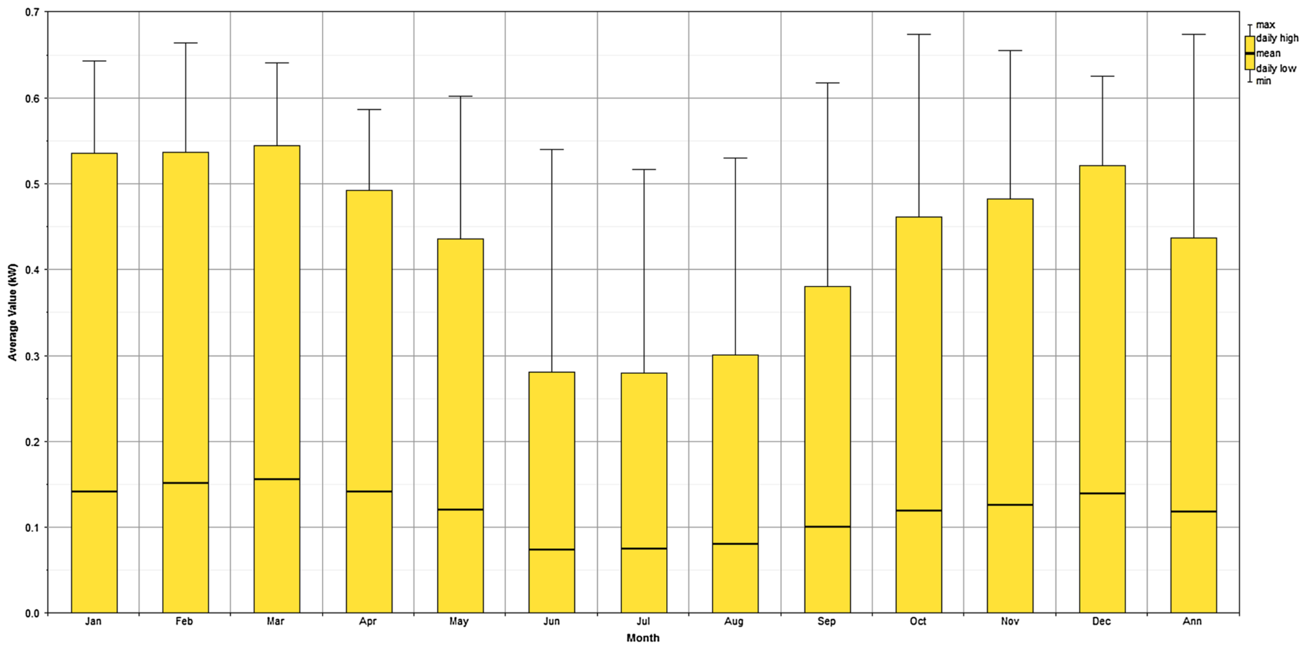
(b)

Fig. 4 Monthly average power consumed by dc motor: **a** DC primary load monthly averages. **b** Load profile

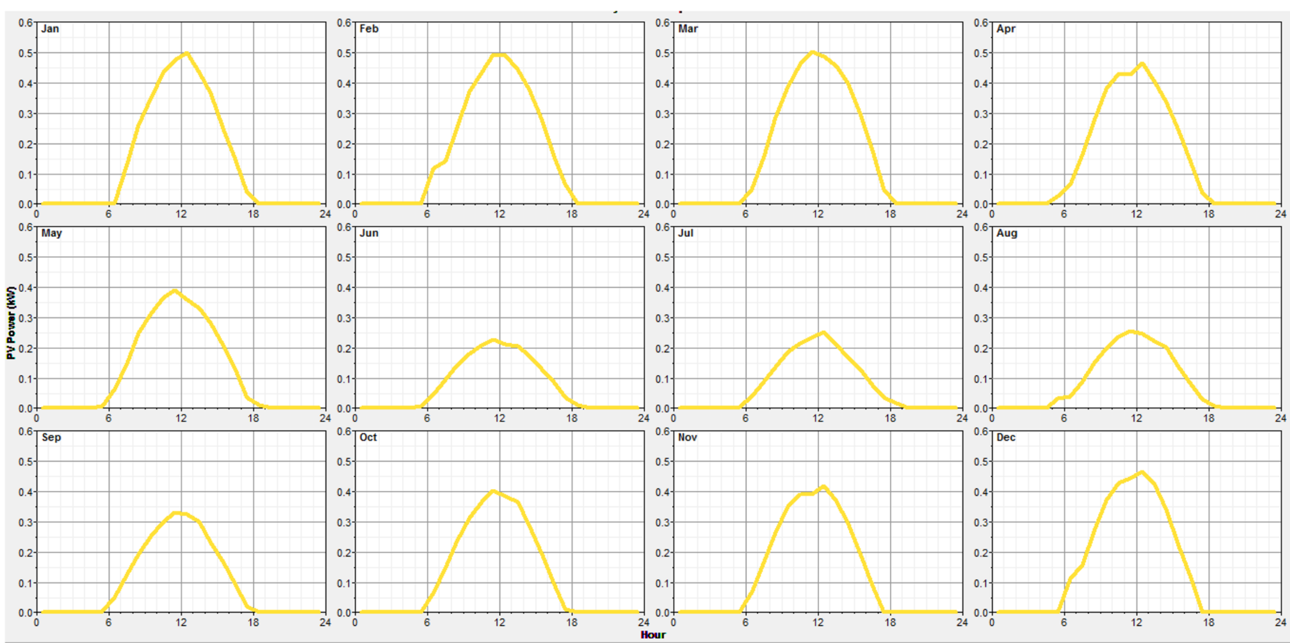
respectively. With increasing hull length, the required motor power is expected to be decreasing linearly, while the hull speed is kept constant. The decrease in required power is largely due to the decrease in drag force with increased hull length. The motor speed maintains a piecewise linear relationship with the required power which is consistent with the concept of motor increasing in speed that draws an additional amount of current.

Intelligent-assisting system (IAS)

The main objective of IAS is to assist the sailors with critical information and control. This system is adaptive in nature which acquires and processes information from sensors and network interface to provide intelligent support. Modular approach is followed in the design of the system. Figure 12 shows the functional



(a)



(b)

Fig. 5 Monthly average output power from solar PV array: **a** PV array power output monthly averages and **b** PV array power output profile

modules of IAS which provide different assisting functionalities to the sailors. The modules are controlled and synchronized by a central programmable controller (CPC) unit to process data and perform control functions. The following modules are incorporated with the CPC:

– charge controller (for controlling the charging of battery by the hybrid source);
– ignition Controller (for controlling the initial motor torque);
– boat submergence depth information (to determine the safety level of the boat);
– sensor module (for additional sensory information);
– GPS module (for the acquisition of location information);
– network interface (for accessing wireless network);
– visualization module (for displaying critical system parameters);

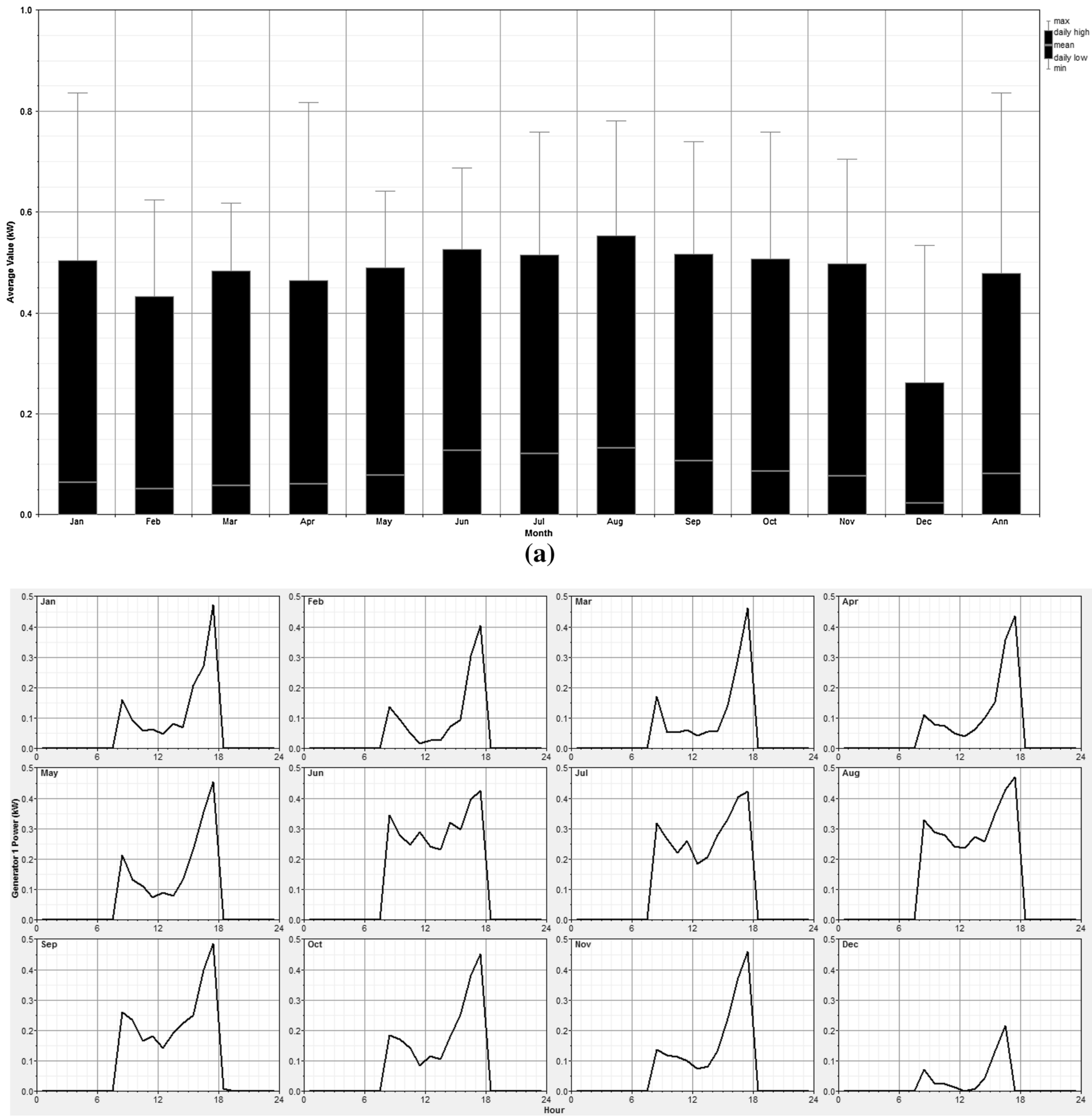


Fig. 6 DEG's monthly average output power: **a** DEG electrical output monthly averages and **b** DEG electrical output profile

– voice synthesis (for alarm purpose by auditory mean);
– visual alarm (for alarm purpose by visual mean).

Charge and ignition control

Battery charge control is performed by a conventional charge controller, which uses a PIC18f876 micro-controller. The storage used here is a bank of four 12 V batteries. In automated control mode, the central controller controls the starting phase of the motor. If all the vital parameters which are related to the safety of the vessel, e.g., depth of submergence information, weather information, etc. fall within the safety margins provided by the system operator, then upon pressing a key, CPC will signal to rotate the motor.

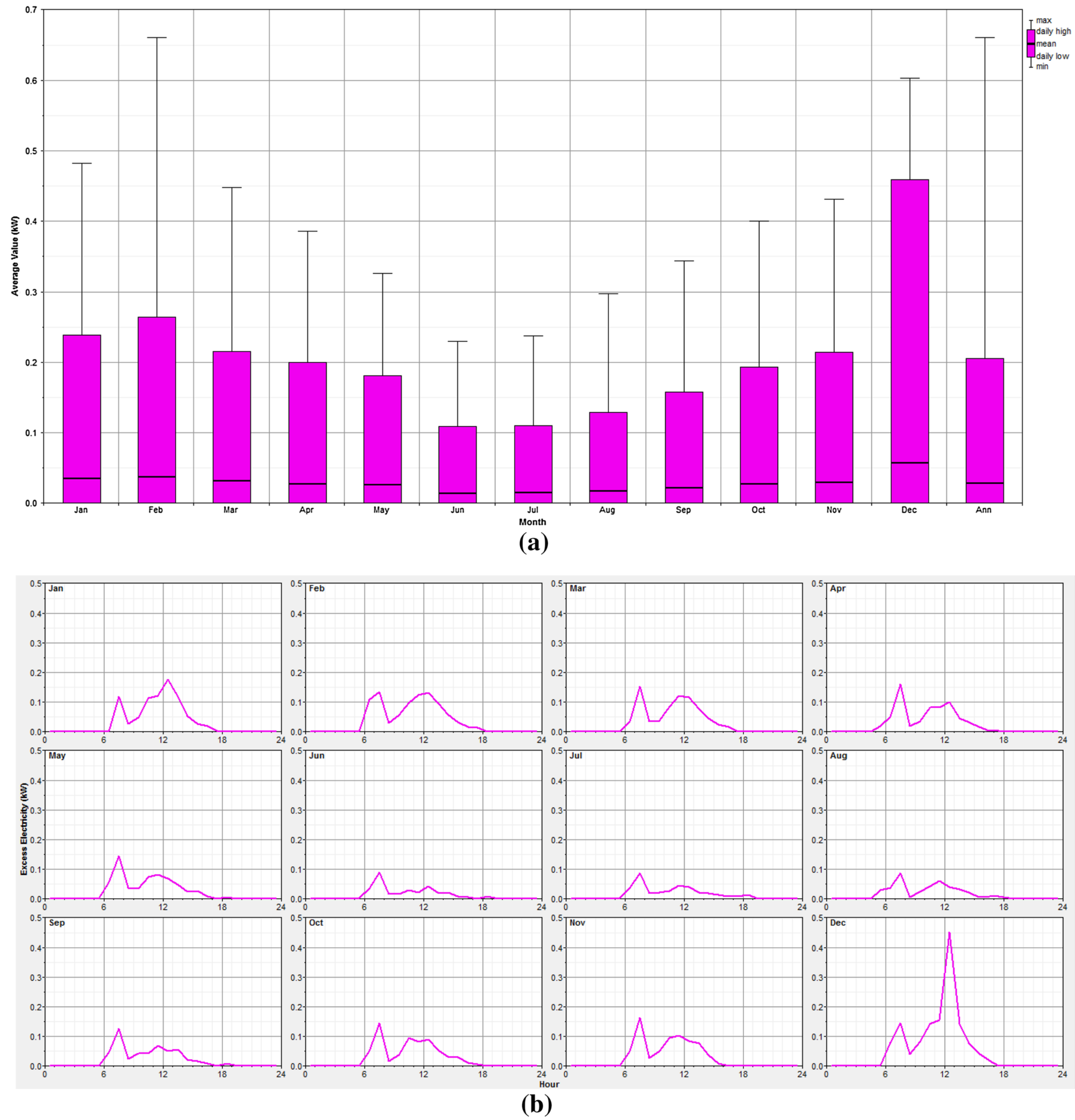


Fig. 7 Monthly average excess generated electrical power: **a** Excess electrical production monthly averages and **b** excess electrical production profile

Boat submergence depth information

Measuring the vertical submergence height of the boat is significantly important, as it directly relates to the safety issues of the boat. The main challenge to measure the depth of submergence of a boat is that there is no reference plane other than the water surface to measure the distance from. A technique is devised to compensate the problem utilizing the water surface as the reference plane and measuring the vertical distance from the top of the boat to that surface. Figure 13 illustrates the principle of this technique. The measurement of distance using ultrasonic signal is an extensively used technique in many applications which provides accurate measurement of distance with low cost [26–28]. The concept of horizontal distance measurement using ultrasonic signal is modified and used to measure the

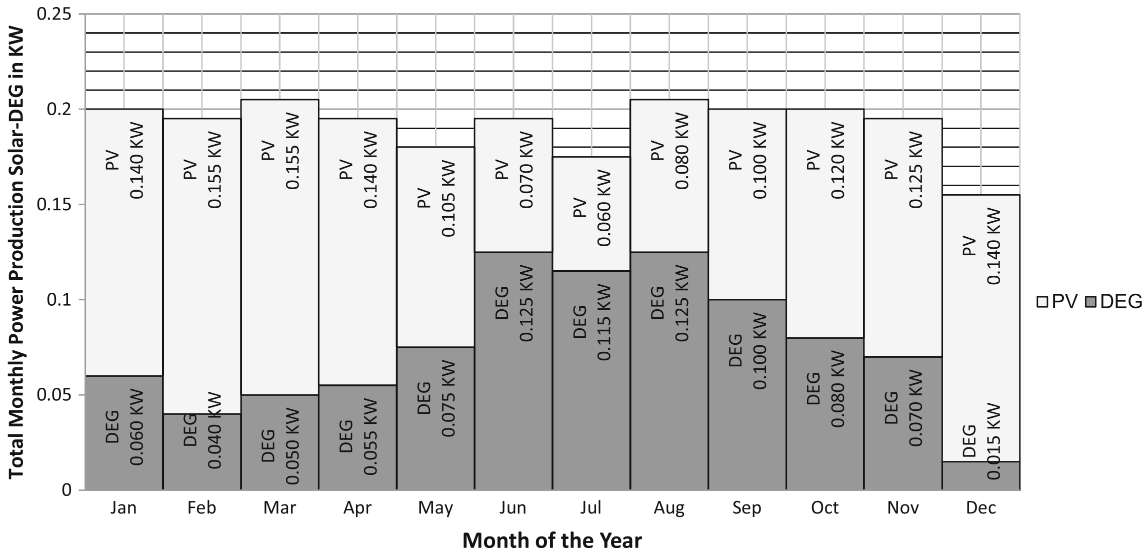


Fig. 8 Monthly average electrical power production from PV and DEG

Table 1 Optimized result obtained by HOMER model

PV	DEG	Battery	Rectifier (kW)	C_i	NPC	F	Diesel (L)	DEG (h)
0.6	1	4	1	$770	$4102	0.61	279	1423
0.6	1	0	1	$590	$15,085	0.27	1383	8697

Table 2 Annualized cost (in USD) of the components

Components	*Cc*	*Ac*	*Ar*	*Af*	*AT*
PV	226	17.7	0	0	18
DEG	334	26.1	34.7	170.9	232
Battery	180	14.1	28.7	0	43
Rectifier	90	2.3	0.8	0	3
Total	830	60.3	64.2	170.9	321

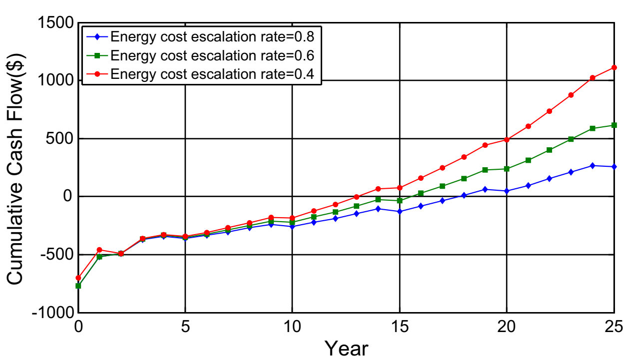


Fig. 9 Effect of energy cost escalation rate on the cumulative cash flow analysis

Table 3 Simulation parameter for cumulative cash flow analysis

Avoided cost of energy	$/L	0.4
GHG emission reduction credit	$/$tCO_2$	2.0
GHG reduction credit duration	year	25
GHG credit escalation rate	%	2
Avoided cost of capacity	$/kW-year	120
Energy cost escalation rate	%	6
Inflation	%	2
Discount rate	%	6
Project life	year	25

vertical height from the water surface. As the ultrasonic signal would not reflect very well from the water surface and on to the receiver module, a reflector is used which floats on the water. The main obstacle was to restrict the reflector in an area, where the ultrasonic module and the reflector are perfectly aligned. To ensure that the reflector object stays within that particular area of concern, a pipe-like structure is used which contains the reflector within the pipe as well as the measurement module on top of it. The structure is attached to a side of the boat in a way that the ultrasonic module is at the same plane as the bulwarks.

The pipe has two open ends with a hole near the top. This hole is placed intentionally, so that when the water enters from the bottom end of the pipe, there is no pressure due to the compressed air column inside the pipe. This hole helps the water to enter the pipe without any obstruction, and the water stops entering the pipe when the level of

Table 4 Comparison of annual emissions(kg/yr) of pollutants of proposed system (Case A) and diesel engine powered boat (Case B)

Pollutant	Emission (kg/Ye) from Case A	Emission (kg/Ye) from Case B
Carbon dioxide	734	2134
Carbon mono-oxide	1.813	2.341
Unburned hydro carbon	0.201	0.511
Particulate matter	0.1367	0.165
Sulfur dioxide	1.475	4.484
Nitrogen oxides	16.8	48.0

Table 5 Sensitivity analysis of NPC and COE with the increase in diesel price

DEG unit cost	NPC ($)	COE ($/kWh)	f_{ren}	DEG (L)
0.4	2941	0.165	0.59	379
0.7	4102	0.23	0.61	279
0.8	4474	0.25	0.61	272
0.9	4853	0.272	0.61	266

Table 6 Required electrical power calculation

Length of hull	0.5 m
Wetted area of hull	2.2 m^2
Speed	2 m/s
Ditto	7.2 km/h
Ditto	3.88 Kts
Reynold's number	1,000,000
Coefficient of drag	0.0051
Drag	23 *N*
Propulsive power	46 W
Eta propeller	90 %
Eta motor	90 %
Eta motor controller	98 %
Battery voltage	24 V
Current	9 A
Cable power loss	3 W
Eta cable	97.4 %
Electrical power (motor)	56 W
Electrical power (battery)	114 W

water inside the pipe is as the same as what is the outside of the pipe [29].

The number of measurement modules is dependent on the precision of measurement required and also the system specification. At least four modules are recommended for an optimum level of measurement—roughly placed on the four corners of two imaginary intercepting diagonals over the boat.

Geo-location information

Global-Positing System (GPS)-based acquisition of geo-location information is one of the key features of this system. A GPS module is attached to the CPC through serial interface. Periodic acquisition and decoding of the location information are done by the CPC to keep track of the location of the vessel.

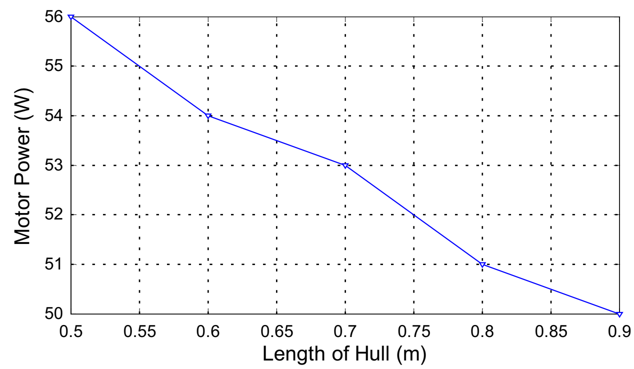


Fig. 10 Effect of hull length on the required motor power

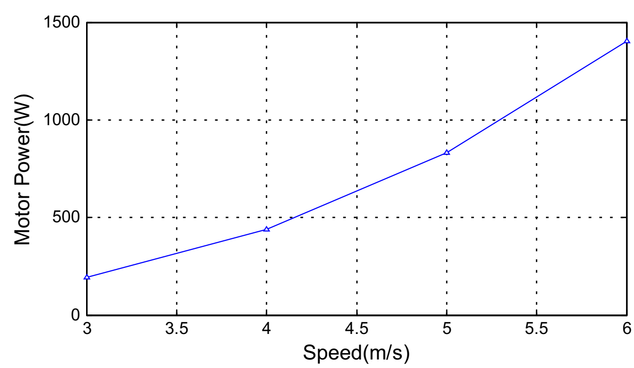


Fig. 11 Effect of motor speed on the required motor power

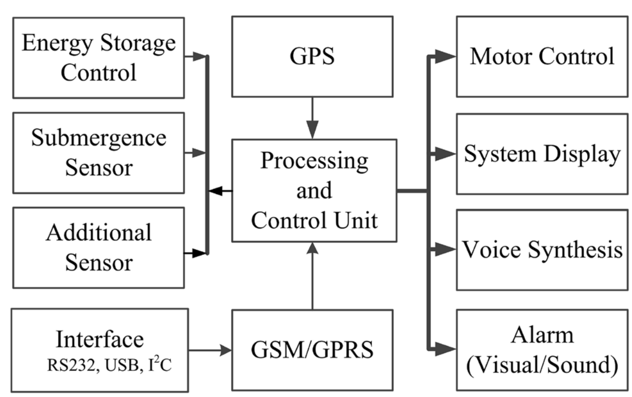


Fig. 12 *Block diagram* of the IAS

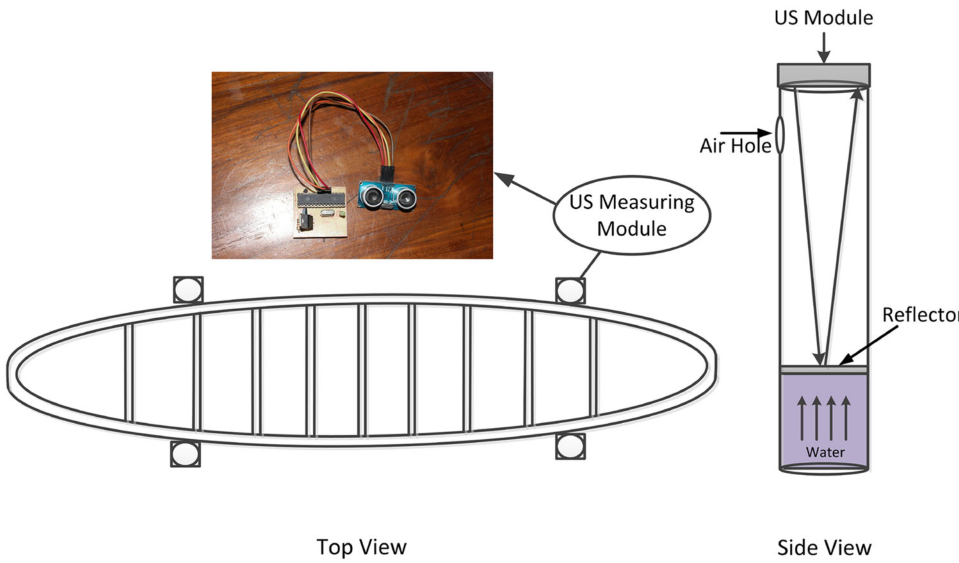


Fig. 13 *Top view* and *side view* of the devise for measuring the depth of boat submergence

Network interface

For the purpose of network access, there is a GSM/GPRS modem connected through serial interface available on the system module. This modem is primarily responsible for receiving SMS from an on-shore control center and for passing the SMS for processing to the CPC when requested. Other means of communication with the CPC is also available through USB and I^2C buses. These buses facilitate the easy inclusion of other system modules with the processing and control unit without much modifications to the proposed design.

Audio-visual alert information

Critical system parameters, such as depth of submergence, GPS location, and any weather information, are visualized on an LCD. If any SMS arrives at the network adapter placed on the system, the CPC decodes the information contained within the SMS and decides if any alarm is necessary or not. If any alert information is extracted from the SMS, controller looks up to a table, and determines the type and content of the alert. A voice synthesizer is attached to the CPC that receives the information and plays pre-defined voices from a multimedia card according to the information. In addition to the voice synthesizer, a simple visual alert, such as red-colored LED, is employed to indicate any noticeable development regarding safety issues, and prompts the navigator to look for further details on the LCD.

Auxiliary sensors

Some additional sensor information could be used in addition to the water-level information for a better and more accurate accumulation of information during the navigation of the vessel, e.g., humidity, barometric pressure, speed of the boat, etc.

IAS firmware

The individual modules, which have handles information-processing tasks, e.g., voice synthesis, submergence sensor, etc, use individual microcontrollers. The central controller is a microcontroller which co-ordinates among the different modules. A system firmware is the central microprocessor responsible for controlling the system functionalities in a sequential and timely manner. Algorithm 1 illustrates the generic firmware of the system. In addition to this, an interrupt service routine (ISR) handles the tasks when an external interrupt arrives. This ISR serves the purpose of acquisition of GPS data and sends it to the control center when requested. This is enabled at the initialization phase of controller.

When worst case scenario evolves, an interrupt is generated by means of an external switch. This causes the control to go into ISR and check for the condition flags. The basic task of interrupt service routine includes acquiring instantaneous GPS data and creating an SMS with the coordinates of vessel within it. This SMS is sent through the GMS modem which is attached and thereby causing an SOS message to be broadcast.

Algorithm 1: Algorithm for Firmware

```
Data: abc
Result: abc
initialization of system parameters;
set counter = 1;
Acquire sensor information;
if Submergence < threshold then
    Display system critical parameters;
else
    Display warning;
end
if Weather = Normal then
    Activate motor ignition;
end
Wait for manual override;
Activate motor ignition;
Set timer for GPS Data Collection;
while counter = 1 do
    Decode incoming SMS;
    if Warning then
        Consult LUT and Synthesize Voice;
        Light Red indicator;
    end
end
```

Conclusion

In countries, where waterways play a major role in the national transportation systems, solar boats could be a potential mode of low-cost transportation. In this paper, a hybrid solar–DEG is proposed and developed to mitigate the drawbacks imposed by the traditional solar-energy-powered boats, such as low generation during no or partial insolation, lack of financial feasibility, etc. A techno-financial analysis of a solar–DEG hybrid source-powered boat is presented, and the financial analysis is done considering a hybrid energy source involving a DEG along with PV source, to make the energy generation system more competent in terms of technology and economy. In addition, an IAS is proposed and designed to reduce the possibility of accidents due to over-weight and inclement weather. With the sensors installed on the boat, IAS supports sailors to operate the vessels without compromising the safety issues of the boat. The proposed design of the boat with IAS is realized and tested for functional accuracy. The test runs yield satisfactory performance even during partial cloudy days with a proper indication of boat's loading condition.

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