ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25apr2233

Cost Comparative Analysis of Solar/Utility and Diesel/Utility Hybrid Power System for a Typical Residential Building

Aki, A.O.[1]; Obonyano, K. N.[2]; Sanni, O.O.[3]; Nurudeen, S. E.[4]; Usman, S.[5]; Oshogwe, L. O.[6]; Afolayan, U. J.[7]; Olori, O. K.[8]

[1,3,4,5,6,7,8]Electrical/Electronics, [2]Computer Engineering
[1,2]Delta State University of Science and Technology, [3,4,5,6,7,8] University of Benin
[1,2]Ozoro, Delta State,
[3,4,5,6,7,8]Benin City, Edo State,
[1,2,3,4,5,6,7,8]Nigeria

Publication Date: 2025/05/19

Abstract: For a typical residential block in Ugbowo, Benin City, this article compares the costs of renewable energy sources, including solar/utility and diesel/utility power systems. Numerous hybrid power solutions have been implemented for various purposes as a result of Nigeria's epileptic power issue. For a normal residential construction, appropriate ones must be identified. Therefore, the goal of this study is to compare the costs of a diesel/utility hybrid power system with a solar/utility hybrid power system for a typical residential home in Benin City. A simulation program named HOMER (Hybrid Optimisation for Electric Renewable) was used to do this.

The study is being conducted in Ugbowo, Benin City. A load study was conducted to determine the household's overall power consumption in order to accomplish the goal. We were able to ascertain the capacity of the diesel generator, inverter, PV system, battery storage, and energy obtained from the utility grid thanks to this load study. Each load's working hours were also established. The size, capacity, and beginning capital of the diesel generator, photovoltaic system, battery, and converter were modelled into HOMER in order to do the cost (NPC and COE) analysis of the various energy sources. The most cost-effective hybrid system was identified by comparing the costs of the various hybrid combinations (diesel/utility and solar/utility) over a one-year period.

When the diesel and utility were combined and modelled into HOMER, the COE, NPC, O&M, and fuel usage/cost decreased in the hybrid energy system. This was because HOMER extended the diesel generator's downtime hours and extended the main's operating hours because the main is more cost-effective and emits no carbon emissions.

The energy purchased from the grid decreased when the PV/utility was integrated and modelled into HOMER. This combination turned out to be the best because it has the lowest COE, NPC, O&M cost, and zero carbon emission; however, the unreliability of the grid is a challenge that led us to integrate the three energy sources. It was shown that HOMER decreased the working hours of the polluting and uneconomical energy sources when more energy sources were merged. This resulted in a drop in COE, NPC, O&M costs, and fuel consumption and carbon emissions.

Keywords: *Downtime; Emissions; Residential; Solar; Diesel.*

How to Cite: Aki, A.O.; Obonyano, K. N.; Sanni, O.O.; Nurudeen, S. E.; Usman, S.; Oshogwe, L. O.; Afolayan, U. J.; Olori, O. K. (2025). Cost Comparative Analysis of Solar/Utility and Diesel/Utility Hybrid Power System for a Typical Residential Building. *International Journal of Innovative Science and Research Technology*, 10(4), 4146-4153. https://doi.org/10.38124/ijisrt/25apr2233.

I. INTRODUCTION

Because electricity is useful in so many areas of life, it is considered one of man's essential amenities. Therefore, it is impossible to overstate the importance of having a reliable power source. Unfortunately, life is challenging in undeveloped nations like Nigeria due to the unstable electrical power supply [1].

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25apr2233

Currently, the power generated only accounts for around 9% of the total power needed to electrify the entire nation. Although only 8457.6MW of capacity is installed, about 80,000MW is needed [2]. As a result, the nation still faces severe electricity shortages and protracted power outages, with the average Nigerian home having access to electricity for eight hours per day. Not to mention the BEDC's anticipated bills and tariff instability for their clients.

Global warming is primarily caused by CO2 emissions, which have skyrocketed due to the usage of convectional energy sources derived from fossil fuels [3]. Compared to the start of the industrial revolution, the atmospheric CO2 content has risen by about 40% [4]. Alternative energy sources that have the ability to lower pollution and create a sustainable energy supply have been identified as a result of these problems [5]. By combining several energy sources, a hybrid energy system can be created that will address reliability issues while offering an eco-friendly solution.

Software like Hybrid Optimisation on Model for Electric Renewable (HOMER), which makes it easier to assess designs of both off-grid and grid-connected power systems for a range of applications, was used to carry out this hybrid system design. HOMER identifies the components to include in the system design, the size and quantity of components to be employed. By calculating the energy balance at each time step of the year , HOMER replicates how the system would function [6]. HOMER computes the energy flow to and from each system component for each time step by comparing the system's capacity to supply energy to the electric and thermal demand during that time step. For fuel-powered generators or battery systems, HOMER also determines whether to charge or discharge the batteries and how to run the generators at each time step. HOMER analyses the cost of constructing and running the system during the project's duration and runs these energy balance calculations for each system design, determining if it can supply the power demand under the stated parameters [7].

Three distinct energy sources—utility, diesel generator, and solar—were used. Power may be swapped between the three energy sources because the system was built so that they would complement one another. or avoid overtaxing the PV system, which could result in battery drain and eventual failure, diesel generators or utilities take over as the primary source of electricity for households during periods of little or no sunlight. PV takes over as the primary energy source during periods of high sunlight, displacing the need for diesel generators and utilities [8]. By doing this, the cost of diesel and utility bills from the utility companies will be reduced, the harmful pollutants released by diesel generators will be reduced, and the PV system's lifespan will be increased.

Due to the nature of solar radiation, the diesel generator/utility must be used to maintain base loads when solar radiation is low and battery capacity is at its lowest [9]. An uninterrupted power source was taken into consideration. Solar PV made up 90% of the total energy supply during the extreme sunny period. In other words, utilities and diesel will make up 10% of the overall energy source, whereas solar PV was utilised 18 hours a day. Diesel and utilities, which make up 60% of the overall energy source, would provide as a backup during the winter months when there is a sharp decrease in sunshine [10].

The batteries utilised in this design were connected in series to generate a 48 volt voltage. The capital cost of each battery, as well as the cost of replacement, operation, and maintenance, will be calculated using HOMER. Based on its fuel consumption, operating and maintenance costs, which are influenced by the generator power, load power, and hours employed, the diesel generator—which was also utilised as a backup—was modeled [11]. This design also took into account the energy that was purchased from the electric grid.

Proper component sizing and a workable energy management plan are essential for the best hybrid system design. Choosing a workable energy management system is essential since it dictates how the system will behave, regulating energy flow and assigning a priority to each component. Accordingly, an effective energy management plan can reduce the cost of energy (COE), guarantee power supply continuity, increase power system stability, and shield components from overload-related damage [12].

II. METHODOLOGY

The method employed to achieve the aim of this work is outlined below,

A. Site Description

Fig 1: A Typical Residential Building in Benin City.

There are no large trees at the site, which could shade the PV modules and lessen the amount of sunshine they receive. There was enough room on the building's top for the solar panels. The average annual temperature at the location is 25°C.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25apr2233

B. *Collection of Data*

Based on the electrical equipment, this component pre-designs the household's load profile. These preparations were supplemented by comprehensive hourly load data for a single year, which was used as a HOMER simulation input. The first step is to collect information on the amount and energy usage of the equipment.

Table 1: Load Profile Data

EQUIPMENT	POWER RATING	NUMBER	HRS	TOTAL POWER	WH
WASHING MACHINE	500W	1	1	500W	500WH
LAPTOP	90W	1	5	90W	450WH
WELL PUMP	746w	1	1	746W	746WH
CEILING FAN	80W	3	12	240W	1440WH
LED TV	60W	1	7	60W	420WH
CFL BULBS	7W	11	12	77W	924WH
FREEZER	200W	1	8	200W	1600WH
PRESSING IRON	1000W	1	0.25	1000W	250W
TOTAL				2913W	6630WH
TOTAL WH/DAY					6630WH
TOTAL KWH/YEAR					2419KWH

The peak load consumption for the day is displayed in the above table. The most energy-intensive appliances, such as washing machines, pressing irons, and well pumps, are used when the power grid is operational or, in the event that it is not, diesel generators. In order to determine the PV system's peak operating period, NASA provided the solar GHI and temperature resource through HOMER. The Benin City temperature resource for each month of the year is displayed in the table below.

Table 2: Monthly Average Temperature of the Year in Benin City

Month	Daily Temperature (^oC)
January	25.89
February	26.32
March	26.7
April	26.87
May	26.53
June	24.79
July	23.59
August	23.44
September	24.08
October	25.00
November	25.59
December	25.78

According to the above table, sunshine peaks between January and May and then declines between June and September. The sunshine is more intense than usual from October to December. This implies that the PV system will be highly effective from January to May and from October to December, reducing the need for other energy sources during these sun-heavy times.

C. *PV Array Size and Battery Calculation*

HOMER uses the following equation to calculate the output of the PV array:

$$P_{PV} = Y_{PV}\, F_{PV}$$

$$\left[\frac{GT}{G_{T,STC}}\right]\left[1 + \propto_p \left(T_c - T_{c,}STC\right)\right] \qquad (1)$$

Where

Y_{PV} = the rated capacity of the PV array
F_{PV} = the PV derating factor (%)
G_T = the solar radiation incident on the PV array
$G_{T,STC}$ = the incident radiation at standard test condition

$\propto p$ = the temperature coefficient of power
T_C = the PV cell temperature in the current time step (^{0}c)
$T_{C,STC}$ = the PV cell temperature under standard test conditions (25^{0}c)

Monocrystaline solar panels were selected. The capacity of the PV was chosen to be above the capacity of the load. The power output of the PV array is a function on the maximum sunlight. Based on the data obtained from HOMER, the table below was created.

Table 3: Photovoltaic Characteristics

Cell Technology	Monocrystaline
Installed PV power	3500w
Efficiency	80%
Nominal operating cell temp.	47^{0}c
Life cycle	25yrs
Cost/PV module	N56,000 or $143
Derating Factor	80%

D. *Battery Storage*

In the hybrid system, the storage battery provides energy to the inverter while staying within its bounds. In order to reduce carbon emissions, fuel costs, and utility bills, it is intended to shorten the generator's operating hours and the amount of time it uses the electricity grid. Depending on the amount of operation cycles, the battery choice will affect the system lifetime. Deep cycle batteries were the battery types utilised in this design. A maximum power point tracking charge controller was employed to prevent the battery from being overcharged or undercharged.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25apr2233

The storage bank's maximum power absorption capacity is determined by HOMER. The battery bank's maximum power absorption capacity is determined by:

$$P_{batt\,cmax\,kbm} = \frac{KQ_1 e^{-k\Delta t} + QKC(1-e^{-k\Delta t})}{1-e^{-k\Delta t} + C(K\Delta t - 1 + e^{-k\Delta t})} \quad (2)$$

Where
Q1 = available energy in the storage at the beginning of the time step
Q = total amount of energy in the storage at the time step
C = the storage capacity ratio
K = the storage rate constant
Δt = the length of the time step

The storage charge power corresponding to the maximum charge rate is given by:

$$P_{batt,cmax,mcr} = \frac{(1-e^{-\propto_c \Delta t})(Q_{max} - Q)}{\Delta t} \quad (3)$$

Where
$\propto_c$ = storage's maximum charge rate (A/AH)
Q_{max} = total capacity of the storage bank

The maximum charge current is given by:

$$P_{batt,cmax,mcc} = \frac{N_{batt} I_{max} V_{nom}}{1000} \quad (4)$$

Where
N_{batt} = the number of batteries in the storage bank
I_{max} = the storage's maximum charge current
V_{nom} = the storage's nominal voltage

Table 4: Battery Characteristics

Battery type	Gel deep cycle battery
strings of battery	4
nominal voltage	12
nominal capacity (kwh)	2.4
capacity (ah)	200
Efficiency	90%
maximum charge current	33.4
cost/battery	N115,000 or $294
life cycle	3-4yrs

The above battery characteristics were based on the data obtained from HOMER.

E. Diesel Generator

The capacity of the diesel generator was selected to accommodate the total load capacity. A 10kw diesel generator was chosen for this design.

Table 5: Diesel Generator Characteristics

Existing Diesel Generator Details	Characteristics
Capacity	10kw
fuel type	Diesel
fuel consumption	0.480l/hr
fuel consumption/load/hr	0.286l/hr
carbon emission/litre	19.769
operation/maintenance procedure	oil replacement
cost of oil/gallon	N4,000 or $10.2
cost of diesel/litre	N224 or 0.59usd
Cost of plugs	N300

HOMER calculates the fossil fuel consumption of the diesel generator by the following equations:

$$M_o = P_{fossil}(F_O . Y_{gen} + F_1 . P_{gen}) \quad (5)$$

$$M_o = M_{fossil} + \frac{M_{gas}}{Z_{gas}} \quad (6)$$

$$M_{gas} = Z_{gas}(M_o - M_{fossil}) \quad (7)$$

$$X_{fossil} = \frac{M_{fossil}}{M_o} \quad (8)$$

Using equation 2 & 3

$$M_{gas} = Z_{gas}(M_o - X_{fossil} M_o) \quad (9)$$

$$M_{gas} = Z_{gas} M_o (1 - X_{fossil}) \quad (10)$$

$$X^*_{fossil} \le x_{fossil} \le 1 \quad (11)$$

$$M^*_{gas} = Z_{gas} M_o (1 - X_{fossil}) \quad (12)$$

$$Y^*_{gen} = \tau . Y_{gen} \quad (13)$$

$$M^*_{gas} = Z_{gas} P_{fossil}(F_o . Y_{gen} + F_1 . Y^*_{gen}).(1 - X^*_{fossil}) \quad (14)$$

$$M_{gas} = MIN(M^*_{gas}, M^*_{gas}, a_{gas}) \quad (15)$$

$$X_{fossil} = 1 - \frac{M_{gas}}{Z_{gas} M_o} \quad (16)$$

$$M_{fossil} = X_{fossil} . M_o \quad (17)$$

Volume 10, Issue 4, April – 2025 International Journal of Innovative Science and Research Technology
ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25apr2233

Table 6: Nomenclature

Symbol	Units	Description
ρ_{fossil}	kg/L	Density of fossil fuel
τ	%	Generator derating factor
a_{gas}	kg/hr	Available biogas flow rate
$\dot{m}_0$	kg/hr	Fossil fuel flow rate (in pure fossil mode)
$\dot{m}_{fossil}$	kg/hr	Fossil fuel flow rate (in dual-fuel mode)
$\dot{m}_{gas}$	kg/hr	Biogas flow rate (in dual-fuel mode)
$\dot{m}^{*}_{gas}$	kg/hr	Maximum value of biogas flow rate
$\dot{m}^{t}_{gas}$	kg/hr	Target value of biogas flow rate
x_{fossil}	%	Fossil fraction
$\dot{x}_{fossil}$	%	Minimum fossil fraction
z_{gas}	None	Biogas substitution ratio
		Generator fuel curve intercept coefficient
		Generator fuel curve slope
		Power output of the generator
		Maximum output of generator at minimum fossil fraction
		Rated capacity of the generator

III. SIMULATION SYSTEM

Two distinct hybrid combinations—PV/Utility and diesel/utility—were used for the experiment. The goal was to compare the two hybrid systems' costs and environmental effects while also determining the initial capital cost, NPC, COE, and operation/maintenance costs. It was possible to determine the hybrid power mix appropriate for a typical residential dwelling thanks to these comparisons. The tariff imposed on customers for electricity purchased per KWH, known as the LCOE, is calculated using:

$$COE = \frac{C_{ann,tot}}{E_{ann,load}} \tag{18}$$

Where

$C_{ann,tot}$ is the total annualized cost
$E_{ann,load}$ is the total annualized load served by the system in kwh

➢ *NPC is expressed as:*

$$C_{npc.tot} = \frac{C_{ann,tot}}{CRF\left(i, P_{lifetime}\right)} \tag{19}$$

Where
$C_{ann,tot}$ is the total annualized cost ($/year)
i is the annual real interest rate %
$P_{lifetime}$ is the project lifetime (years)
CRF represents the capital recovery factor

A. Diesel Generator and the Utility System

The utility's blackout hour was covered by the diesel generator in this design. The utilities and the diesel generator shared the same operating hours each day. Below is the basic configuration.

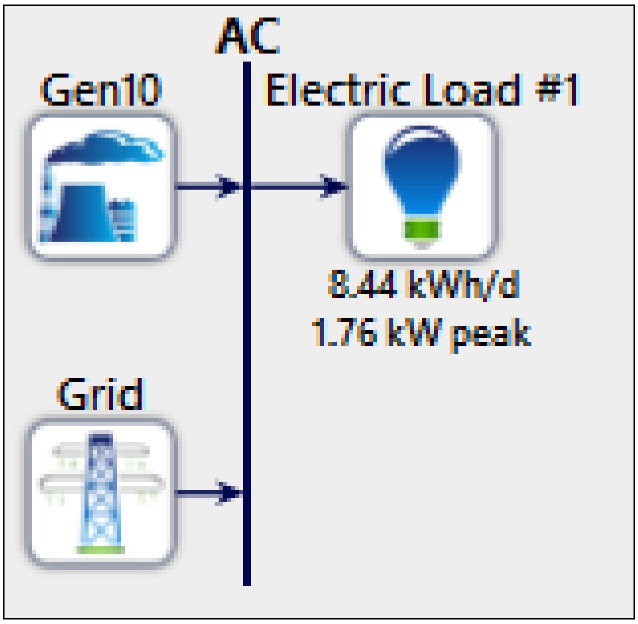


Fig 2: Diesel Generator/Utility Grid Block Diagram

The utility and the diesel generator split the daily loads. The utility's blackout hours were covered by the diesel generator. Due to its unreliability, the utility grid's operating hours were uncertain. When there is no utility supply, the diesel generator may operate for longer periods of time each day. The diesel generator had a minimum runtime of 720 minutes per day and a 12-hour downtime. Data was entered into HOMER according to the utility's electricity rate and the generator's capacity. Cost/environmental effect comparisons were performed, and the COE, NPC operating/maintenance cost, and fuel cost/usage were acquired. Determining the degree of reduction in fuel consumption/cost and carbon emission rate is the aim of this combination.

B. PV/Utility Grid

In this design, the PV system was the major source of energy. Only the heavy duty loads were used on the utility grid. The utility grid working hours was minimized to 3hrs/day so as to minimize the electricity bills. There was a drop in the energy purchased from 1.92/kwh to 0.47/kwh.

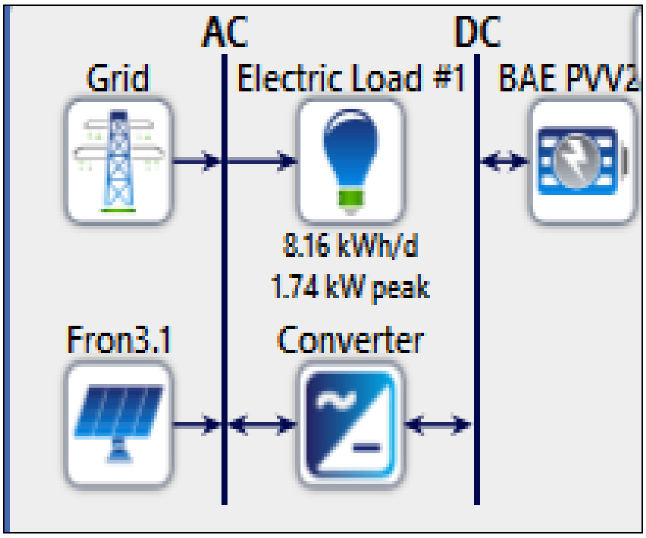


Fig 3: PV/Utility Grid Block Diagram

The capacity of the PV, converter, battery storage and current energy purchased was inputted into HOMER. The simulated result showing the COE, NPC, O&M cost was obtained. The purpose of this hybrid combination is to ascertain the level of reduction in the purchase of energy from the utility grid thereby reducing cost.

IV. RESULTS

A. Diesel/Utility Grid Optimized Results

The HOMER simulated outcome demonstrates that the utility grid was given priority. In order to reduce the cost and consumption of fuel as well as the carbon emissions from the diesel generator, a large amount of electricity was supplied by the utility grid. Since the utility grid is more cost-effective than running a diesel generator for a year and the utility does not emit carbon emissions, HOMER made the utility the primary source of power supply, which resulted in a decrease in the utility grid's NPC, COE, and operating costs. When the diesel generator and the utility were utilised in a hybrid form, the COE, NPC, operating cost, O&M cost, fuel cost, total fuel consumed/year, and the energy purchased/year all drastically decreased compared to when these systems were used separately.

Table 7: Diesel/Utility Grid Optimized Result

Component	COE	NPC	OP. COST	TOTAL FUEL (L/YR)	O & M COST	INITIAL CAPITAL
Diesel/Mains	$0.286	$25,010	$1,819	2,079	$522	$1,500

B. PV/Mains Optimized Result

The optimal outcome of harmonising the PV system and the mains was displayed in the table below. In this instance, HOMER minimised the amount of energy acquired from the utility grid by making the PV the primary energy source for the household. Operating costs also decreased when the amount of electricity purchased from the utility grid was reduced.

Table 8: PV/Mains Optimized Results

Component	COE	NPC	OP. COST	INITIAL COST
PV/Utility	$0.00438	$346.01	-$64.26	$1,117
PV/Battery/Con./Utility	$0.0629	$4,781	$186.94	$2,364
Utility	$0.470	$18,099	$1,400	$0.00

PV/utility grid, PV/battery storage/converter, freestanding utility, and battery storage/utility/converter were the four optimised outcomes of the aforementioned experiment. Operating costs were lowest on the PV/utility grid. These are systems in which the grid is directly synchronised with the solar panels. In comparison to when the utility was used in a hybrid combination with the diesel generator, it was found that the utility grid running cost decreased from $2,928 to $1,400. Due to the significant decrease in COE, NPC, and operating costs, PV/battery storage/converter/utility is a better option than diesel/mains. This hybrid technology completely reduces gasoline consumption and costs while also reducing carbon emissions.

Table 9: Comparing the Energy Purchased in the PV/Mains System

Equipment	Energy Purchased
PV/Mains	1,822kwh
PV/Battery/Mains/Converter	1,633kwh
Mains	2,979kwh
Battery/Mains/Converter	2,972kwh

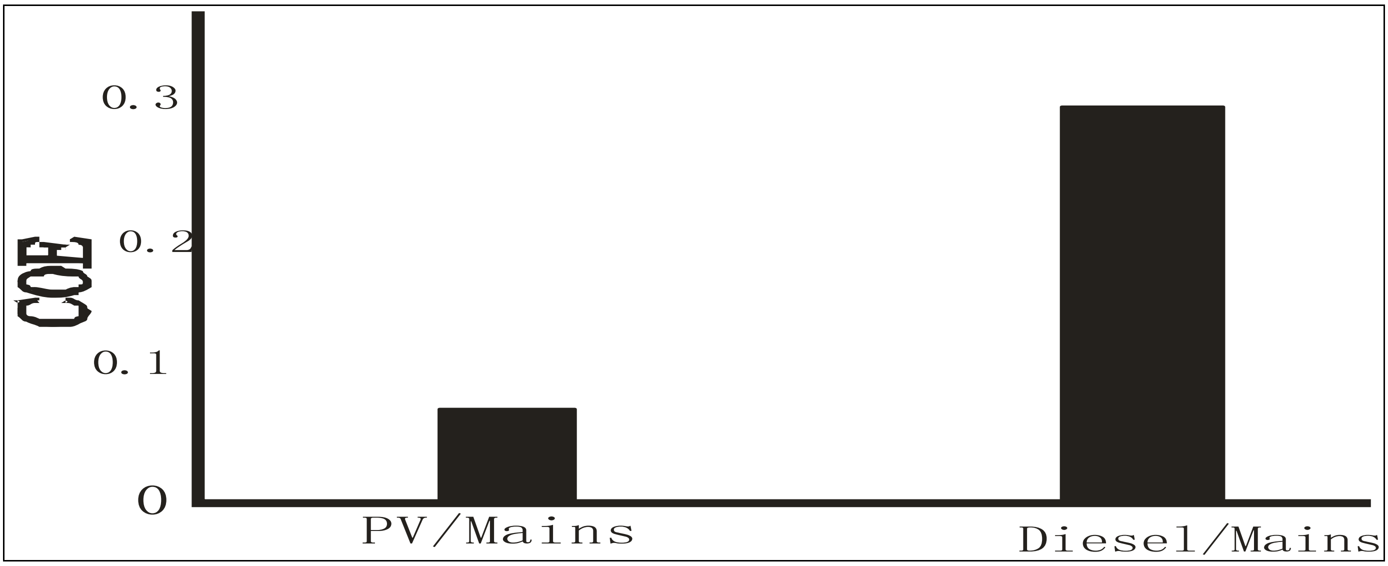
Because backup batteries can provide energy over time in the event that the sun or mains supply are unavailable, it was observed from the above table that less energy was acquired from the utility grid in the PV/battery/converter/mains system.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25apr2233

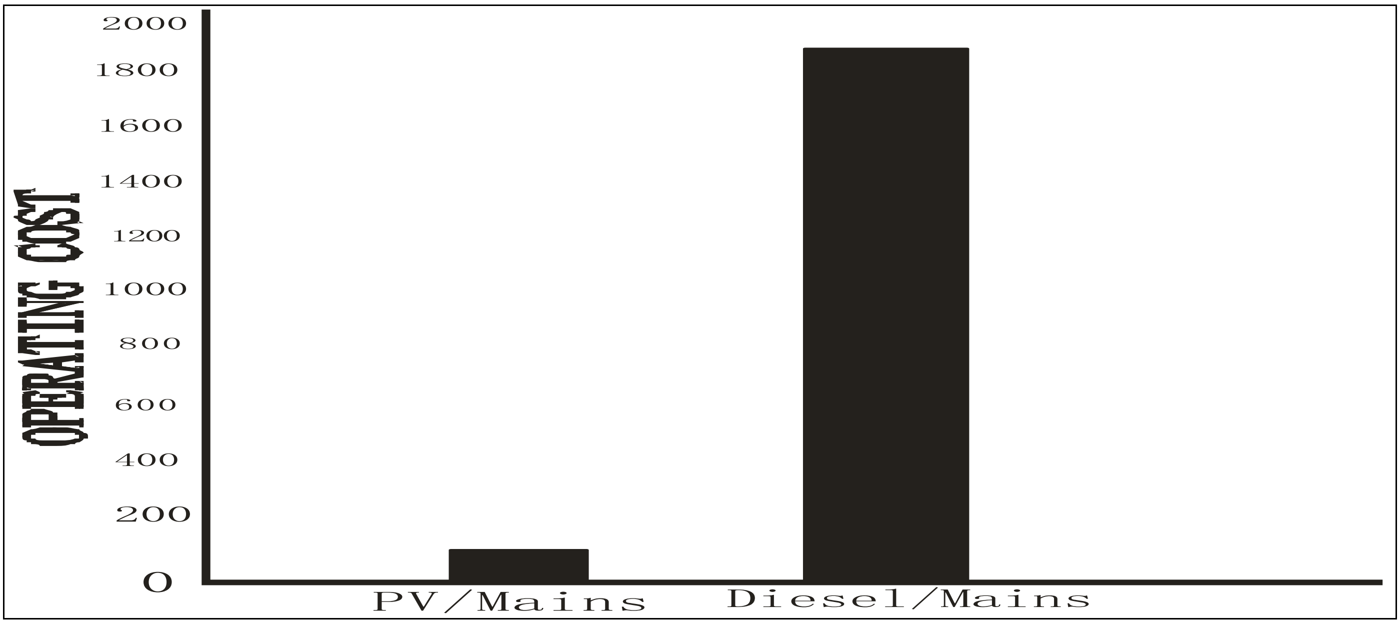
Table 10: Cost Comparisons between PV/Mains and Diesel/Mains

Equipment	COE	NPC	Operating Cost	Energy Purchased	Fuel Usage/Yr
Diesel/Mains	$0.286	$25,010	$1,819	2,407kwh	2,079L
PV/Mains	$0.062	$4,781	$186	1,633kwh	Nil

From the above comparisons, the PV/Mains hybrid system was proven to be more efficient, feasible and economical. The result from HOMER showed the PV/Mains has a 90% drop in the COE, NPC and operating cost.



Graph 1: COE Comparison



Graph 2: Operating Cost Comparison

V. CONCLUSIONS

The design analysis confirms that switching to hybrid energy sources in homes is dependable. The ideal system findings from HOMER included a 3.5kw converter, 10kw generator, 48v battery string, 3.5kw PV, and energy acquired from the utility grid, as can be seen from the design, for domestic loads of 7.5kwh/day. The utility grid or the diesel generator were used to handle the heavy loads. To keep the PV system from being overloaded, the working hours of each load were established. During power grid outages, the generator was a viable choice. The COE decreased from $0.399 to $0.116, the NPC decreased from $69,806 to $7,210, and the operating cost decreased from $5,284 to $374 according to the economic comparison between the diesel generator/utility grid and the PV/battery/converter/utility grid. The PV/battery/converter/utility grid is more economical than the diesel generator/utility because to the reduction of NPC, COE, and operating costs.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25apr2233

When evaluating the two hybrid combinations' effects on the environment, the PV/Utility had zero carbon emissions because it did not require fuel. The best, most cost-effective and carbon-emission-free PV/utility combo was hindered by the utility grid's unreliability.

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