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Comparative study of Hybrid versus Stand-alone Generating systems in Covenant University power system network

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Abstract

Hybrid power systems incorporate several electricity generation components which include wind, PV, Battery and generator. The advantage of this hybrid power system is that it enhances the reliability of the power system networks. In this paper, focus is on a comparative cost implication of installing a hybrid PV/Wind/battery/Diesel generator system in Covenant University in comparism to the existing CU stand-alone generator power system in meeting the electrical daily load demand. A one-year period of hourly data of wind speed and solar radiation of this hybrid system is analyzed using Weibull distribution and MatLab software tools. The modeling and simulation of the hybrid system was carried out using the HOMER Software. The cost analysis which includes the Systems total investment cost (STIC), the systems initial equipment cost (SIEC) of the hybrid system and CU stand-alone generator system was calculated. The results show that in a 15 years' period, the Net Present value of running the hybrid system to the CU stand-alone generator system was $39.18 million, and the cost saved was estimated to be $102.07million proving that the hybrid system is a viable more alternative in the cost saving potential.

Keywords: Cost analysis, PV, wind turbine, diesel, SIEC, STIC

I. INTRODUCTION

The generation of electrical energy through the use of alternative sources such as wind and solar, has become more attractive and these sources are widely used for substituting fossil fuels in the process of electrical power energy generation since 1970s (R.luna-rubio, m.trejo-perea, Ríos-Moreno, & Vargas-Vázquez, 2012). In Nigeria, it has become a necessity due to the current power challenges. Although, over dependence on fossil fuel which drives generators cannot be totally foregone, it can be drastically reduced by the introduction of wind and solar, with battery bank. Although, these alternative energy sources are expensive in their individual investment costs, a hybrid combination, which includes alternative energy sources (wind and solar) with diesel generators and energy storage requirements, often has a lower operating cost than the system which has only one of the above alternative sources.

Hybrid systems are a combination of different power generating sources with different prime movers (conventional and renewable) that are uniquely interwoven, with each constituent system strengths complementing each another to efficiently meet load demand at relatively cheaper cost. Hybrid energy systems with or without renewables, are classified, according to their configuration, as series, switched hybrid, or parallel hybrid (Wichert, 1997).

According to Bindu and Parekhs' study on modelling and simulation of distributed energy system with PV/Wind/Diesel hybrid system *uses* HOMER. It was concluded that at lower wind speeds, PV/Battery/Diesel configuration is optimum while at medium and higher wind speeds, Wind/PV/Battery and PV/Wind/Diesel/Battery configurations are feasible respectively. As wind speed increases, the penetration of PV and diesel reduces (Parekh & Kansara, 2011).

Benjamin O. Agajelu et.al analyzed the Life Cycle Cost (LCC) of a diesel/photovoltaic hybrid power generating system for an off-grid residential building in Enugu, Nigeria. He concluded that when the net present value of the hybrid system is compared with that of PV stand-alone system, with the diesel stand-alone system as the base case, the hybrid system has a higher NPV than PV stand-alone system. The hybrid system has an internal rate of return of 26.3% while the PV stand-alone system has an internal rate of return of 24.6%, and that the hybrid system will help in extending the life of the non-renewable energy sources.

II. MATERIALS AND METHODOLOGY

II.1. Diesel Generator System

Literature shows that generator operates most efficiently when running between 80-90% of its rated power (Nafeh, 2010). Efficiency decreases as load decreases. The rated power (P_{rated}) of the diesel generator should be at least equal to the peak load demand (P_{load}) as follows:

$$P_{RATED} \geq P_{LOAD} \quad (1)$$

The fuel consumption of the diesel generator at no load is almost 30% of the corresponding fuel consumption at the rated power. Thus, it is recommended that the diesel generator operation below 30% of full load for long periods should be avoided in order to avoid serious maintenance problems, like chemical corrosion and glazing (Kaldellis, 2007).

II.2. System Schematic and Components

Figure 1 gives a description of the hybrid power system configuration. The energy sources are the PV system, Wind turbine system, battery storage and the diesel generators. The system controller is the brain of the hybrid system, it monitors and controls the entire operation of hybrid system ensuring balance in energy distribution to the battery storage system. The inverters convert the DC power from the batteries to AC to meet the load requirements.

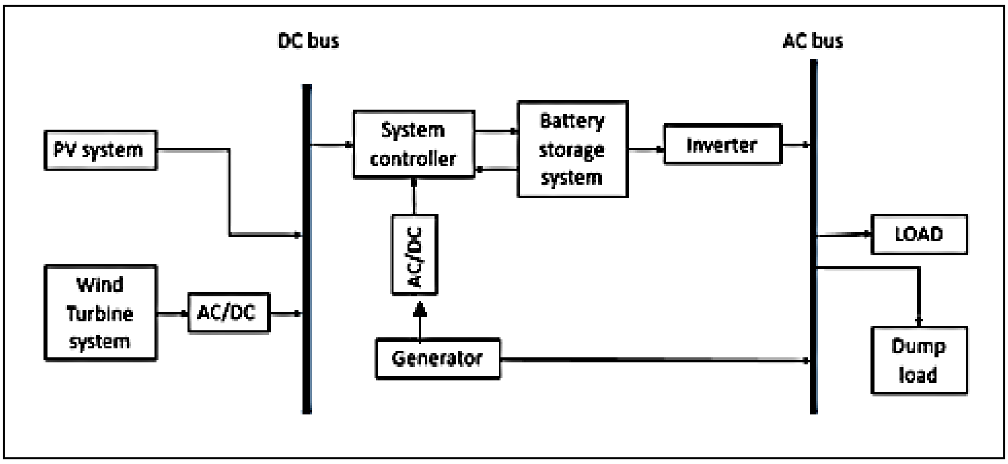

Fig. 1: Hybrid power system configuration.

Since the output power of the PV module and the wind turbine is intermittent due to the climatic conditions and the necessity to provide the constant power supply to the load side, a group of battery banks is required as an energy storage system. The excess power generated by the PV module and the wind turbine is stored in the battery bank until full capacity of the storage system is reached. Once the power is deficient, the battery bank will discharge to supply the shortfall in the load demand. The diesel generator is operated when the PV module and the wind turbine fail to satisfy the electrical power demand. The dump load was included for consuming the surplus power generated by the hybrid system.

II.3. Mathematical Model of the Wind Turbine

Wind speed height correction: The recorded anemometer data at a reference height (hr.) should be adjusted to the desired hub center (h) using the wind power law. This can be done through the following expression (Borowy & Salameh, 1996):

$$v(t) = v_r(t) * \left(\frac{h}{h_r}\right)^y \qquad (2)$$

where v(t) is the hourly wind speed at the desired height h, $v_r(t)$ is the hourly wind speed at the reference height h_r. and y is the power law exponent ranging from 1/7 to 1/4 (D.M. Eggleston and R.S. Stoddard, 1987). The hourly wind speed was taken at a reference height of 15 meters, the desired tower height specification is 100m. The tower height of the wind turbine is an important factor which significantly influences the operating performance of the wind turbine. It can also be well over half the cost of the wind turbine system overall. (Lu Zhang, Georges Barakat, Adnan Yassine, 2012)

II.4. Weibull probability density function

Probability density function (pdf) is the best description for variation of wind speed. The pdf calculated the probability that an event will occur between two end points. Note that the pdf curve shape and its height provide, in some way, that the area under the pdf curve from 0 to infinity is exactly 1. This means that blowing of wind speed will be between 0 and infinity (m/s). The Weibull pdf is defined as

$$f = \frac{B}{A}\left(\frac{v}{A}\right)^{B-1} e^{-\left(\frac{v}{A}\right)^B} \qquad (3)$$

where B is the shape factor, A is the scale factor and v is wind speed. The value of B controls the curve shape. The smaller shape factor shows that the distribution of wind speed is near the average. The scale factor in figure 2 shows how the bulk distribution lies and how it stretched out.

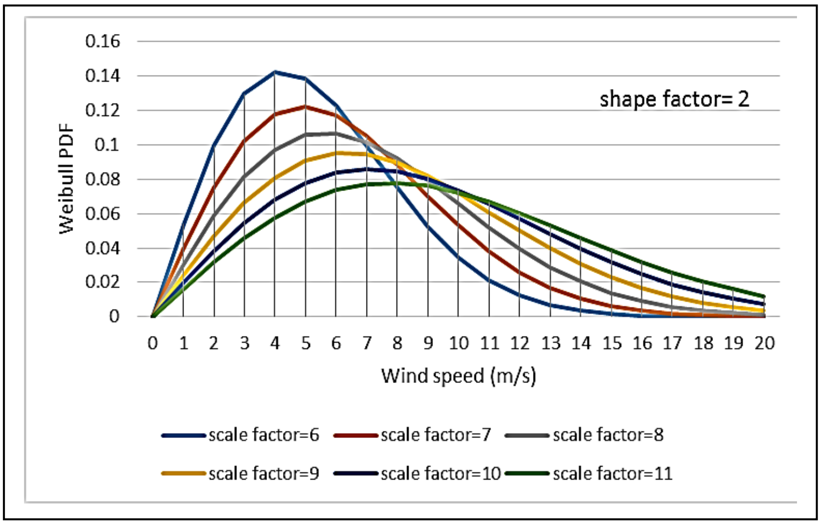

Fig. 2: Weibull probability density function against the wind speed.

The hourly output power of the wind turbine P_{WT} (t) was determined using the following formula:

$$P_{WT}(t) = \begin{cases} a * v^3(t) - b * P_r & v_{ci} < v < v_r \\ P_r & v_r < v < v_{co} \\ 0 & otherwise \end{cases} \quad (4)$$

where

$$a = \frac{P_r}{v_r^3 - v_{ci}^3} \quad \text{and} \quad b = \frac{v_{ci}^3}{v_r^3 - v_{ci}^3}$$

v_{ci},, v_r and v_{co} are respectively the cut-in wind speed, rated wind speed and cut-off wind speed. P_r is the rated power

III. RESULTS AND DISCUSSIONS

There were 456,420 valid data points per minute readings for the wind speed and direction, 441,960 for solar radiation. Matlab was used to analyze this data, and unwanted data points were eliminated, and the per hour averages were found. Excel was used to plot the graphs and financial calculations were carried out.

III.1. Load Profile Assessment

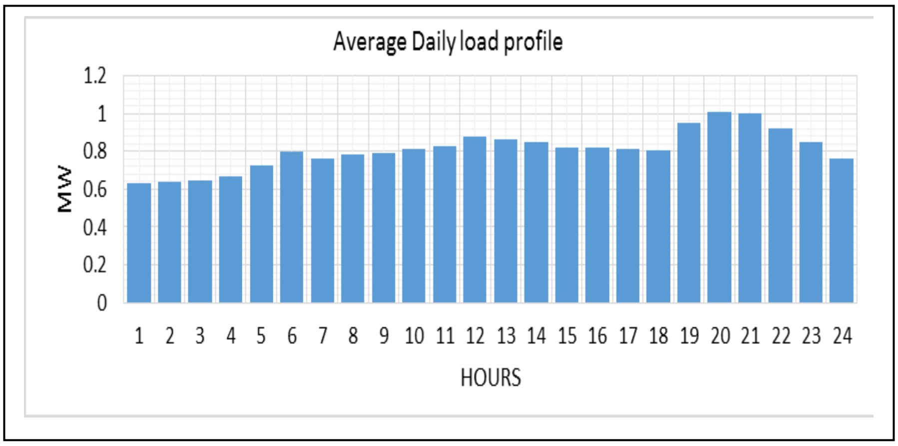

Fig. 3: Average daily load profile.

Fig 3 shows the average daily load profile of Covenant University. It has an average peak load of about 1.1 MW, during the hours between 7pm and 9pm, and a recorded maximum load of 1.37MW during the month of February. The average load is to be shared between the wind and solar power systems in the ratio 1:9. The solar resource is more abundant in Covenant University than the wind. The average daily load demand for 6 months is 20MWh/day (approx.). The generators are used as backup or supplement in cases where the load demand is greater than what the hybrid system can handle or in cloudy seasons.

III.2. The Solar Resources Assessment

The collected data of the solar was analyzed in order to plan for the structure of the hybrid system. The figure below shows the hourly solar irradiation over a period of time.

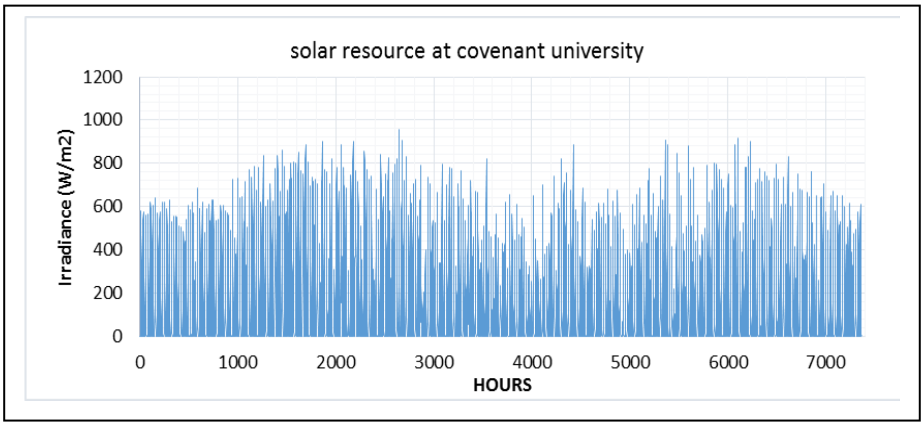

Fig. 3: Solar irradiance vs hours in Covenant University

Covenant University is endowed with high solar per day insolation of over 3,500 Whr/m^2/day, with the highest recorded average of hourly irradiance of over 900W/m^2. The months of June, and July (the months associated with high rainfall) recorded the lowest solar insolation. Figure 4 shows the solar irradiance at Covenant University for one year.

III.3. Wind Resource Assessment

A wind resource assessment involves measuring and analyzing the wind speed and other meteorological data at a site. This is necessary in order to estimate the annual energy production of proposed wind turbine installations, which will determine the economic feasibility of the project. Fig. 5 shows the wind speed at Covenant University for a year.

A pre-feasibility study was carried out on the site proposed for the wind turbine. An anemometer was used at 15m height to measure the wind speed profile. Data was collected for one year and was stored on site by the data logger.

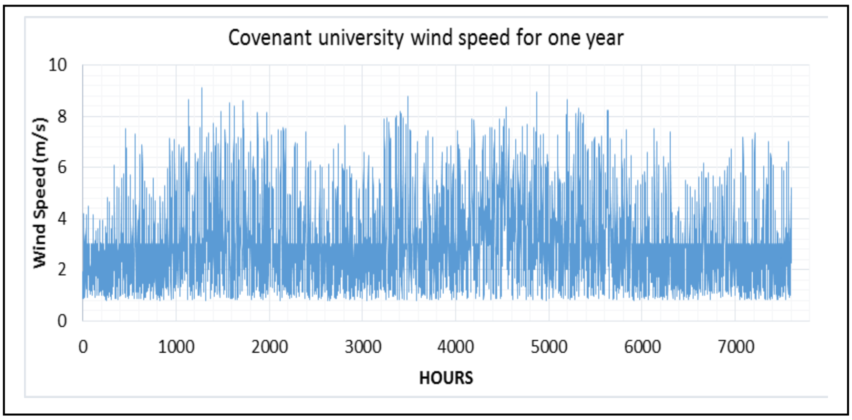

Fig.5: wind speed vs hours in Covenant University

A MATLAB algorithm was written to treat the data and eliminate false data points as well as calculate the wind speed at the desired height. The average wind speed was found to be 3m/s.

III.4. Wind Speed Variability

As can be seen in Fig.6, the wind speed distribution often varies with wind direction, height above ground, season, and the time of the day. The relationship between wind speed and wind direction is typically presented as a wind rose plot, of wind speed vs. wind direction in polar coordinates

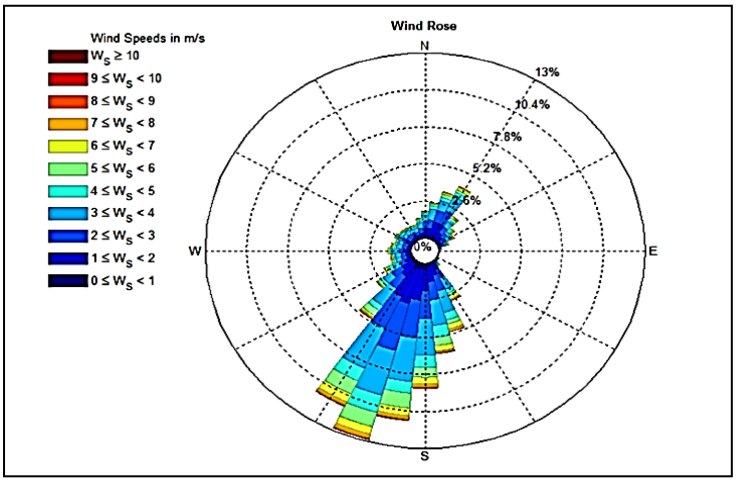

Fig. 6: Wind rose in Covenant University

The wind resource analysis showed that the wind direction was predominantly towards the SSW and SW direction i.e. wind from the Atlantic Ocean.

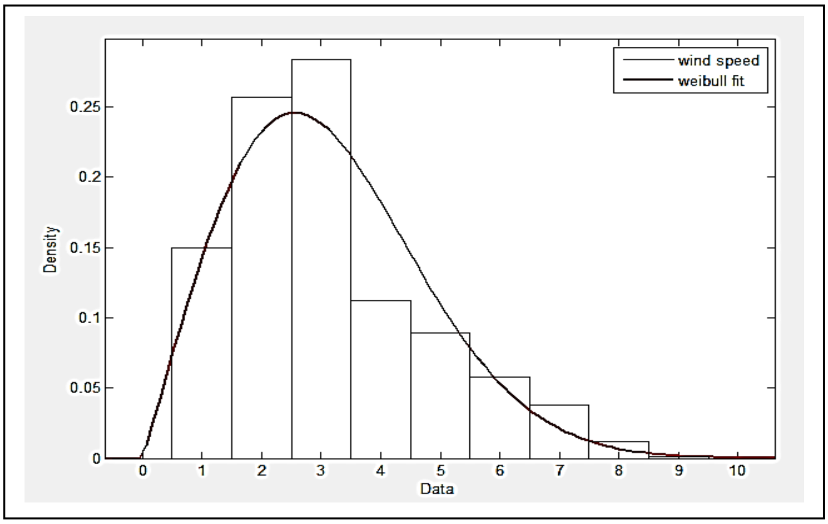

Fig. 7: Wind profile

The wind profile and its output power were represented by treating samples of wind velocity as a random variable with a Weibull distribution (saha & Kastha, 2010) and (Carpentiero, Langella, Manco, & Testa, 2008) as shown in fig. 7. In the sizing process of distributed energy sources, the wind uncertainty is represented by the Weibull probability density function. Fig.8 shows the wind turbine energy chart for Covenant University.

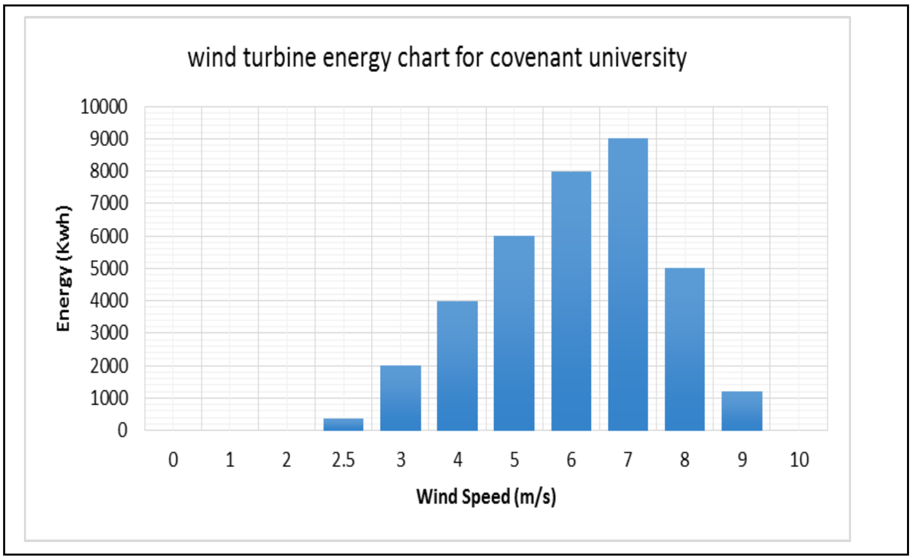

Fig. 8: Wind Turbine energy chart for Covenant University

III.5. Economic Assessment

This assessment was carried out based on the use of Cost-benefit evaluation techniques such as

Net Profit, Payback period, Return on Investment, Net Present Value, Internal Rate of Return.

$$Net\ profit\ =\ Total\ income - Total\ costs \quad (5)$$

(In this study, the net profit is represented as cost saved)

Payback period = Time taken to make up the investment back (6)

Return on Investment (ROI) or Accounting Rate of Return (ARR) is given as

$$= \frac{\text{average annual profit}}{\text{total investment}} \times 100\% \quad (7)$$

Internal Rate of Return is the discount rate which equates the present values of the future cash flows of an investment to the initial investment (Accounting Explained, 2013)

Net present value (NPV) is the sum of the present values of all future amounts. Present value is the value which a future amount is worth at present. It assumes a discount rate for future cash flows. Discount rate is the annual rate by which we discount future earnings.

$$\text{PV} = \frac{\text{value in year } n}{(1+r)^n} \quad (8)$$

where *n* is the number of years and *r* is the discount rate

$$NPV\ =\ \sum PV - Initial\ Investment \quad (9)$$

In this study, the economic assessment was done by comparing the cost of running the hybrid system and the CU generator system over the same period of 15 years at a discount rate of 10%. The running cost (i.e. the O&M cost, replacement cost, and every other cost in operating the system) of the CU generator system was used as a base line cost.

Cash flow=$CUGEN_{RUN}$ – $Hybrid_{RUN}$

A positive value indicates that the proposed system saves money at that particular time of the project compared to the base case system.

IV. COST ANALYSIS

IV.1. System total investment cost (STIC)

STIC is composed of the capital cost (C_{CAP}), the installation cost (C_{ins}) the annualized Operation and Maintenance (O&M) cost ($C_{O\&M}$), the replacement cost (C_{REP}) of the PV modules, the wind turbines and the battery banks and the operation cost of the diesel generators (C_{diesel}) throughout the system lifetime. In this study, the replacement cost of the battery banks is considered equal to the sum of their capital cost and installation cost. The capital and installation costs, including the balance of systems (BOS), are calculated together. The cost of constructing the tower height and the cost of maintenance, all form part of the installation cost. More detailed form of the STIC function is expressed in the following equation:

$$STIC(N_{PV}, N_{WT}, N_{BAT}) =$$

$$Npv * (C_{cap} + C_{INS} + S_{LIFETIME} * C_{0\&M} + R_{PV} * C_{REP}) +$$

$$N_{WT} * (C_{cap} + C_{INS} + S_{LIFETIME} * C_{0\&M} + R_{WT} * C_{REP}) +$$

$$N_{BAT} * (C_{cap} + C_{INS} + (S_{LIFETIME} - R_{BAT} - 1) * C_{0\&M} + R_{BAT} * (C_{CAP} + C_{ins})) + C_{DIESEL} \quad (10)$$

where N_{PV}, N_{WT}, $S_{LIFETIME}$ and N_{BAT} are respectively the total number of the PV modules, the total number of the wind turbines, system lifetime and the total number of the battery banks and R_{PV}, R_{WT}, R_{BAT} are respectively the number of times of the PV modules, the number of times of the wind turbines and the number of times of the battery banks will be replaced over the system lifetime.

The calculation of operation cost of the diesel generators can be determined as follows (Zhang & Barakat, Modeling and Optimal Sizing of PV/Wind/Diesel System, 2011), (Zhang, Belfkira, & Barakat, Wind/PV/Diesel Energy System: Modeling and Sizing Optimization, 2011):

$$C_{DIESEL} = C_{INS} + C_{O\&M} + \frac{C_{AQU}}{D_{LIFETIME}} + C_{FUEL} \quad (11)$$

where C_{INS}, $C_{O\&M}$, C_{AQU}, $D_{LIFETIME}$, C_{FUEL} respectively present the installation cost of the diesel generators, the diesel generator's hourly O&M cost, the diesel generator's acquisition cost, the diesel generator's lifetime and the cost of the fuel consumed by the diesel generators. The equation below shows the fuel consumption cost for 1 h of running the diesel generator (Skarstein & Ulhen, 1989)

$$C_{FUEL} = P_{fuel}*(A*P_D + B*P_{D\ RATED}) \quad (12)$$

where P_{fuel} is the price of fuel, P_D is the power generated and P_{Drated} is the generator's rated power,

A = 0.246L/Kwh and B = 0.0845L/Kwh are the fuel curve coefficients.

IV.2. The system initial equipment cost (SIEC)

The SIEC can be calculated as SIEC (N_{PV}, N_{WT}, N_{BAT}) =

$$Npv * \left(C_{cap} + C_{INS} + \frac{C_{0\&M}}{S_{LIFETIME}}\right) +$$

$$N_{WT} * \left(C_{cap} + C_{INS} + \frac{C_{0\&M}}{S_{LIFETIME}}\right) +$$

$$N_{BAT} * \left(C_{cap} + C_{INS} + \frac{C_{0\&M}}{(S_{LIFETIME} - R_{BAT} - 1)}\right) + C_{DIESEL}(\text{Per year}) \quad (13)$$

IV.3. Sizing and Cost of the Hybrid System

The average load is to be shared between the wind and solar power system in the ratio 1:9. The solar resource is more abundant in Covenant University than the wind. The average daily load demand for 6 months is 20MWh/day.

IV.3.1. Estimating the energy demand

The estimated average daily energy demand for 6 months (January-June) in Mwh/day is tabulated as shown in Tab. 1.

Tab. 1.

January	February	March	April	May	June
19.38	24.89	21.21	24.67	14.63	11.97

IV.3.2. E*nergy requirement of the PV modules.*

Energy requirement of the PV modules is calculated by multiplying peak energy requirement in MW h/day by 1.3 (the energy lost in the system i.e. 10% loss due wiring and connection, 20% losses in the battery) to get the total MW h/day which must be provided by the panels.

Based on the load sharing, the peak energy requirement =18MWh/day (approx.)

The Energy requirement of the PV modules was calculated as

$$18 * 1.3 = 23.4\text{MWh/day}$$

IV.3.3. The panel generating factor (PGF)

The peak watt (Wp) produced by the PV module depends on the size and climate of the site, Hence, the need to find PGF.

The PGF was determined by obtaining the lowest month kWh/m^2/day value was 5.5KWh/m^2/day (approx.), Since the Wp (peak watt) of the panel is rated using a value of 1,000 W/m^2, then, each Wp of the panel would therefore deliver 5.5 Wh/day if the conditions were perfect. The conditions are not perfect so we have to correct for the variations from standard conditions. Corrections include (Herb Wade, 2008):

- 15% for temperature above 25 C
- 5% for losses due to sunlight not striking the panel straight on (caused by glass having increasing reflectance at lower angles of incidence)
- 5% allowance for dirt
- 10% allowance for the panel being below specification and for ageing

∴ The total power was calculated as

$$Total\,power\ =\ 0.85\ *0.95\ *0.95*0.90\ =\ 0.69\ of\ the\ original\ Wp\ rating.$$

Hence, the PGF was calculated as:

$$5.5*0.69\ =3.8\text{wh/Wp/day}$$

The total watt-peak rating needed by the PV module was calculated as:

$$(23.4*10^6)/3.8\ =6.2\text{MW panel}$$

The number of 300-W panel required to generate 6.2MW can be given as:

$$(6.2*10^6)/300\ =20{,}666.7$$

That is 20,667 panels will be required to meet the solar panel energy requirement

IV.4. System total investment cost (STIC)

Tab.2: System total investment cost (STIC)

	N	C_{CAP} + C_{INS}	$S_{LIFETIME}$	$C_{O\&M}$ (each component $/yr.)	R	C_{REP}
PV system	20,667	$598.8	15	$4.8	0	0
Wind system	22	$102,600	15	$2,580	0	0
Battery	195	$64,800	15	$4,320	1	$64,800

STIC of the PV system can calculated as:

N_{PV}=20,667

$C_{O\&M}$ = $16/Kw (NREL, 2016)

STIC (N_{PV}) = 20667*(598.8 + (15* 0.016*300) = $13,863,424

STIC of the wind system can be calculated as

STIC (N_{WT}) = 22*{$102,600 + (15*$2,580)} = $3,108,600

$C_{O\&M}$ = $43/Kw (Christopher, Tyler, Ben, & Edward, 2015)

STIC of the battery system can calculated as

STIC (N_{BAT}) = 195* {$64,800 + $4,320*(15-1-1) + (1*$64,800)} = $36,223,200.

$C_{O\&M}$ = $20/Kw (Nicholas, Aron, & Steven, 2015).

IV.5. The Diesel Generators

In this study, 2 x 250-KVA generators are used, and are assumed to run together for an average of 6 hours every day as shown in table 3.

Tab 3: Cost of 2x250 kva generator

Item	Capital Cost	Installation cost	O&M cost ($/yr.)	Lifetime (hours)
2 X 250 KVA	$146,667	$7,333	$39,200	35000

The operation cost of the diesel generators (C_{DIESEL}) over the system lifetime of 15 years is $3,370,395.

Tab 4: SIEC and STIC of the hybrid system

	PV	Wind Turbine	Battery	Generator	TOTAL
SIEC	$12,474,601	$2,313,960	$12,700,800	$224,693	$27,714,054
STIC	$13,863,424	$3,108,600	$36,223,200	$3,370,395	$56,565,619

IV.6. The cost of electric power network in Covenant University

Covenant University has eighteen (18) diesel generators with an installed capacity of 9,750KVA, sourced from three different manufacturers: Caterpillar (13), Perkins (2) and Cummins (3). When power supply from the public utility fails, eight generators will have to run simultaneously to produce power between 3,750kVA (minimum units combination) and 6,000kVA (maximum units combination) at any instant in time (Orovwode, Adegbenro, Awosope, Idachaba, & Abdulkareem, 2014). The capital and installation costs of these generators were put as $3,096,500. The generators have an average lifespan of 35,000 hours and they operate everyday throughout the year (i.e. approx. 7000 hours). Hence, they are replaced every 5 years. The cost of replacement is assumed to be equal to the cost of purchase. Studies show that the total fuel consumed by these generators annually is 12,544,320 liters (Orovwode, Adegbenro, Awosope, Idachaba, & Abdulkareem, 2014), hence the annual cost of these consumption at diesel cost of $0.721/liter (N220) is $9,044,454. The cost of maintenance of these 18 generators is $955,500/yr.

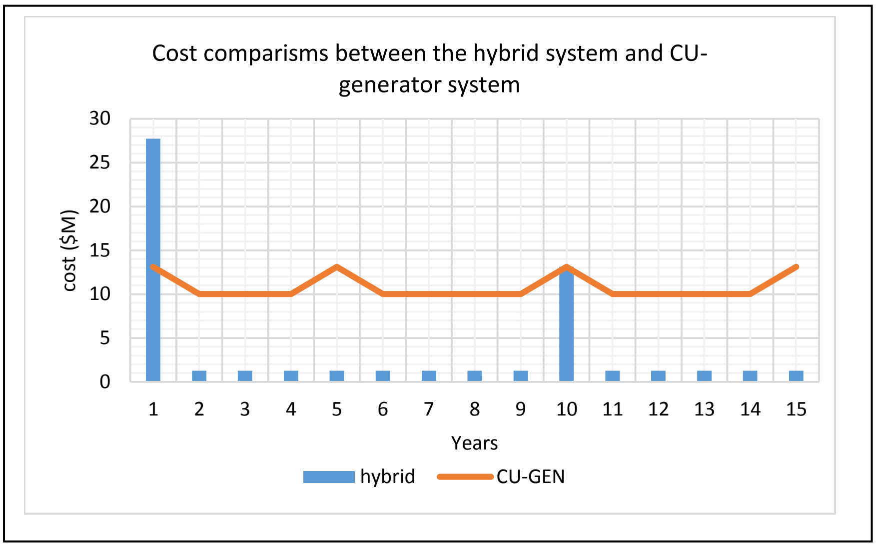

Fig 9: Cost comparisms between the Hybrid system and CU-generator

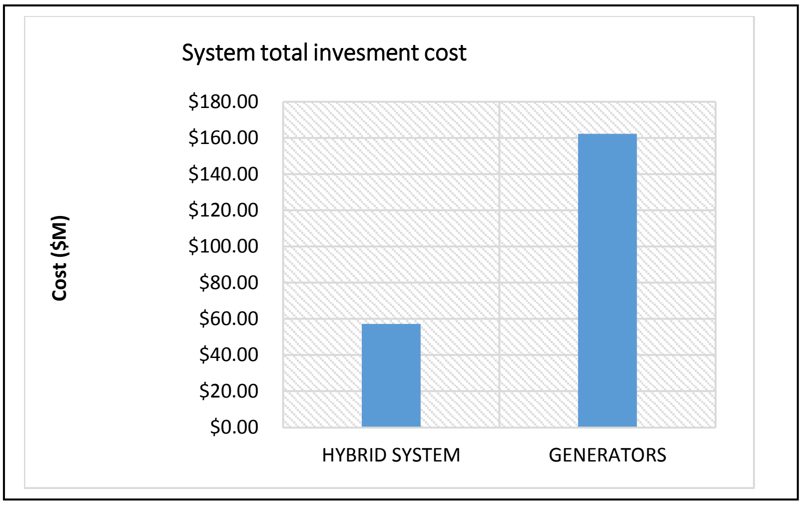

Fig10: system total investment cost

The total cost of running these generators over a period of 15 years, all things being equal, is $162,396,950.

V. CONCLUSION

This study compared the cost of running the hybrid system with the CU-generator system on ground over a period of 15years at a discount rate of %10, the NPV was

$39.18 million, the cost saved was estimated to be $102.07 million, an internal rate of return (IRR) of 20%, a payback period of 4 years and a 31% return on investment. Based on this assessment it can be concluded that the hybrid system project is a viable one with cost saving potential.

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