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Assessment of an Optimum Off-grid Hybrid Energy System for Electrification in a Rural Area of Bangladesh

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ABSTRACT
It is not economically feasible and effective to extend central power line to the remote islands. Isolated hybrid energy systems can be an alternate approach for electrification in such area. In this study a hybrid system is developed for electricity generation in an off grid rural area called Sonadia island, Bangladesh (21°30.1'N, 91°53.5'E). An investigation into the technological and financial viability of different configurations of hybrid energy designs is carried out. and an optimum system is opted based on low cost of energy, net present cost and low emissions. The optimal configuration comprises PV Panel/Diesel/Battery. The optimized setup has Cost of Energy of 0.411 $/kWh and Net Present Cost of $ 437,633. When compared to the grid, diesel the optimal system emits less than 45% and 74% of each, respectively. HOMER simulation is employed to conduct the techno-economic study of the proposed system.

Keywords: Hybrid energy system, net present cost, cost of energy, HOMER, techno economic

1.Introduction

Energy is the foundation of contemporary civilization and a requirement for sustainable growth. Located in Southeast Asia, Bangladesh is a developing nation. Fig.1 shows the power production by fuel type (%) in Bangladesh which implies that power generation in Bangladesh is comprised of 93.11% fossil fuel share.

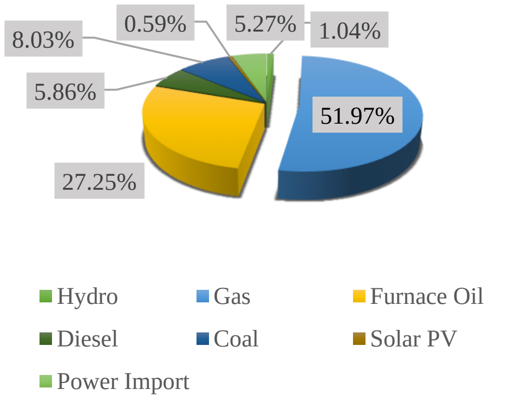

Fig.1 Power production by fuel type (%) in Bangladesh [2]

Despite having power producing capacity to provide electricity to all the citizens, due to the international fuel crisis and high fuel price, the diesel powerplants have stopped generation and the gas powerplants are not being able to utilize their full generation capability. Because of these circumstances, there is a clear gap between demand and supply of power. This deficit in power generation is meet through a systematic power cut which is known as load shedding. But load shedding is not a great solution as it hampers economic and industrial growth. This poses a serious threat to the development of this developing nation.

Fossil fuel burning is a major source of carbon emission which is causing large scale environmental pollution and climate change. In 2009 climate conference in Copenhagen, the world's governments set a target to limit global mean temperature change to below 2°C [1]. Which in turns mean that the emission of carbon dioxide (CO_2) has to be reduced by 50-80% by the end of year 2050 [1]. As a result, it is high time we seek for sustainable energy sources to meet our energy demands. Off-grid renewable energy sources are entirely dependent on environmental conditions and have a sporadic supply, therefore they cannot provide electricity without interruption[3][4]. To increase reliability, the hybrid energy systems are sought after. A solar photovoltaic (PV) source is regarded as being both technically and economically practical, coupled with a wind turbine, batteries, or fuel-based engines[5][6].

Table 1 Summary of previous configurations of hybrid energy systems

Location	Grid type	Configuration	Evaluation Criteria	Methodology
Bangladesh[7]	Off-grid	PV + Wind + Biomass + DG + Battery	NPC+COE +LCE	HOMER
Banglades	Of	PV + DG	NPC+COE	HOMER

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h[8]	f-grid	+ Battery		
Saudi-Arabia[9]	On-grid	PV + Wind + DG + Battery	NPC+COE	HOMER
Iran[10]	Off-grid	PV + Biomass + Wind + Battery	NPC	HOMER
India[11]	Off-grid	PV + WTG + BGG + BMG + FC + Battery	NPC+COE +LCE	MATLAB + HOMER
China[12]	Off-grid	PV + Wind + BDG + Battery	NPC+COE	HOMER
Bangladesh[13]	Off-grid	PV + Battery + DG	NPC+COE +LCE	HOMER

The literature review makes it clear that other researchers have examined the configurations that are being discussed in this paper. However, the current study examines the renewable energy sources existing in Sonadia of Cox's Bazar district, a Bangladeshi island that is unserved and plagued by poverty.
The primary objectives of this study are (i)to propose a hybrid energy system model for electrification of an off grid rural area of Bangladesh, (ii) to perform the technoeconomic and feasibility analysis of the proposed model.

2.Methodology

2.1 Estimation of Electrical Load of the Selected Area and Meteorological Data

The work was done considering the remote island of Sonadia, Bangladesh (21°30.1'N, 91°53.5'E), which was considered as an off-grid area. The demand of load for daily usage of a single household is estimated to be 7.71 kWh, which is multiplied by 35(Number of household) to get the total demand of load 269.85 kWh/d. The load curve is presented in Fig.2 is predicted by load estimation. Wind speed and Solar irradiation of that meteorological area is presented in Fig.3 & Fig.4, which were sourced from National Renewable Energy Laboratory (NREL) through HOMER Pro.

Table 2. Load calculation for a single household

Components	Rating(W)	Quantity	Operating hour (h/d)	Demand (kWh/d)
Light (LED)	20	8	6	0.96
Ceiling fan	70	4	8	2.24
Television	150	1	5	0.75
Refrigerator	150	1	24	3.6
Mobile charger	10	4	4	0.16
Total	400	16	47	7.71

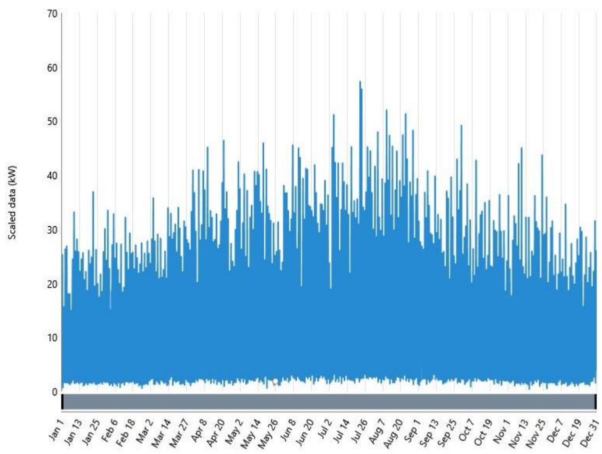

Fig.2 Load Profile of the Area

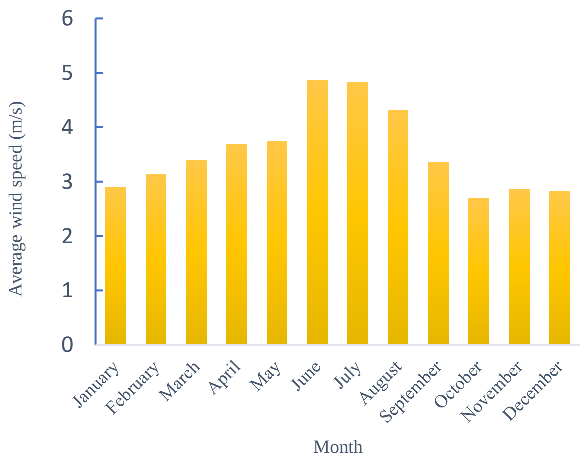

Fig.3 Wind Speed Data of Considered Area

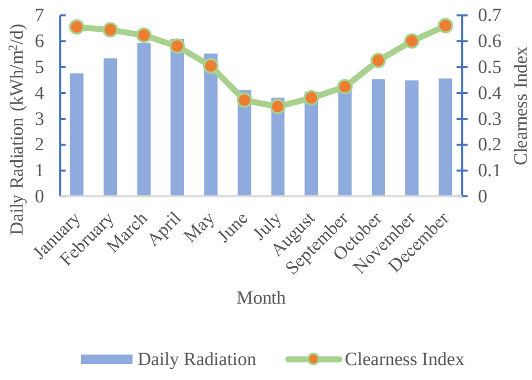

Fig.4 Solar Radiation Data of Considered Area

2.2. Mathematical Modeling for Different Components

Solar PV module is one of the main components of our hybrid system. The output power from PV cell is determined using Eq. (1) [14]

$$P_{pv} = P_{rated} D_F (\frac{G}{G_S})[1 + \alpha_p (T_c - T_s)] \quad (1)$$

The temperature of the PV cell is obtained using the following Eq. (2) [14]

$$T_c = T_a + G(\frac{\tau\alpha}{U_L})(1 - \frac{\eta_{PV}}{\tau\alpha}) \quad (2)$$

The wind turbine power output is expressed as Eq. (3), [13]

$$P_w(V) = \begin{cases} 0 & for, & V < V_1 \\ aV^3 - bP_r & for, & V_1 < V < V_r \\ P_r & for, & V_r < V < V_2 \\ 0 & for, & V > V_2 \end{cases} \quad (3)$$

$$a = \frac{P_r}{(V_r^3 - V_1^3)} \qquad b = \frac{V_1^3}{(V_r^3 - V_1^3)}$$

However, the actual electric power output from the wind turbine is calculated using Eq. (4) [13], where $A_w(m^2)$ is the swept area, η_w (%) indicates the wind turbine generator and corresponding converter efficiency,

$$P_{wt} = P_w A_w \eta_w \quad (4)$$

In this study, the purpose of the diesel generator is to supply the necessary power demand when the renewables (i.e., PV and wind) and battery bank are not able to meet the load demand. The diesel fuel consumption can be calculated using Eq. (5) [13]

$$F = F_{0,dg} Y_{dg} + F_{1,dg} P_{dg} \quad (5)$$

In the study which follows, the Duty Factor (DF) (kWh/start-stop/yr.) is the ratio of energy generation from supplementary prime movers to the total start-stop and can be calculated by using Eq. (6) [13] where $N_{s/s}$ is the number of start-stop

$$F = \frac{P_{dg}}{N_{s/s}} \quad (6)$$

In the hybrid energy system design, the storage component is important equipment that is utilized to keep the voltage constant during the time when less power is being produced. Typically, a battery of the Li-ion type is used for power storage. The maximum discharge of battery is obtained from Eq. (7) [14]:

$$B_D = (-crN_m + cN_I^{-c\Delta t} + N_T cr(1 - e^{-c\Delta t}))/(1 - e^{-c\Delta t} + r(c\Delta t - 1 + e^{-c\Delta t})) \quad (7)$$

Similarly maximum power can be calculated from Eq. (8) [14]:

$$B_D = (cN_I e^{-c\Delta t} + N_T cr(1 - e^{-c\Delta t}))/(1 - e^{-c\Delta t} + r(c\Delta t - 1 + e^{-c\Delta t})) \quad (8)$$

The main purpose of the inverter is to change into the AC current for AC loads from the DC current DC bus. The following Eq. (9) [13] is using to determine the load side power,

$$P_{in} = \frac{P_{out}}{\eta_{inv}} \quad (9)$$

2.3 Economic Criteria

The financial parameters are necessary for HOMER simulation. This study includes Net Present Cost (NPC), Cost of Energy (COE) and Life Cycle Emissions (LCE).

Based on the NPC, which is determined using the following Eq. (10-12) [13], the HOMER simulation results are arranged,

$$C_{NPC} = \frac{C_A}{CRF(i,N)} \quad (10)$$

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (11)$$

$$i = \frac{i' - f}{1 + f} \quad (12)$$

Cost of Energy is calculated from Eq. (13) [13]

$$COE = \frac{C_A}{E_S} \quad (13)$$

2.4 Technical and economic data for hardware components used as an input for these simulations:

Components	Technical description	Capital cost ($)	Replacement cost ($)	O & M cost ($)	Lifetime (yr.)

PV Module	327 W	1500/kW	0	20/yr.	25.00
Diesel Generator	50kW,50Hz	380/kW	290/kW	.05/h	15,000h
Wind turbine	1kW	4200	2500	100/yr.	20
Li-ion battery	6V,1kWh	650	450	10/yr.	20
Converter	1kW	700	600	8/yr.	15
Discount rate (%)	10.0	-	-	-	-
Fuel cost ($/l)	1.2	-	-	-	-

3.Simulation Results, Optimization and Discussion

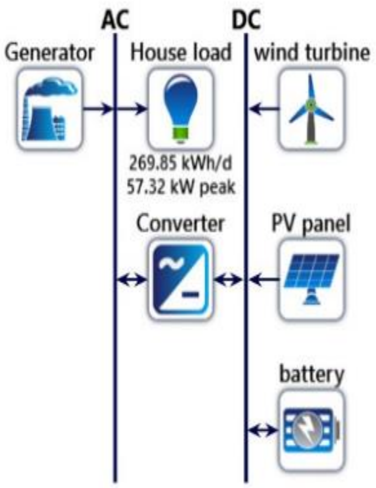

Fig.5 Schematic of Hybrid System

HOMER PRO software is used to simulate different hybrid energy systems and determine the feasibility of the systems over the year with different configurations. The parameters which have been focused on are Cost of Energy (COE), Net Present Cost (NPC), Excess Energy (EE), Emissions of CO_2 etc.

3.1 Economic & Emission Analysis:

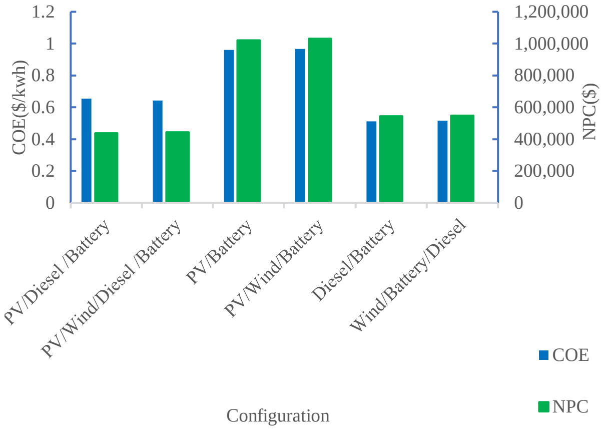

Fig.6 Comparison of COE & NPC for Different Hybrid System Configuration

The tecno-economic analysis present in Fig.6 shows that COE and NPC is lower for PV / Diesel / Battery (0.411$/kWh and 437633$) when compared to other configuration PV / Wind / Diesel / Battery (0.415$/kWh and 442707$), PV / Battery (0.960$/kWh and 1020000$), PV / Wind / Battery (0.967$/kWh, 1030000$), Diesel / Battery (0.511$/kWh and 544223$), Wind / Diesel / Battery (0.515$/kWh and 549031$). Annualized cost of the optimized hybrid system is shown in Fig.7.
Comparison of CO_2 emissions of different configuration is shown in Fig.8.

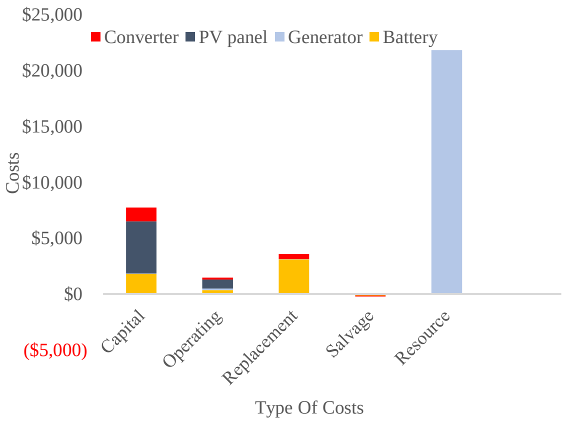

Fig.7 Cost Associated with Different Required Components for the Proposed System

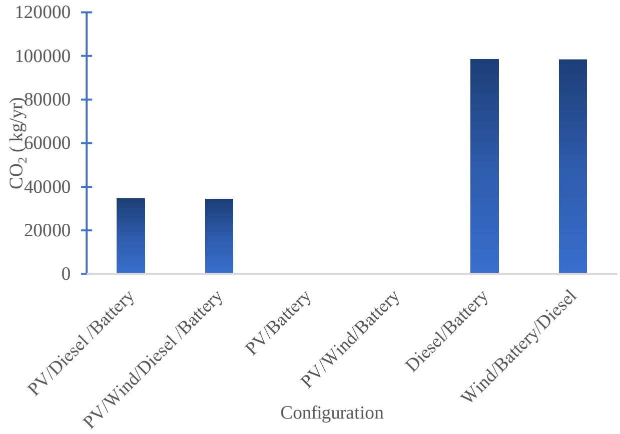

Fig.8 CO_2 Emissions from Different Hybrid System Configuration

4.Conclusion

This paper represents an efficient energy meetup technique for an off -grid rural area. The primary objective is to optimize the hybrid system based on NPC, COE and mitigation of the pollutant gas emissions. The hybrid system is optimized to fulfill the load requirement of the remote island settlement. After comparing the obtained results for those configurations, the proposed hybrid model provides the most economic and environment friendly solution. The proposed system has a large percentage of renewable penetration, which reduces the use of diesel making the system sustainable and reliable.

5.References

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NOMENCLATURE

D_F	: factor of derating
G	: incident solar irradiation, kW/m^2
G_S	: standard solar irradiation, kW/m^2
α_p	: coefficient of solar power (−0.35%/◦C)
T_c	: temperature of the PV cell, ◦C
T_S	: standard temperature of the PV cell, ◦C
T_a	: atmospheric temperature, ◦C
$\tau\alpha$	: transmittance−absorbance, 0.9
η_{PV}	: efficiency of the PV cell
V_1	: cut-in speed, m/s
V_2	: cut-off speed, m/s
V_r	: rated speed, m/s
P_r	: rated power, kW
F_0	: fuel curve intercept coefficient (0.000205m^3/h)
F_1	: fuel curve slope (0.00025 m^3/h/kW)
Y_{dg}	: rated capacity of the generator
P_{dg}	: electric output of the generator
$N_{s/s}$	: number of start-stop
c	: battery rate constant
r	: ratio of the capacity of the selected battery
N_m	: Maximum capacity of the battery, kWh
N_I	: initial available energy on the storage system
N_T	: available energy in the battery bank (in total)
Δt	: the time length, hours
P_{in}	: DC power input to the inverter, kW
P_{out}	: AC power output, kW
η_{inv}	: inverter efficiency
C_A	: total annualized cost, ($/year)
CRF	: capital recovery factor
i	: annual real interest rate
i'	: nominal interest rate
f	: annual inflation rate
N	: project lifetime, year
E_S	: Energy served in a year