# Optimal Design, Dynamic Modeling and Analysis of a Hybrid Power System for a Catamarans Boat in Bangladesh

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Abstract — Bangladesh is a land of rivers, canals, and lakes where water transportation is an essential means of transport. The country use boats as one of the leading resources of a carrier in its widespread inland waterways. Most of the currently used boats use only diesel for fuel. Appropriate use of renewable energy sources, particularly solar energy with diesel generators, could reduce diesel consumption. In this paper, a typical boat energy requirement was calculated to be 42.10 kWh/day. A boat could be driven by a DC motor using electrical power generated using an onboard PV system, battery, and a small generator. The carrying capacity of the vessel is 20passenger for 8hours a day. The designed system consists of a 10.6 kW PV, 1.6kW rated small gas generator, onboard battery storage consists of 16 batteries, each placed 6V, 333 Ah, and a 48 V DC motor rated 5 kW 3000 rpm with a speed controller. The paper includes system design details and sizing using HOMER Pro and dynamic simulation using MATLAB Simulink.

*Index Terms*— Renewable energy, Catamarans type passenger boat (CPB), Hybrid power system, Solar boat, Solar energy.

#### I. INTRODUCTION

Global warming and climate change are the most critical concerns that the world is chasing nowadays. The utilization of solar energy is one of the best solutions to overcome, as it does not generate any harmful contaminants to the environment leading to global warming. Bangladesh is a South Asian developing country. Either the petrol engine or diesel engine typically operates country boats. Recently, the world is thinking about green power and seeking to stay away from fossil fuels, and subsequently, the best option is electric power for driving a boat [1]. The average solar radiation in Bangladesh is around 4-6.5 kWh/ $m^2$ /d, with the peak amount in April and the lowest in December [2]. Solar energy use can assist in energy independence, long term financial benefits, and a degree of reliability and security [3]. Henceforth, solar power-driven electric boats for water transportation can be a part of clean transportation.

#### II. LITERATURE REVIEW

In the literature, various studies related to the expansion and exercise of renewable energy, especially solar powered boats, have been found. The electric motorboat Revolution did not move further in the last century due to a lack of technology, energy source, and energy-storing facility in the

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electrical system. Also, electric motor efficiency was not up to the mark [4]. Solar energy has become the most popular electrical power resource because of advanced, highly efficient solar PV modules [5]. Nowadays, developing countries like Bangladesh are using Solar PV modules to establish the solar home system and massive uses in telecommunication tower in the off-grid areas [6], [7], and worldwide, overall electrification has been practicing by solar PV modules. Kabir et al. [8] described a solar-powered ferry boat in Bangladesh developed to carry 1200 kg by converting a conventional ferry boat. This ferry boat was made of local wood. They designed the PV module, motor, and battery storage system but did not report the total control system.

Moreover, the water drag force to run the boat is also not discussed. Mahmud et al. [9] proposed a solar power-driven electric boat for specific load and specific distance movement, but a complete design technique is absent. The light composite material was considered to make a boat. They calculated boat dimensions and hydrodynamics, boat propulsion system, PV capacity, and battery bank size. The boat movement was achieved by using motor driven engine. However, control system was not reported to keep the constant boat speed while increasing boat passengers.

Postiglione et al. [10] presented a permanent magnet synchronous motor (PMSM) motor-driven zero-emission electric propulsion boat used for public transportation and water sports events. They introduced two PMSM motors, and each engine is rated 12 kW and a dc-dc converter for providing steady dc-bus voltage. The boat is a wave penetrating, Catamaran characterized, powered by lithiumion batteries and the option to charge at the harbor and, partly, with photovoltaic solar panels. This paper has focused on boat speed, duration of power deliver by the battery, does not describe charge control and motor control procedure.

Simonetti et al. [11] proposed an optimistic control technique of a solar-powered vessel driven by an indirect vector-controlled induction motor. To ensure the anticipated method, a trial drive load was coupled and experimented within the laboratory. This paper does not have sufficient field data regarding solar power and induction motor performance and impact.

Obaid et al. [12] designed an electric boat with a threephase asynchronous machine powered by solar and diesel hybrid power systems. They used the MPPT system to get maximum PV array output for driving the electric boat. However, a diesel generator was used as secondary power

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when solar irradiance was inadequate. They also showed the prior solar irradiance forecasting by using a neural network, which assists in planning hybrid power operation for driving the electric boat.

Spagnolo et al. [13] proposed a solar electric tourist boat with advanced management technology for charging and discharging energy storage batteries and could operate pollution-free with a low operating cost. They have used solar PV arrays, battery (45 Ah), catamaran boat ( $14 \times 5.5$  m), MPPT controller, boost converter (DC-DC), inverter (DC/AC), charge-discharge controller, and power management controller for the proposed scheme.

Campillo et al. [14] tried to discuss the existing tendency of electrification for boat propulsion, assessing the wind and photovoltaic systems.

Ahmed et al. [15] studied the probability of using PV and wind power on seafaring. The system comprises a PV array, wind turbine, diesel generator, AC/DC converter, DC/AC inverter, and battery storage. They showed that the solar PV panel could be installed on available space in the ship, contributing a significant percentage of energy generation.

Similarly, Reza et al. [16] have analyzed a marine boat powered by solar PV for fishing purposes in Bangladesh using a combination of HOMER, PVsyst software, and manual calculation. The main challenge is to get the maximum output from the solar panel while moving.

J. Hua [17] described the feasibility of renewable energies and their expansion and incorporation for naval transportation. The solar photovoltaic is the first excellent viable and substitutable source to power up the Taiwan maritime industry's commercial vessel.

Chennai et al. [18] designed a PV/Diesel/Fuel-cell hybrid power system to meet the main and auxiliary power loads for Dubai passengers. He used HOMER software for the configuration and simulation. He showed that his proposed architecture is the best eco-friendly hybrid power system, but there is no discussion regarding the investment payback scheme.

Leung et al. [19] designed a PV-powered boat with zero greenhouse gas emissions. They performed case studies by varying solar efficiency. This system saved costs and reduced  $CO_2$  emissions.

Chakraborty et al. [20] designed an MPPT based solar PV for fast charging lead-acid battery by using a buck converter and PID controller to fulfill a fishing trawler's power requirement. However, costing details and a payback period of investment was not reported.

Liu [21] explored a model to reduce  $CO_2$  and  $NO_x$  gas emissions and enhanced energy productivity by deploying solar PV and storage systems on a ship. It has been disclosed that the projected energy storage system could save the battery replacement 25% to 35% at least.

Tamunodukobipi et al. [22] introduced a naval boat powered by the solar PV system. This study used an electric motor for boat thrust, storage battery bank (235 Ah, 12 V). They faced a challenge for installing solar PV arrays due to lack of space because the proposed system either increases the boat hull's width and length or recharge the battery from the land power grid.

#### III. INLAND WATER TRANSPORT STATUS IN BANGLADESH

Bangladesh is a densely populated South Asian country with a population of 175 millions. Bangladesh's economy is primarily agriculture-based; however, other sectors, like industry, trade, and services, are contributing more to its economy. The transportation sector plays a vital role in the economic activities of a country. Adequate transportation implies both infrastructures and ensures the supply of energy required for the service to keep the economic activities alive. The transportation system of Bangladesh comprises roads, railways, waterways, two seaports, maritime shipping, and civil aviation. The country has about 24,140 kilometers of perennial canals (which increases during the monsoon) and Mongla and Chittagong's ports. Being a riverain country with almost 800 rivers, a riverway is an essential means of transportation in Bangladesh. During the rainy season, boats are the primary means of transport. They are used to carry passengers and freight primarily in rural areas because inland waterway transport is less expensive for the poor and essential for local trade.

Inland water transport (IWT) is maintaining transport links between the various remote parts of the country and at the same time contributing export-import trade. Currently, riverway transportation is commonly undertaken by dieseldriven boats due to faster transport and colossal load-carrying capacity. However, diesel-driven boats are very energy inefficient and used imported diesel fuel. Diesel driven boat is one of the extensive contributing human activities responsible for greenhouse gas emissions. The power imported in Bangladesh over the last ten years is presented in Fig. 1. It is observed that diesel fuel shares most of the imported energy, and it has been increasing steadily over the period. The transport sector's share in the total consumption of petroleum products is about 56%, which is about three times higher than the agricultural industry [23].



Fig. 1. Summary of imported fuel in the last ten years in Bangladesh [23].



Fig. 2 shows the number of registered water boats in Bangladesh from 2011 to 2019, according to BIWTA, Bangladesh [24]. The numbers of the motorized boat have

been increasing steadily over the period. Currently, there are 80,000 motorized boats, 107,000 passenger boats, and 58,000 cargo services in Bangladesh. These boats are mainly dieseldriven and produce emissions. The government is aware of the diesel consumption and GHG emissions and has already taken various measures. Incorporating a solar-based energy system into the conventional diesel boat without any doubt will increase energy efficiency for the water transport sector and reducing both energy demand and GHG emissions in Bangladesh.

## IV. DESIGN OVERVIEW OF SOLAR BOAT

An electric motor (which is rated 5 kW, 3000 rpm) drives a boat powered by a hybrid power system, which includes solar PV (10.6 kW), DC gas generator (1.6 kW), and battery bank (333 Ah) is the perfect solution for a conventional water boat. The Catamarans type passenger boat (CPB) made of fiberglass polyester material, 12 m in length and 4.8 m in width, has been considered. The CPB speed is measured 10 km/h (5.4 knots), and it could carry 20 passengers at a time. The schematic diagram of a hybrid-powered CPB is shown in Fig. 3. Solar Photo Voltaic (PV) panel will be installed in such a way so that it could work as an energy source and roof of this proposed system boat simultaneously. PV power is controlled by an MPPT controller (each rated 70 A), and its output is connected to the battery through constant current (CC) 25 A and constant voltage (CV) 49 V charge controller and boost converter. The dc gas generator is connected to the battery bank (BB). BB is linked to the Motor Speed Controller (MSC) through the overcurrent protection device (140 A rated DC relay). Motor ON/OFF manual switch is proposed between Motor speed controller and motor. Finally, the DC motor transmit mechanical rotative power to the boat propeller via coupler and shaft mechanism, while the Switch is in an ON state.



Fig. 3. The schematic diagram of a hybrid-powered Catamarans type passenger boat (CPB).

## V. DESIGN METHODOLOGY

#### A. System Architecture

A schematic layout of the proposed hybrid power system for a boat is shown in Fig. 4. In this study, PV modules are used to produce baseload demand. In contrast, a diesel generator is also used as a standby option when there is an insufficient supply of electricity from PV due to solar inaccessibility, thus increasing its reliability. The excess energy from PV modules and diesel generators are charged to the battery and used to supply the load demand until it reaches its minimum state of charge (SOC). The system does not need any bi-directional converter since there are no AC components. The proposed model of each system component's mathematical modeling is briefly described in the following subsections.



Fig. 4. Schematic layout of the proposed hybrid energy system for solar boat.

## B. Load Assessment

The load demand consists of the motor, light, control system, computer, and miscellaneous. Table I shows the load demand for a catamarans boat in climatic conditions of Bangladesh.

TABLE I: ENERGY DEMAND FOR PV SYSTEM			
Equipment	Run time (h)	Power (kW)	Energy Consumed (kWh)
BLDC Motor	8	5.00	40.00
Light-1	1	0.06	0.06
Light-2	3	0.04	0.12
Cockpit control and others	8	0.24	1.92
Total Load			42.10

Following the load consumption in HOMER software, some hypothesis that solar boat will be in operation 08hours in a day and starts the journey from 08:00 am stopped at 04:00 pm while the boat is in rest 01:00 pm. The daily load profile for the boat is presented in Fig. 5. In this research, a small BLDC motor with a capacity of 5 kW is considered to propel the boat at 10 km/h, where the constant daily load demand is 42.10 kWh with an average load of 1.75 kW and peak load demand 5.34 kW. In the simulation undertaken, the load demand is considered constant irrespective of the proposed hybrid system season. A residential load is selected in HOMER software, which produces a monthly average data profile based on Table I. This total electric load profile is then scaled with the peak load demand of 3.22 kW, the average load of 1.06 kW, and the average load demand of 25.38 kWh/d. The annual average energy demand is scaled 25.38 kWh/d as the boat will run 220 days a year. The ship required constant power to run all the time, and hence day-today random variability in load and unexpected time steps are considered 0% because there is no power variation. Additionally, the baseline and scaled load factor are 0.33.



Fig. 5. Daily load profile for the proposed energy system of Catamarans Boat.

## C. Resource Assessment

The monthly average solar radiation data and clearness index profile was collected from NASA using the HOMER tool as sufficient measured data was unavailable for the desired location Sadarghat, Bangladesh. It can be seen from Fig. 6 that the solar radiation data vary in a range of 4.02 to  $5.76 \text{ kWh/m}^2/\text{day}$ , where the scaled annual average value is  $4.65 \text{ kWh/m}^2/\text{day}$  with a clearness index of 0.52. It is also noted that high solar radiation periods are observed from February to May with the highest intensity in April ( $5.76 \text{ kWh/m}^2/\text{day}$ ) and the lowest intensity period started from June to December with minimum passion in September ( $4.02 \text{ kWh/m}^2/\text{day}$ ).



## D. PV Module

The output power  $P_{pv}(t)$  of the PV generator during hour t of the year is calculated by using (1), whereby,  $R_{PV}$  is the rated capacity (kW),  $D_{PV}$  is the PV derating factor (%),  $G_T$  is incident solar radiation (kW/m<sup>2</sup>),  $G_{T,STC}$  incident radiation in STC (standard test conditions),  $\alpha_P$  is power temperature coefficient (%/°C),  $T_{cell}$  and  $T_{cell,STC}$  are the cell temperature (°C) at operating and STC conditions, respectively.

$$P_{pv}(t) = R_{pv} D_{pv} \left( \frac{G_T(t)}{G_{T,STC}} \right) \left[ 1 + \alpha_p \left( T_{cell}(t) - T_{cell,STC} \right) \right]$$
(1)

 $T_{cell}$  is the PV cell temperature (°C), which can be calculated by using (2), whereby,  $T_a$  is the ambient temperature (°C),  $\tau$  is solar transmittance (%),  $\alpha_P$  is solar absorptance (%),  $\eta_c$  is conversion efficiency (%), and  $U_L$  overall heat transfer co-efficient (kW/m<sup>2</sup>°C).

$$T_{cell} = T_a(t) + G_T(t) \left(\frac{\tau \alpha}{U_L}\right) \left(1 - \frac{\eta_c}{\tau \alpha}\right)$$
(2)

The term  $\frac{\tau \alpha}{v_L}$  in (2) is difficult to measure, and therefore manufacturers introduce nominal operating cell temperature (NOT), that is, a cell temperature quantified using solar radiation of 800 W/m<sup>2</sup>, no-load condition ( $\eta_c = 0$ ), and at an ambient temperature of 20 °C. The term  $\frac{\tau \alpha}{v_L}$  is calculated using (3).

$$\frac{\tau \alpha}{U_L} = \frac{T_{cell,NOCT} - T_{a,NOCT}}{G_{T,NOCT}}$$
(3)

In this proposed system, we have studied PV lifetime 25 years and no tracking system. The capital cost of PV has examined  $0.65/W_p$  [25], [26]. We have considered, there is no replacement cost as the project lifetime has assumed 10 years. Evaluating present market value, operation, and maintenance (O &M) cost is considered \$10.00/year. For this research, the Canadian Solar CS6U-330P model has been considered, consisting of 330 Watts, 24 Volts, and  $1.96\times0.992$  m polycrystalline 72-cell solar panel [26].

#### E. Diesel Generator

HOMER assumes that the fuel consumption curve for a diesel generator is a straight line. The fuel consumption for a generator is calculated using (4), whereby *a* the co-efficient due to the fuel curve is intercept (0.0165 l/h/kW), *b* is the slope of the fuel curve (0.267 l/h/kW),  $R_{DG}$  is the diesel generator's rated capacity, and  $P_{DG}(t)$  is the power generation at any time interval.

$$F_{DG}(t) = aR_{DG} + bP_{DG}(t) \tag{4}$$

Technical details of the generator:

For the emergency, if the PV output and battery stored energy are insufficient to drive the load, this situation generator will provide additional power to overcome. In this research, a small-sized Champion 1600 W / 2000 W inverter generator has considered which has capacity 1.6 kW, capital cost \$600.00, replacement cost \$400.00, O & M cost \$.05/op.hr, the lifetime of generator 12000 h and fuel cost \$0.76/lit [27].

#### F. Battery

In this study, lead-acid is considered for simulation, which receives surplus energy during charging and provides energy at the time when RE sources are unable to satisfy load requirements. The maximum amount of power that can be absorbed by a battery system is given by applying (5), whereby  $Q_s(t)$  refers to the available energy at the beginning of the time step. Above minimum state of charge level (BOC<sub>min</sub>=20%), Q(t) refers to the total energy at the beginning of the time step, c is the storage capacity ratio, k is the storage rate constant, and  $\Delta t$  is the amount of time in the time step.

$$P_b(t) = \frac{kQ_s(t)e^{-k} + Q(t)kc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})}$$
(5)

The maximum battery discharge power can be calculated with (6), where  $Q_{max}$  is the total capacity of the storage.

$$P_b(t) = \frac{-kcQ_{max} + kQ_s(t)e^{-k\Delta t} + Q(t)kc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})}$$
(6)

# Technical details of the battery:

While the solar PV power generation is not sufficient to run the boat motor, then additional power will be delivered by the battery bank in horrible weather conditions while there is no sun. This research has considered a Trojan SAGM 06 220 kinetic battery model with nominal voltage 6.0 V, nominal maximum capacity 241 Ah (1.45 kWh). The capital cost, replacement cost, and O & M cost for a single Battery have considered \$362.00,\$330.00, and \$15.00, respectively [28]. Also, the battery string size is defined as 48V, known as the system BUS voltage.

# G. Solar Charge Controller

Maximum power point tracking (MPPT) is a system included in charge controllers used for extracting full available power from the PV module under certain conditions by regulating voltage and current. Maximum capacity varies with solar radiation, ambient temperature, and solar cell temperature. The MPPT is rated based on the following equation [29]:

MPPT current rating = 
$$\frac{\text{total required power}}{\text{BUS voltage}} = \frac{5.34\text{kW}}{48\text{V}}$$
  
= 111.25 A

For safety and to overcome unexpected light reflection factors, the rating is considered 25% more.

MPPT current rating =  $111.25 + 111.25 * 25\% \cong 140$  A

This analysis judged a charge controller with a capital cost of \$100.00, the replacement cost of \$100.00, O & M cost \$10.00/yearly, and a lifetime of 4years [25], [30].

## VI. RESULTS AND DISCUSSION

# A. Optimized Sizing for Meeting the Boat Load Demand

In this study, the hybrid PV/Diesel/Battery energy system is designed to fulfill a Catamarans Boat's load demand for its proper operation and control. Table II shows the summary of different hybrid configurations with their optimal operating characteristics.

 TABLE II: SUMMARY OF OPTIMIZED RESULTS OF HYBRID SYSTEM

 CONFIGURATIONS

Parameters	PV/Diesel/batt	PV/batt	Diesel only
COE (\$/kWh)	0.228	0.350	0.321
NPC (\$)	15,625	23,985	21,980
Diesel genset (kW)	1.60	-	4.00
PV module (kW)	10.6	14.8	-
Battery (kWh)	16	40	-
Genset energy (kWh/yr)	779	-	9,264
PV energy (kWh/yr)	15,990	22,346	-
Diesel consumption (L/yr)	223	-	2914
Excess Energy (kWh/yr)	7,325	12,920	0
Unmet load (kWh/yr)	2.87	6.18	0
Capacity shortage (kWh/yr)	7.93	8.86	0
Renewable fraction (%)	92.1%	100	0

After the technical and economic parameters were set, the system was simulated by the HOMER software tool to optimize the system components according to the load

profile. The corresponding results are presented in this section. It is found that PV/Diesel/Battery is the optimized system with the least COE 0.228 \$/kWh. The system is also able to supply the load with maximum renewable penetration of 92.1%.

On the other hand, PV/Battery shows excellent emission characteristics; however, the electricity cost is very high at 0.350 \$/kWh. Table IV shows the annualized cost summary of different hybrid system configurations. The PV/Diesel/Battery requires a total minimum NPC of only \$15,625, whereas the PV/Battery is the most expensive configuration with NPC \$23,985. The individual results are presented in the following sections.

# B. PV/Diesel/Battery

Optimal design of the PV/Diesel/Batt system for the boat consisting of the different components comprising 10.6 kW PV, 1.6 kW diesel generator, 16 kWh storage batteries as best optimized and economic configuration simulated, as presented in Table II. HOMER provides this optimized result based on NPC, COE, and initial capital investment. Total Net present cost (NPC), total capital cost, and cost of electricity (COE) of the optimized PV/Diesel/Batt configuration are \$15,625, \$13,557, and \$0.228/kWh. Fig. 7 shows the energy share for hybrid PV/Diesel/batt system over a week in March. It is found that solar PV covers most of the load demand during that time. However, this configuration needs 223 L diesel in an entire year in addition to this PV power. The battery comes into play during the unavailability of renewable sources. The system also generates 7,325 kWh of excess energy after meeting the charging load demand of the battery. Fig. 8 shows the cost distribution for the hybrid PV/Diesel/batt system. The system requires \$13,357 capital cost followed by a replacement cost of \$142 in his lifetime of 10 years. The replacement cost of the course is high due to the limited lifetime throughput of the battery. However, the operating cost is higher than replacement and resource cost at only \$2801. The system has some salvage value of \$1,903 after its operational period. Table III shows the energy balance of a hybrid PV/Diesel/Battery system.

TABLE III: SUM	MARY OF HYBRID PV/DIES	EL/BATT SYSTEM

System	sizing	Cost su	mmary	Electrica	al energy
PV	10.6	COF	0.228	PV	15,990
Module	kW	CUE	\$/kWh	energy	kWh
Diesel	1.6 kW	NPC	\$15,625	Diesel	779 kWh
Battery	16 kWh	Annualized cost	\$2115.00	Total	16,719 kWh







Fig. 8. NPC for costs for hybrid PV/Diesel/batt system.

#### C. Emission analysis

The proposed PV/Generator/Battery system comprises clean technologies. It offers close to zero-emission during operation since the designated generator will produce only 7.9% of the total electricity required in a year. However, it should be compared with the PV/Battery and conventional stand-alone generator system to observe the proposed system's economic and environmental viability. The hybrid system is compared with a gas generator in terms of net present cost and GHG emissions in the study. A diesel-based design meeting the same load as the load profile described in section 4.2 is optimized in HOMER. The cost components are presented in Table IV. It has observed that, PV/Generator has the highest annualized cost, and it has a low replacement cost of \$142.86 due to the controller. In contrast, the stand-alone generator system possesses a maximum replacement cost of \$1558.65. Besides, the generator's operating and maintenance price is slightly lower at \$ 2775.48 compared to the PV/Generator/Battery and PV/Battery, which are \$2801.20 and \$5607.24, respectively. On the other hand, Table IV illustrates the system's summary in terms of COE, NPC, energy generation, diesel consumption, and CO<sub>2</sub> emission. The environmental emissions of systems have been given in Table V. However, the proposed PV/Generator/Battery system causes insignificant environmental degradation by emitting 584 kg of CO<sub>2</sub> per year while only gas generator system emits 7630 kg CO<sub>2</sub> annually. The analysis shows that the proposed system is beneficial in both economically and environmentally over conventional stand-alone diesel system and PV/Battery system for the boat.

TABLE IV: ANNUALIZED COST SUMMARY OF HYBRID SYSTEM

CONFIGURATIONS			
Costs (\$)	PV/Diesel/batt	PV/batt	Diesel only
Capital	13,357.63	24,174.27	1600.0
Operating	2,801.20	5607.24	2775.48
Replacement	142.86	142.86	1558.65
Resources	1,255.18	0	16,393
Salvage	-1,903.99	-5911.15	-319.16
Total	15,652.88	24,013.23	22,007.77

TABLE V: ENVIRONMENTAL EMISSIONS OF HYBRID SYSTEM

Emission	PV/Generator/	PV/	Diesel
components	battery	batt	only
CO <sub>2</sub> (kg/yr)	584	-	7,630
CO (kg/yr)	3.65	-	47.6
UHC (kg/yr)	0.161	-	2.10
PM (kg/yr)	0.0219	-	0.286
$SO_2(kg/yr)$	1.43	-	18.7
$NO_x$ (kg/yr)	3.43	-	44.8

## VII. DYNAMIC MODELING OF THE PROPOSED SYSTEM IN MATLAB SIMULINK MODEL

Matrix Laboratory is known as MATLAB, a useful scientific computing method and familiar for analyzing complex engineering and scientific problems [31]. The MATLAB and Simulink (graphical programming platform) are functioning in the same forum; henceforth, modeling, simulation, and analyzing could perform in one or the other mood [32]. As mentioned earlier, the system's dynamic modeling and simulation will be examined in the MATLAB platform. The author will be able to predict how the scheme will function if implemented in real life.

HOMER optimization offers a highly reasonable solution for the Solar PV-Generator-Battery based system. The Homer optimized power system and relative system components are designed in MATLAB using the Simulink block diagram under Simulink platforms to analyze the system components' dynamic performance. The proposed scheme is built with an Irradiation and Temperature signal generator, PV array (330 Wp/module and a total of 32 modules, 2 in series and 16in parallel), MPPT (P & O), Boost converter, DC gas generator (1.6 kW), PMDC motor rated 5kW and 3000rpm, DC motor driver, 48V lead-acid battery, Battery charge controller, Battery discharge controller, generator and motor switching and BUS bar. The Simulink model of the proposed system in MATLAB is shown in Fig. 9.

## A. PV Array

It has been found from the HOMER optimization solution that 10.6 kWp solar PV is required to generate sufficient power to run the 5 kW, 3000 rpm rated DC motor and other loads (Light and computer) as well. PV array parameter has given in Table VI. Hereafter, the total number of PV string enhances 16 parallel and 2 series per string to achieve the designated power10.6 Wp.

TABLE VI: SOLAR PV MODULE INPUT PARAMETER FOR MATLAB

SIMULIAR DEOCK		
Open Circuit Voltage Voc (V)	45.6	
Voltage at maximum power point Vmp (V)	37.2	
Temperature coefficient of Voc (%/deg.C)	-0.31	
Cells per module (Ncell)	72	
Short-circuit current Isc (A)	9.45	
Current at maximum power point Imp (A)	8.88	
Temperature coefficient of Isc (%/deg.C)	0.05	

The solar PV cell equivalent circuit diagram is shown in Fig. 10, and for the output voltage V and current I, the equivalent equation could express accordingly:

$$I = I_L - I_D - \frac{(V + IR_s)}{R_{sh}}$$

where

 $I_L$  – Light generated current=9.652A.

 $I_D$  – Diode saturation current=1.888e<sup>-09</sup> A.

 $R_s$  – Series resistance=0.44 $\Omega$ .

 $R_{sh}$  – Shunt resistance=85.739 $\Omega$ .

The Solar Photovoltaic (PV) array circuit diagram, drawn by using the Simulink model in the MATLAB platform, has been demonstrated in Fig. 11.

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Fig. 11. Solar Photovoltaic array Simulink block.

The V-I characteristics curve and the power curve for a single PV module have been obtained after simulation in MATLAB, shown in Fig. 12 and Fig. 13, respectively.



## B. Maximum Power Point Tracking (MPPT)

PV module should need to be functioning near specific PowerPoint for the individual working situation so that the PV module output is proximate to a maximum power point (MPPT). Under this particular circumstance, the way PV module operating is known as full power point tracking (MPPT), and boosting PV cell application depends on the maximum PV power harvest [33]. Many techniques were projected to achieve MPPT, such as Perturbation and Observation (P & O), Incremental Conductance (IC), hillclimbing method, neural network, fuzzy logic, and temperature-based, etc., and their assessment has given in [34].

The Perturbation and Observation (P & O) MPPT controller algorithm has been illustrated in Fig. 14.



The main reason to choose the Perturbation and Observation (P & O) to execute in the proposed system is to offer superior efficiency against the normal atmospheric circumstances. Oscillation and power loss are the significant disadvantages of the P & O method, which arises near the maximum power point due to constant Perturbation. Table VII reveals the constraint for the Perturbation and Observation (P & O) method.

TABLE VII: CONSTRAINTS FOR PERTURBATION AND OBSERVATION
(P & O) METHOD

(I & O) METHOD	
Preliminary value for duty cycle D	0.5
The minimum threshold for duty cycle D	0.4
Maximum threshold duty cycle D	0.6
Increment rate to either increase or decrease	3e <sup>-4</sup>

## C. Boost Converter

MPPT controller generates the duty cycle and then converted into Pulse signal, which goes to IGBT of Boost converter and hit gate (g) signal. Pulse amplitude is 0.6, which is designated by the system to block all firing pulses by implementing an equivalent signal level 1 at input "g" of IGBT in the Simulink prototype. Boost converter Simulink circuit diagram is shown in Fig. 15.



## D. Battery Bank

The battery bank (BB) has been assembled using the leadacid battery as a negligible temperature impact on the battery. The lead-acid battery storage system's input parameter is given in below Table VIII, and Fig. 16 shows the Battery bank Simulink model.

TABLE VIII: INPUT PARAMETER OF	THE LEAD-ACID BATTERY
Nominal voltage (V)	48
Rated Capacity (Ah)	333
Initial state-of-charge (%)	67
Battery response time (s)	10

#### A. DC Generator

A wound-field type DC Machine is chosen to form a DC Generator which delivers 1.6kW to the 48V bus system. A 48V DC voltage has applied across the field terminal denoted by "F," and negative value of shaft torque (T<sub>L</sub>) implied which is the mechanical input to operate DC machine as a DC generator shown in Fig. 17.



Fig. 17. DC Generator Simulink model.



Fig. 16. Battery bank Simulink model.

## B. Permanent Magnet DC Motor (PMDC)

A permanent magnet type DC Machine is chosen to form a DC Motor. A positive value of shaft torque  $(T_L)$  implied the mechanical input to operate the DC machine as a DC Motor. The applied torque  $(T_L)$  is proportional to the motor speed  $\omega$ (rad/s) but through the gain denoted by "K."

Torque and Gain calculation are given below:

$$T(rated) = T_L = \frac{P(rated)}{\omega(rated)} \cong 16N.m$$

Also, we know,

$$T_L = K \times (\omega_{rated})^2$$
  
So,  $K = \frac{16}{(314.16)^2} \cong 0.0001612$ 

The DC motor's armature is powered through a three-step starter and a switch controlled by the stair generator, and it is shown in Fig. 18. The three-step starter's pulse generator generates a pulse in 0.1 s, 0.2 s, and 0.3 s successively while the motor starts. Fig. 19. express the Simulink model of a three-step starter to start the engine.

The armature circuit belongs to ports denoted by "A" of the machine block. It is signified by a series RaLa wing and placed in series with a Current Measurement block and a Controlled Voltage Source in Fig. 18.



Fig. 18. Motor connections.



# C. Motor Driver

The motor driver regulates the motor revolution (rpm) according to the requested rpm. The requested rpm could set by using a motor speed changer knob, which is shown in Fig. 20.



Fig. 20. Motor speed changer knob.

The motor driver consists of a motor controller, gate driver chopper, and a bridge switch shown in Fig. 21.





#### D. Solar Irradiance and Temperature

One of the objectives of dynamic modeling and simulation of Solar PV-Generator-Battery based power system in the MATLAB platform for a solar electric boat is to monitor the effect on Battery charging, gas generator, and motor speed status with the change of solar irradiance and temperature within the solar boat operating time, also the performance of Battery without PV and Generator. The dynamic model will consume many days to compute one solar day while performing simulation, as it contains a few complex blocks. Henceforth, the simulation has been done for 40 s duration to overcome this difficulty. The way solar irradiance and temperature data are selected so that both curves decline and rise in a small portion because of clouds for up to 10 s and is defined as a partial cloud situation. The condition reform to the previous status while clouds back off are defined as an exact sky situation, and it happens from 10 s to 20 s. The full cloudy case is described while irradiance and temperature value are zero, and it happens from 20 s to 40 s. Fig. 22 represents the solar irradiance and temperature profiles for thirty seconds. The resulting shapes correspond to the change of irradiance and temperature of one solar day.

The above-explained Solar irradiance and temperature signals are generated in MATLAB Simulink using signal builder for the PV array inputs. The system has been programmed in such a way so that from time T=0 s to T=20 s, only PV and Battery will be delivered power, T=20 s to

T=30 s, the only battery will be provided power, i.e., discharged energy to the motor, and T=30 s to T=40 s, Gas Generator and Battery bank will be delivered power to the load (dc motor).



#### VIII. WORKING PRINCIPLE OF THE DYNAMIC SYSTEM

The working principle has been described in the flow chart in the following Fig. 23, which represents the dynamic system's functional flow chart.



Fig. 23. Functional flow chart of the proposed dynamic system in MATLAB Simulink.

## IX. ANALYSIS OF THE MATLAB SIMULATION RESULT OF THE PROPOSED SYSTEM

The MATLAB simulation total time has been considered for 40 s. In contrast, the first 20 s (T=0 s to T=20 s) for only PV capability and Battery discharge functionality observing and the rest of the 20 s (T=20 s to T=40 s) for Gas generator and Battery discharge capability watch to run the motor, that is why PV irradiance  $(W/m^2)$  turns into zero at T=20 c to T=40 s. As a result, after T=20 s PV voltage, current and power becomes zero and remain till the end of the simulation, i.e., T=40 s. Initially, the battery state of charge (SOC%) was chosen 67% for this dynamic simulation, and a 48V lead-acid battery terminal voltage appeared 48.4 V. The system has been programmed in such a way so that the gas generator was turned ON at T=20 s, but it was kept disconnect till T=30 s to examine the battery discharge mode and the capability to operate the motor at the required speed. The gas generator has connected directly with the battery; subsequently, while the generator is in operation, the battery charge controller shows zero charging current.

After the end of the simulation, it has been concluded that the 48 V, 333 Ah rated battery serves the desired current to run the motor at the desired rpm 0 rpm to 3000 rpm. The designed PV could generate 8.81 kW power and charge the battery at the constant current 25 A and constant voltage 50 V through the battery charge controller. The system simultaneously operates the rated DC motor (5 kW, 3000 rpm) at 3000 rpm. Meanwhile, MPPT trigger pulse according to the PV output voltage.

On the other hand, 1.6 kW rated DC gas generator is also verified and found that it could concurrently run the motor at a maximum of 2500 rpm and charge the battery at the constant setting current 25 A and constant voltage 50 V. DC motor speed control system, i.e., the motor driver has been tested with random speed by varying speed knob at 2500 rpm, 1000 rpm, 1500 rpm, 3000 rpm, 2000 rpm, 2500 rpm, 1500 rpm, 1000 rpm and 500 rpm, respectively, and found that the motor responded according to the requested speed.

Graph of PV irradiance (W/m<sup>2</sup>), PV Voltage (V), PV Current (A), PV mean power (kW), and PV Duty cycle amplitude versus time in seconds is explained in Fig. 24. Graph of Motor speed (rpm), motor armature current (A), and motor torque (N.m) versus time in seconds is shown in Fig. 25. Graph of Battery state-of-charge, i.e., SOC (%), Battery current (A), and Battery voltage (V) versus time in seconds, is given in Fig. 26. Battery Charger Charging Current (A) and Voltage (V) versus time in seconds are shown in Fig. 27.

The MATLAB simulation results have explained in four steps and described in the followings:



Fig. 24. Graph of PV irradiance (W/m<sup>2</sup>), PV Voltage (V), PV Current (A), PV mean power (kW), and PV Duty cycle amplitude versus time in seconds.

#### Step 1: Partial cloudy (T=0 s to T=10 s):

During the interval of T=0 s to T=10 s, it has been found from the simulation result that, while partial cloudy, PV produced power on an average 3 kW, which is not enough because of lower irradiance and temperature in Fig. 24, to achieve the desired motor speed 2500 rpm in Fig. 25 and to charge the battery as well, consequently, the battery goes to discharge mode to deliver necessary current in Fig. 26 and motor driver able to latch the motor speed as requested motor speed (rpm) within a short period. When motor speed is set to 1000 rpm and 1500 rpm, the PV produced power could run the motor and charge the battery at a constant current 25 A, and continuous voltage lies between 49 V and 50 V in Fig. 27. Henceforth, this mode expresses the charge-discharge method.

### Step 2: Clear day (T=10 s to T=20 s):

During the interval of T=10 s to T=20 s, it has been found from the simulation result that, while the sky is clear, PV produced power (8.82 kW) is enough because of higher irradiance and temperature in Fig. 24 to achieve the highest desired motor speed 3000 rpm in Fig. 25 and to charge the battery as well in Fig. 26. The system has programmed so that if motor speed exceeds 2500 rpm, then battery discharge mode will open to provide supplementary current if necessary, and found PV produced power is enough to serve the Battery charging and run the motor simultaneously. The motor driver could latch the motor speed as requested motor speed (rpm) within a short period. The battery keeps charging the battery at a constant 25 A, and continuous voltage lies between 49 V and 50 V in Fig. 27.

Step 3: Completely cloudy and only battery back-up (T = 20 s to T = 30 s):

During the interval of T=20 s to T=30 s, it has been found from the simulation result that, while the sky is full of cloud, the temperature falls abruptly and solar irradiance falls into zero, then PV produced power becomes zero in Fig. 24, and the gas generator turns into ON. Also, the battery discharge path opens automatically. The generator was still kept disconnected to check the battery bank's capability and found the battery bank starts discharging in Fig. 26 to run the motor according to the requested speed but limited to 2500 rpm in Fig. 25.



Step 4: Completely cloudy with Generator (T = 30 s to T =

40 s): During the interval of T=30 s to T=40 s, it has been found from the simulation result that the gas generator turns into ON and starts delivering power to the load (motor and battery), correspondingly, the battery discharge path was kept opening and found that the gas generator can charge the battery bank in Fig. 26 and operate the motor in required speed in Fig. 25.

The system has been designed in such a way so that PV charges the battery bank through constant current (cc) and voltage (cv) battery charger, and the gas generator charge the battery directly, i.e., bypass the charger. That is why the charging current falls into 0 A at T=30 s. During partial cloud, irradiance was low, and PV produced voltage was more down than 50 V, henceforth till T=4 s charger could not stabilize charging current. While PV has grown sufficient voltage, the battery charger took 2 s to become stable and set the Battery while T=6 s, at constant current 25 A and voltage, lie between 49 V and 50 V. The reflection is visible in Fig. 27.



Fig. 26. Graph of Battery state-of-charge, i.e., SOC (%), Battery current (A), and Battery voltage (V) versus time in seconds.



Fig. 27. Battery Charger Charging Current (A) and Voltage (V) versus time in seconds.

#### X. CONCLUSION

This paper presents the optimal design and dynamic modeling and simulation of a hybrid power system for a solar boat in Bangladesh. The total system is composed of 1) hybrid power system, which consists of the photovoltaic, small-sized gas generator and battery back-up, and 2) Control system which consists of MPPT controller, battery charge controller, motor speed controller, fixed voltage controller (DC-DC converter) and battery discharge controller and 3) a permanent magnet DC motor. The dynamic performance of the system elements is evaluated thoroughly as well by considering: (i) partial cloudy weather condition (PV & Battery), (ii) full cloudy weather (Generator & Battery), and (iii)sunny day (PV & Battery). The MATLAB simulation analysis determines that the PV produces 8.8 kW power, almost equal to HOMER's required power, with only 12% variation. It could run the motor 3000 rpm and charge the battery at constant current 25 A and 49 V simultaneously. After 3 hours, the battery will be 80% charged, and 5hours after, the battery will be fully charged (100%). While the generator comes in operation and motor speed equals 500 rpm, it could charge the battery with the constant 25 A and 49 V — the motor driver responds to the requested rpm and latches accordingly. MPPT controller response according to the required power in the system, whereas the fixed voltage controller ensures constant 49 V to the motor. Battery discharge power according to the system requirement, which is controlled by the battery discharge controller. Some economic analysis and detailed dynamic simulation results are presented in this paper.

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