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Techno-Environmental Analysis of Hybrid Energy System for Offshore Oil Rig Black Start

Abraham Olatide Amole[a*], Adebimpe Oluwaseun Adeyeye[a], Daniel Oluwaseun Akinyele[b], Kehinde Adeleye Makinde[c], Stephen Oladipo[d]

[a] *Department of Electrical, Electronics, and Telecommunication Engineering, College of Engineering, Bells University of Technology, Ota, Nigeria.*
[b] *Department of Electrical and Electronics Engineering, Olabisi Onabanjo University, Ago-Iwoye, Nigeria.*
[c] *School of Computing, Design and Digital Technologies, Teesside University, Middlesbrough, UK.*
[d] *Department of Electrical and Electronics Engineering, University of Johannesburg, Johannesburg, 2006, South Africa*

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ABSTRACT

The use of Diesel Generators (DGs) and gas turbines to power oil rigs is characterized by pollution due to the emission of harmful gases like carbon dioxide, very high noise levels, high maintenance costs, and the inability to start the platform if the DG fails. Offshore wind energy generation system provides a viable alternative means of powering the oil rig and can also be integrated to operate in parallel with gas turbines. However, offshore wind energy might fail if not properly designed due to the high variability of wind resources. Hence, the objective of this work is to design offshore Wind Turbine Generator (WTG) energy generation system, DG, and hybrid DG-WTG for the black start of an offshore oil rig. The designed energy systems are simulated using HOMER Pro. Furthermore, the performance of the simulated systems was evaluated using the electrical production, unmet load, and emission profile as the performance metrics. The results of the hybrid DG-WTG powered black start revealed that 150kW DG generated 322,071kWh/yr representing 6.77% of the total generation and 1.5MW WTG generated 4,434,632kWh/yr representing 93.2% of the total generation. The comparison of the emissions from DG and DG-WTG revealed that 294,058kg/yr, 1,945kg/yr, 80.9kg/yr, 9.02kg/yr, 720kg/yr, and 688kg/yr of CO_2, CO, UH, PM, SO_2, and NO, respectively, were released into the atmosphere by DG-WTG which is very low compared to 969,129kg/yr, 6,109kg/yr, 267kg/yr, 37kg/yr, 2373kg/yr, and 5739kg/yr of CO_2, CO, UH, PM, SO_2, and NO, respectively, released into the atmosphere by DG. The sensitivity analysis revealed that while the electrical production of 100kW and 50kW DGs decreased with an increase in WTG height, the electrical production of 1.5MW WTG increased with an increase in WTG height. It was further revealed that the higher the WTG height the smaller the quantity of the emission released into the atmosphere.

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1. INTRODUCTION

The conventional means of generating energy poses a lot of challenges emanating from high costs and emissions. Nigeria is currently battling with energy deficiency arising from poor power networks, ageing power infrastructure, and insufficient generation (Makinde et al, 2021; Amole et al., 2020). According to Ijeoma, 2012), there are numerous obstacles militating against the development and the present state of energy generation and utilization. The author also discussed the ways the Nigerian government is operating the existing power sector and the plans to attract private companies to contribute to the growth of the sector. The global communities continue to develop interest in renewable energy as a means of addressing global energy challenges and climate change issues and significant efforts have been made to develop and create eco-friendly alternative energy generation techniques (Attabo, 2019; Chakraborty et al., 2011). A comparative study of renewable energy sources in (Salih et al., 2014) revealed that wind energy was the most promising, economical, and fast-growing renewable energy source. The market potential, ample availability, and cost competitiveness of wind energy led to a consistent technological development, which has made it easier and more effective to exploit its energy potential (Aazami et al., 2022; Hosseini et al., 2022). Another renewable energy source that has similar potential is solar photovoltaics. Both have been widely utilized in replacing conventional energy generation sources such as gas, crude oil, and coal (Ajibola and Balogun, 2019) and have helped to reduce atmospheric pollution and the level of harmful gas emissions.

In response to the growing demand for environmentally-friendly energy generating sources, energy providers are making significant investments in the development of wind energy (Kumar et al., 2018, Brimmo et al., 2016). Electricity generation using wind energy has the fastest growth and development rate among other renewable energy sources, as reported in (Lop´ez-Guevara et al., 2020). Nigeria is still lagging behind in the implementation of these eco-friendly energy-generating technologies. The United State wind energy generating capacity stood at 16,818 MW in 2007 with additional 8,358 MW in 2008 and 9,922 MW in 2009 (Olalekan

*Corresponding Author's Email: *aoamole*@bellsuniversity.edu.ng (A. O. Amole)
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et al., 2020). As of the beginning of 2010, the generation capacity increased to 35,098 MW, which is double what was generated in 2007 (Ajayi et al., 2014, Pritesh et al., 2016). Today, offshore WTGs with capacities as high as 10 MW to 14 MW are available. Further, several manufacturers have announced and are testing offshore WTGs up to 14 MW. Yet, no WTGs larger than 15 MW have been announced (Energinet, 2015).

Further development has been made to maximize the energy being generated from the WTG (Arshad and O'kelly, 2013, Adedipe et al., 2018). Offshore wind energy has been one of the most significant outcomes of this development since there are enough wind resources to harness offshore. Therefore, the development of WTG with a higher energy-generating capacity has been made possible (Aardal et al. 2012). One of the major challenges of energy generation using wind energy is the availability and variability of wind resources (Arshad and O'kelly, 2013, Kumar et al., 2021, Ajibola and Balogun, 2019). These challenges are mostly responsible for the failure of several wind energy system installations (Pham and Shin, 2020). Installation of WTGs offshore has offered better wind availability and less variability, making the generation of electricity through this means more efficient and reliable (Rohan et al., 2020). Offshore wind energy eliminates the cost of transmitting energy from the grid or onshore wind farm for offshore usage since the offshore wind turbines are much closer to such loads (Vales and Soares, 2020).

Renewable energy has found usage in different areas, thereby lessening the demand for conventional energy sources. For example, solar PV has been variously used to energize different loads such as residential (Dioha and Kumar, 2018; Makinde et al., 2021; Hosseinian et al., 2016; Imam et al., 2020), telecommunications (Anayochukwu and Onyeka 2014; Amole et al., 2021), water supply (Okakwu et al., 2022; Stoyanov et al., 2021), and healthcare (Babatunde et al., 2019; Olatomiwa et al., 2018, Oladigbolu et al., 2021). In the same manner, the wind energy system has been used to provide the required energy for several services and businesses among which one include water supply (Ayodele et al., 2018) and electricity supply (Ohunakin et al., 2012). Grid integration of wind energy systems is one of the most common phenomena in renewable energy system design and implementation as it has been found to offer several advantages such as strengthening of weak transmission lines (Butt et al., 2022), real power loss reduction (Mahat, 2006), and WTG performance improvement (Aazami et al., 2022). The biogas energy system is another fast-growing renewable energy source that aids a cleaner environment and an energy-sufficient world (Akinbomi et al., 2014; Odekanle et al., 2020). Energy from bio-gasifier has been used for powering rural healthcare facilities (Achirgbenda et al., 2020) and providing support to the grid (Jumare et al., 2020). Hybridization of these renewable energy sources has been widely adopted for design and performance improvement (Ndukwe et al., 2019; Teo and Go, 2021; Gabbar et al., 2020; Mazzeo et al., 2021). The idea behind hybridizing energy sources is to increase the reliability of the system, which is the desired factor for efficient operation (Kitindi 2021). This also helps reduce the generator running time, thereby reducing fuel usage and running cost. Then, it backs up the system during the period where the wind speed is not enough to drive the WTG to produce enough energy (Jayswal, 2017).

Generally, the sustainability of renewable energy depends on many factors that are complex and highly dynamic. The STEEP model is a model that gives a comprehensive account of factors that generally affect renewable energy systems (Akinyele et al., 2021). The model has been used to evaluate different designs of renewable energy systems. For instance, techno-environmental studies (Erixno and Rahim, 2020; Lubritto et al., 2011; Aberilla et al., 2019; Amole et al., 2021) of different energy systems allow for technical evaluation and environmental impacts of such systems. While techno-economic analysis (Gabbar et al., 2020; Oladigbolu et al., 2019; Jahid et al., 2020; Imam et al., 2020; Jamil et al., 2012) of renewable energy systems permits technical assessment and economic implications of such systems, techno-economic and environmental studies (Butt, 2022; Kitindi, 2021; Akinbulire et al., 2014; Masrur et al., 2020) give a broader view of technical, economic, and environmental assessments of renewable energy systems in general. The social and policy implications (Kumar, 2020) of any renewable energy system can also be measured with the STEEP model.

Oil rig platforms, which are usually of larger capacities, can be located onshore and offshore. Effective running of the rig depends on reliable and large amounts of electricity (Zhang et al., 2019). The black start unit is a very essential unit of the oil rig platform that provides electricity supply for platform startup and emergency loads, including platform lighting and other loads in the living quarters when the gas turbine is not running. The black start unit provides electricity supply to the gas turbine compressors and pumps that need to be operated even when the rig is not in operation.

Traditionally, oil rig platforms are powered using both DG and gas turbine that involves burning fossil fuel (Agung et al., 2022). The use of gas turbines and DG is, however, accompanied by the emission of carbon dioxide (CO_2), particulate matter (PM), Sulphur dioxide (SO_2), and nitrate-oxide (NO) which are harmful to the eco-system and high running costs. It has been reported that 80% of the greenhouse gas emission from offshore drilling results from these generators (Wu and Re, 2012). In this paper, attention is given to the black start of ExxonMobil offshore platform, Bonny Island, Nigeria which is the DG.

A review of relevant literature presented in the subsequent section indicates that wind energy has been widely used for different applications. However, it has been found that the wind energy system is mostly used in the complementary mode with other energy sources due to its high variability for effective performance. Also, it has been claimed a number of times that there is abundant wind energy offshore and in the coastal areas. However, these resources are yet to be explored for offshore applications. Consequently, this paper examines WTG, DG, and hybrid offshore DG-WTG for the black start of ExxonMobil offshore platform, Bonny Island, Nigeria by considering both the techno-environmental aspect of an offshore hybrid DG-WTG system and the sensitivity analysis since the height of the WTG is a major factor that determines the number of wind resources that WTG can access (Vorpahl et al., 2013). The variability of wind speed remains a major factor that affects the offshore WTG power output and this can severely impact its performance. This is a great disadvantage to the oil rig as the WTG may not be able to generate as much energy as required for the oil rig operation (Yang et al., 2022). Hence, the need to have a hybrid offshore DG-WTG system to provide ancillary support in cases where offshore wind energy is unable to meet the rig black start energy demands for some periods due to wind variability (EWEA, 2009).

2. LITERATURE REVIEW

Despite its abundance of renewable energy resources, wind energy is underused in West African nations such as Nigeria. Wind energy, on the other hand, has been highlighted as a feasible solution to Nigeria's energy poverty and insecurity. According to reports, North African countries remains at the forefront of the African wind energy market while South and Eastern African countries were predicted to make efforts that would reduce the gap. However, the implementation of wind farm projects is scarce in Central Africa and West African countries (Ajayi et al., 2014). In Nigeria, the notion to tackle energy insecurity through sustainable sources has made researchers and some other governmental bodies evaluate the nation's potential for power generation using wind and solar energy, in which some areas have been identified to have good wind resources. The Nigeria Metrological Station identified some states with good wind resources including Jos, Katsina, and Maiduguri with wind speeds as high as 8.07m/s, proving that there is a high onshore wind speed in the Northern part of Nigeria. Although the wind resources in the southwestern region of Nigeria are not so encouraging, few offshore areas in Lagos through Ondo were identified with strong wind potential and others in Bayelsa, Akwa Ibom and River State (Adedipe et al., 2018; Olujobi et al., 2022).

Several studies have gathered data on wind resources in different parts of Nigeria and evaluated the performance of wind energy conversion systems. A study in (Izelu et al., 2013) utilized the wind resources in Port Harcourt to meet the electricity requirement of the University of Port Harcourt (UNIPORT) and at its Teaching Hospital (UPTH), the WTG was installed along the Choba banks of the New Calabar River. It was demonstrated that for a projected power requirement of 21 MW in 20 years, an airfoil shape of NACA 2412 WTGs of 1.5 MW capacity would be needed for a wind velocity of 17.5 [m/s]. The economic value of the system when compared with the existing diesel plant demonstrated a saving of N8,633,032,101.98. An LCOE and present cost-based analysis of WECSs in a different part of Nigeria was carried out in (Ohunakin et al., 2013). It was found that the hub height played a significant role in the amount of energy generated by the WECS.

Grid integration of renewable technologies is another viable solution to achieving sufficient and sustainable energy in Africa. The opportunities and the associated challenges with the integration of renewable energy into Nigeria's power network were extensively discussed in (Adebanji et al., 2022; Uguru-Okorie et al., 2015). The impact of the integration of WECS on the voltage stability of the Nigerian 330 kV power grid was investigated using DIgSILENT Power Factory and MATLAB (Adeokun et al., 2021). The work revealed that DFIG-based WECS was effective in overcoming the overvoltage problem in the Northern region of the country with a Penetration Level (PL) satisfying a bus voltage criterion of 1.0 ± 0.05p.u. The work further demonstrated that loading of all critical power system equipment was 35% and hence, it proffered a viable solution for voltage instability on the weak National grid. Similarly, the fuzzy logic-based peak load-sharing technique for grid-connected wind energy systems was studied in (Ashraf et al., 2017). The result obtained from the work revealed that the improved Pitch Frequency Control (PFC) of the wind energy system was achieved with minimal percentage overshoot and settling time. The General Algebraic Modeling System (GAMS) was adopted for the study of power management in smart 33-bus distribution networks augmented with wind turbines and solar PV (Mehbodniya et al., 2022). The results presented in the work in comparison to conventional power flow studies showed improvement rates of 40.7%, 33%, 36%, and 74.7% for the active and reactive power losses, network energy costs, and voltage deviations, respectively.

The hybridization of different energy sources has proven to be one of the most promising means of providing affordable and clean energy to the growing population. Therefore, several studies have considered hybrid renewable energy technologies for a reliable supply of electricity (Ohiero et al., 2018; Asif and Khanzada, 2015; Kitindi, 2021). Genetic algorithm-based optimization of a hybrid PV-WTG energy system for the Patani community was examined by the authors in (Nyeche and Diemuodeke, 2019) using HOMER, MATLAB, and MS Excel spreadsheet. The result showed that for satisfactory performance of the system, the peak rated powers of 217 kWp and 226050 kW were required for PV and WTG, respectively. The study further illustrates that with a loss of load probability of 0.1086, the Levelized Cost of Energy (LCOE) obtained for the system is 0.27 $/kWh. The Grasshopper Optimization Algorithm (GOA) was employed in (Bukar et al., 2019) for effective energy management in a microgrid comprising solar PV, wind turbine, and diesel generator. A comparison of GOA with Particle Swarm Optimization (PSO) and Cuckoo Search (CS) through MATLAB simulation showed that GOA was optimal sizing using the Cost of Energy (COE) and system capital cost as a benchmark.

The technical and economic aspects of an advanced combined power generation cycle were considered in (Hosseinpour et al., 2020). The system consisted of a biomass gasifier, a cascaded humidified advanced turbine (CHAT), and a steam turbine. The economic result indicates a positive Net Present Value (NPV) with an investment cost per unit of energy of about 909 USD per kW. For a typical building integrated Photovoltaic (BIPV), the energy, economics, and environment were reflected for solar cells slope and azimuth as sensitivity analysis variables in (Dehkordi and Jahangiri, 2022). It was demonstrated that a 30-degree slope and zero azimuth at the per kWh of energy was found to be $0.09 and is the optimal configuration for the BIPV.

Recent studies on renewable energy systems have focused more on the technical and economic implications of these systems (Peña Sánchez et al., 2021; Peloriadi et al., 2022). For instance, the hybrid renewable energy systems for electric vehicle charging applications were presented in (AlHammadi et al., 2022) with the techno-economic indices as the variables of interest. Also, off-grid renewable energy electrification models in rural Namibia were considered with an emphasis on the technical and economic parameters (Amupolo et al., 2022). In recent studies by independent researchers, environmental and economic parameters were prioritized for a standalone hybrid energy system (Chowdhury et al., 2022) and integrated anaerobic co-digestion power plant (Hamedani, 2020).

Subsequently, methods for acquiring data with respect to the energy input and load profiles were determined, and a techno-economic analysis was performed using Hybrid Optimization of Multiple Energy Resources (HOMER) software. The results demonstrated that the optimal electric vehicle charging model comprising solar photovoltaics, wind turbines, batteries, and a distribution grid was superior to the other studied configurations from the technical, economic, and environmental perspectives. An optimal model could produce excess electricity of 22,006 kWh/year with an energy cost of 0.06743 USD/kWh. Furthermore, the proposed battery–grid–

solar photovoltaics–wind turbine system had the highest renewable penetration and, thus, reduced carbon dioxide emissions by 384 tons/year. The results indicated that the carbon credits associated with this system could result in savings of 8786.8 USD/year.

Some WTG-based studies are reported in Table 1 and they demonstrated that wind energy was mostly used in a hybrid mode with other energy sources like solar PV and DGs. The table further indicates that technical, economic, and environmental parameters are predominantly used for quantifying these systems with applications in telecommunications, healthcare, and generic electricity production. The background so far laid has revealed that wind energy has been used for diverse onshore applications. However, despite the enormous wind potential offshore, it is glaring that this potential remained untapped. The offshore oil rig is the right means for harnessing this untapped offshore wind energy. This will ensure a healthier environment for the aquatic lives that are greatly affected by DG emissions and oil rig activities. Consequently, in this work, the feasibility of wind energy deployment for powering the black start load of the oil rig is explored.

Table 1. Some WTG-based studies

Author(s)	System Configuration	Results	Applications
Jahid et al., 2020).	Grid, Solar PV, WTG, and DG	Technical, Economic, and Environmental	Telecommunication
Ajewole et al., 2019) Okundamiya et al., 2014)	Solar PV, WTG	Technical, Economic, and Environmental	Telecommunication
Kitindi, 2021), Abdulmula et al., 2022)	Solar PV, WTG, and DG	Technical, Economic, and Environmental	Telecommunication
Babatunde et al., 2019), Oladigbolu ., 2021), Gbadamosi and Nwulu, 2022), Babatunde et al., 2018)	Solar PV, WTG, and DG	Technical, Economic, Environmental, and Policy	Healthcare
Kumar et al., 2019)	Solar PV	Technical, Economic,	Healthcare
Diyoke et al. 2022)	Hydro, Solar PV, and WTG	Technical, Economic, and Environmental	Electricity
Adaramola et al., 2012)	Solar PV, WTG	Technical, Economic	Electricity
Ajibola and Balogun, 2019)	Grid, Solar PV, WTG, and DG	Technical, Economic, and Environmental	Telecommunication
Kumar et al., 2018), Brinmo et al., (2016)	Solar PV, WTG	Technical, Economic, and Environmental	Telecommunication
Lop´ez-Guevara et al., 2020), Olalekan et al., 2020)	Solar PV, WTG, and DG	Technical, Economic, and Environmental	Telecommunication
Ajayi et al., 2014), Pritesh et al., 2016), Energinet, 2015), Arshad and O'kelly, 2013)	Solar PV, WTG, and DG	Technical, Economic, Environmental, and Policy	Healthcare
Adedipe et al., 2018)	Solar PV	Technical, Economic,	Healthcare
Aardal et al., 2012)	Hydro, Solar PV, and WTG	Technical, Economic, and Environmental	Electricity
Kumar et al., 2021)	Solar PV, WTG	Technical, Economic	Electricity

3. MATERIALS AND METHODS

The materials and the methods used in this work are presented step by step in this section.

3.1 Description of case study

The study area for this research is the ExxonMobil offshore production platform with a water depth of (26-34m) which is located about 28km off southeast, Bonny Island, Nigeria (latitude 4˚ 26′ 34.19″ N and longitude 7˚ 14′ 14.40″ E). This is the only oil and gas platform operating offshore presently in Nigeria. This is floating production storage and offloading platform as shown in Figure 1. The estimated 1.2MW load requirement of the black start is presented in Table 2 showing different pumps, vent fans, compressors, etc.

3.2 Wind resources and WTG model

The monthly average wind data of the study area for the years 2010 and 2011 are given in Table 3 as obtained at 10m anemometer hub height. The wind speed at the WTG hub height can be obtained from the wind speed at the anemometer hub height according to Equation (1), where U_H is the wind speed at the hub height of the WTG (m/s), U_A is the wind speed at anemometer height (m/s), Z_H denotes the hub height of the WTG (m), Z_A is the anemometer height (m), and Z_0 represents the surface roughness length (m). It should be noted that the WTG hub height of 80m is considered in this work and the corresponding wind speed is presented in Figure 2. The energy available in the wind can be harnessed with WTG designed based on Equation (2). Here, ρ, A, and v denote the air density (1.225 kg/m^3), WTG rotor swept area (m^2), and the wind speed (m/s). P_{WTG} is the WTG rated power and is equal to 1.5MW for a black start load of 1.2MW considering a safe operating condition of 0.2. The wind data used in this work is obtained at 80m hub height. The WTG rotor diameter can be calculated using Equation (3), where r is the length of the blade or radius of the rotor.

3.3 DG model

The peak load demand is a key parameter to consider in determining the rated capacity of a DG because the DG is expected to meet maximum demand at all times. The mathematical relation can be described by Equation (4). Here, D_{pk} and σ represent the peak load (kW) and safety factor (%) that accounts for the difference between the DG capacity and the peak load. The DG fuel consumption is calculated by Equation (5), where P_o, P_r, A, and B are the DG's operating power output (kW), DG's power rating (kW), fuel curve slope (0.246 L/kWh), and fuel curve intercept coefficient (0.08415 L/kWh), respectively.

Figure 1. ExxonMobil offshore platform, Bonny Island, Nigeria.

Table 2. Black start equipment and specifications

Equipment	Specification/capacity (y)	Quantity
Hydraulic starter pump	149kW, 415VAC	1
Generator lube oil pump	50kW, 415VAC	1
Vent fans	(150×2)kW, 415VAC	2
Instrument load	Approximately 8kW	1
Compressor	330kW, 415VAC	1
Others (lighting, heating, ventilation and living quarters)	350kW	Quite a few

Table 3. Average wind data for the years 2010 and 2011 at 10m anemometer height

Month	Average wind speed (m/s) Year 2010	Average wind speed (m/s) Year 2011
January	4.67	4.15
February	4.88	4.56
March	4.52	4.27
April	4.96	4.25
May	5.56	6.05
June	6.58	6.87
July	6.56	6.78
August	6.73	6.76
September	6.41	6.09
October	5.82	5.63
November	5.00	5.25
December	4.36	4.94

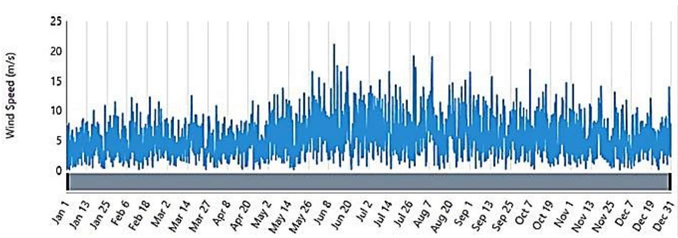

Figure 2. Daily Wind Resources of the area under study at 80m anemometer height

3.4 Design of hybrid DG-WTG

The design of the hybrid DG-WTG is based on Figure 3 using Equations 2 and 4 as presented in Table 4. The control unit is responsible for coordinating the energy interplay among the WTG, DG, and the load, as shown in Figure 4. It should be noted that the DG configuration is such that 50kW and 100kW DGs were synchronized prior to synchronization with the WTG. If $\mathrm{P_{WTG}}$ represents the WTG turbine power, $\mathrm{P_{DG}}$ represents DG power, and $\mathrm{P_L}$ is the black start load, then the power coordination for the control unit is based on Equations 6 to 9. Equation 6 implies that as long as the power available from the WTG is sufficiently greater than the required power by the load, the load is powered by the WTG. Also, Equation 7 implies that when no power is available from the WTG, the DG is fully called into operation. In Equation 8, ΔP represents the power deficit between the WTG and the load. ΔP is dynamic based on wind variability and is equal to P_{DG}. In a condition where the WTG power is less than the load power as in Equation 9, the DG is called into operation to augment the WTG power. It should be noted that the control unit has synchronization capability. The designs in 3.2, 3.3, and 3.4 were simulated using HOMER pro in Figure 5 and the performance of the energy systems was evaluated based on the metrics presented in Subsection 3.6.

Table 4. System model equations

Model Equations	Equations No.
$U_H = U_A \left[\ln\left(\frac{Z_H/Z_0}{Z_A/Z_0}\right)\right]$	(1)
$\mathrm{P_{WTG}} = \frac{1}{2}\rho A v^3$	(2)
$r = \sqrt{\frac{2\mathrm{P_{WTG}}}{\rho \pi v^3}}$	(3)
$DG_c = D_{pk}(1+\sigma)$	(4)
$DG_{fc} = AP_o + BP_r$	(5)
$P_{WTG} \geq P_L, \quad P_{WTG}$	(6)
$P_{WTG} = 0, \quad P_{DG}$	(7)
$\Delta P = P_{WTG} - P_L \approx P_{DG}$	(8)
$P_L \geq P_{WTG}, \quad \Delta P + P_{WTG}$	(9)

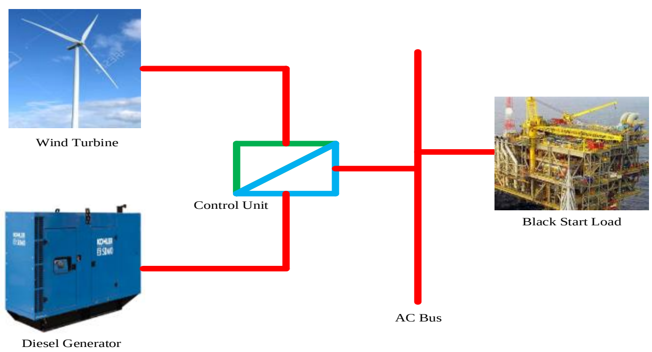

Figure 3. Hybrid DG-WTG Energy System Configuration

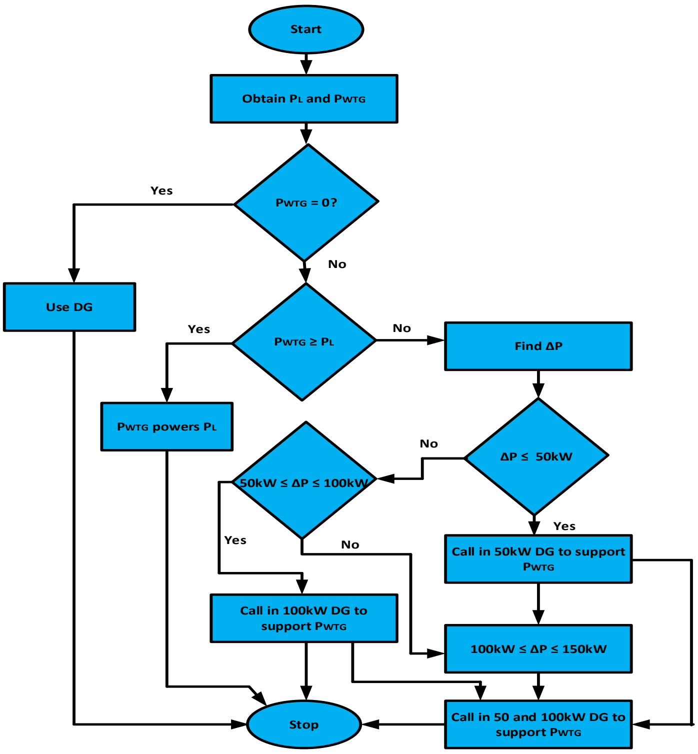

Figure 4. System energy management flowchart

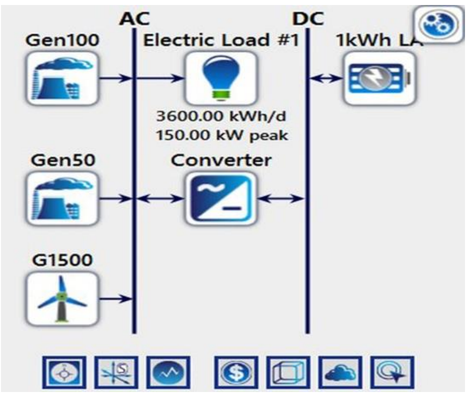

Figure 5. HOMER simulation diagram

3.5 Sensitivity analysis

The independent variable for this analysis is the hub height and it varies from 25m (for smaller WTGs of 50kW or less) to 100m (for larger WTGs of 100kW or more) and even heights higher than 100m in offshore technology for very large wind turbines of multi-megawatt. The effect of the variation in hub height on other variables that determine the quality of the hybrid generator is studied. The impact of the variation in WTG hub height with electrical production, unmet load, fuel summary, and emissions is also examined.

3.6 Evaluation of the hybrid energy system

The following parameters were used to measure the performance of the WTG, DG, and hybrid DG-WTG energy generators for the oil rig black start.

3.6.1 Electrical load served

The electrical load served is the total amount of load the electrical generating system is able to supply adequate power for proper operation. In case of excess production, the excess can be sold to the national grid.

3.6.2 Unmet electrical load

Following the simulation, there were instances when the simulation results revealed that some of the loads in the system did not get the electrical power required for operation; such loads are referred to as an unmet load. It happens when the electricity demand exceeds the supply. HOMER measures the cumulative unmet load as well as the unmet load fraction for each device over the year. By default, the software regards any power system with an unmet load as inadequate because a good power system should be able to cater for the power need of the entire system.

3.6.3 Emission

Emission is a major parameter that must be factored into the design of a power system. The focus of this work is to design a system with minimal emission with the use of WTG.

4. RESULTS AND DISCUSSION

The simulation results of the offshore DG, WTG, and hybrid DG-WTG-powered black start for the platform are presented in the subsequent subsections.

4.1 Simulation results for WTG-powered black start

Table 5 presents the simulation results of the WTG-powered black start. It is shown that 4,434,623KWh/yr is generated by the 1.5MW WTG at a height of 60m. An estimated load of 101,093 kWh/yr equivalent to 7.69% was not served by the WTG-powered black start, which is not acceptable considering the importance of the load being powered by this system. It should be noted that this system poses no environmental concerns as no fuel is used in this system as revealed by the fuel summary. Figure 6 depicts the electricity production of the WTG-powered black start, which indicates that the highest electricity, about 700kW monthly average, was generated in June, while the lowest electricity, about 280kW monthly average, was produced in January. The output power of the 1.5MW WTG is presented in Figure 7 from which it is observed that about 1500kW power is produced by the WTG for most of the periods between May and November. The unmet electric load of the WTG-powered black start is presented in Figure 8, which shows that the system is predominantly unable to serve the start between January to April and the latter part of the year.

Table 5: Simulation results of the WTG-powerd black start

Parameters	Value
WTG Turbine Size	1.5 MW
WTG Hub Height	60m
Electricity Generated	4,434,623 kWh/yr
Unmet Electricity	101,093 kWh/yr (7.69%)
Fuel Summary	0

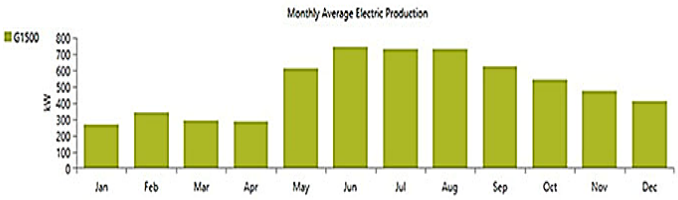

Figure 6. Monthly Average Electricity Production of WTG-Powered Black Start

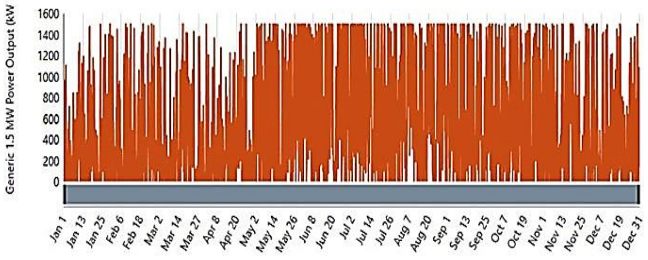

Figure 7. Daily Power Output of the 1.5MW WTG

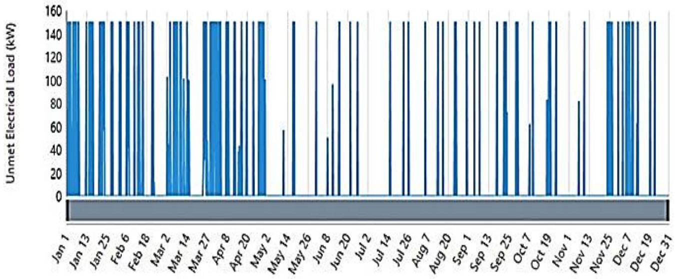

Figure 8. Daily Unmet Electrical Load

4.2 Simulation results for DG-powered black start

The simulation results of the DG-powered black start are presented in Table 6. The table 6 shows that the DG generated 1,314,000 kWh/yr of electricity with a 0% unmet electrical load, which is desirable given the significance of the load this system is powered by. However, it is noteworthy that this system poses a great environmental threat with 969,129kg/yr of CO_2, 6,109kg/yr of CO, 267kg/yr of UH, 37kg/yr of PM, 2373kg/yr of SO_2, and 5739kg/yr of NO released into the atmosphere from 370,234 L/yr of diesel fuel, as presented in Table 8. These emissions are high and must be reduced to enhance a cleaner environment for human beings and aquatic lives. The monthly average electricity production of the DG is presented in Figure 9, illustrating that constant electricity of 150kW was produced by the DG round the year, whereas the monthly average fuel consumption of the DG is shown in Figure 10. The monthly average of about 42L/hr is consumed by the DG around the year. The daily power output by the DG is presented in Figure 11 where a constant power output of 150kW is observed. The result shows no unmet electrical load.

Table 6. Summary of emissions by the DG-powered black start

Parameters	Value
Diesel Generator Size	150 kW
Electricity Generated	1,314,000 kWh/yr
Unmet Electricity	0 kWh/yr
Fuel Summary	370,234 L/yr

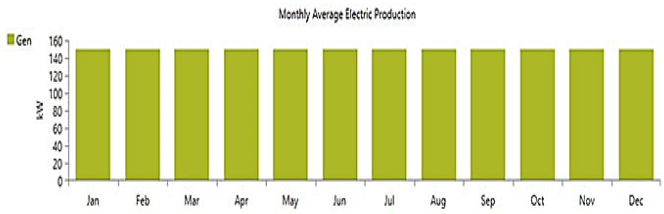

Figure 9. Monthly average electric production of DG

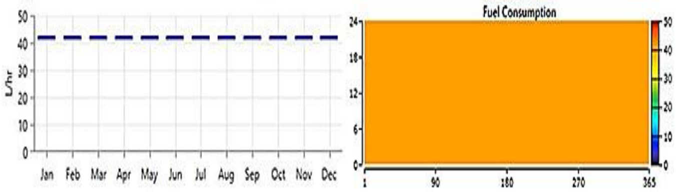

Figure 10. Monthly average fuel consumption of DG

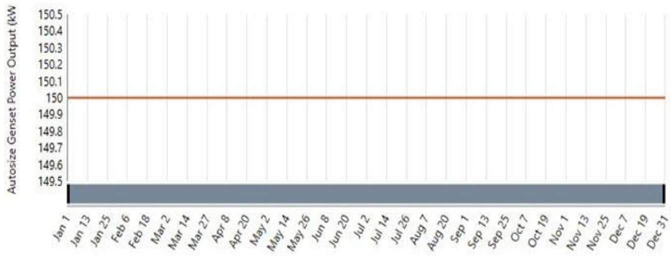

Figure 11. Daily power output of DG

4.3 Simulation results for hybrid DG-WTG-powered black start

The results of the hybrid DG-WTG-powered black start are presented in Table 7. The table shows that the 1.5MW WTG produced 4,434,632kWh/yr, which is 93.2% of the total production, while the 150kW DG produced 322,071kWh/yr, which is 6.77% of the total output. It can be inferred from this result that the WTG provides the backbone of the generation while the DG only provides ancillary support to the system. The table further presents the desired 0% system unmet electrical load with a less environmental threat in terms of emissions from 112,392 L/yr consumed by the system. The comparison of the emissions from DG and DG-WTG-powered black is presented in Table 8. It is evident that 294,058kg/yr of CO_2, 1,945kg/yr of CO, 80.9kg/yr of UH, 9.02kg/yr of PM, 720kg/yr of SO_2, and 688kg/yr of NO were released into the atmosphere by DG-WTG, which is very low compared to 969,129kg/yr, 6,109kg/yr, 267kg/yr, 37kg/yr, 2373kg/yr, and 5739kg/yr of CO_2, CO, UH, PM, SO_2, and NO, respectively, released into the atmosphere by DG powered black start. Figure 12 depicts the monthly average electric output of the DG-WTG powered system, revealing that the maximum electricity, about 800kW, was generated from June to August, with the lowest, nearly 340kW, produced in January. This indicates that the DG is only called into operation when the WTG cannot power the black start load due to wind resources variability.

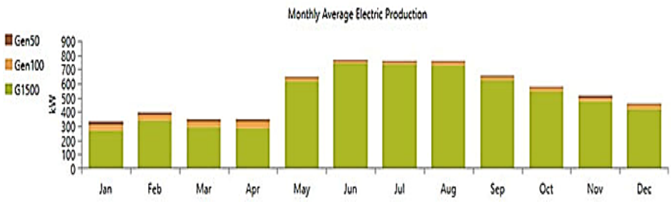

Figure 12. Monthly average electric production by the hybrid DG-WTG powered system

Table 7. Simulation results of the hybrid DG-WTG powered black start

Height (m)	Electrical Production (kWh/yr)		Unmet Electricity (kWh/yr)	Fuel Summary (L/yr)
60	100kW	265,496 (5.58%)	0 (0%)	112,392
	50kW	56,575 (1.19%)		
	1.5MW wind	4,434,632 (93.2%)		

The output powers of the 50kW DG, 100kW DG, and 1.5MW WTG are presented in Figures 13, 14, and 15, respectively. From these figures, it is observed that about 1500kW power is produced by the WTG between May and November, while that of 50kW DG and 100kW DG remains constant around the year. The percentage renewable penetration of the hybrid DG-WTG powered black start is presented in Figure 16, where it is observed that the WTG contributes largely to the total power output of the system.

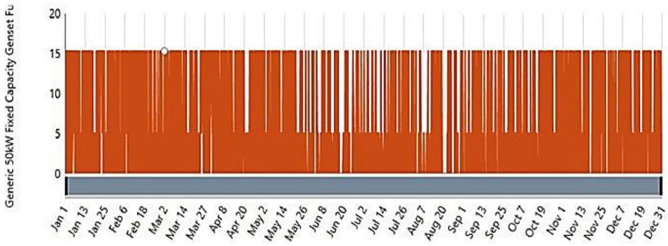

Figure 14. The 50kW fixed capacity of the hybrid DG-WTG powered black start

Table 8. Emission Summary of DG and DG-WTG

System	Height (m)	Emissions (kg/yr)					
		CO_2	CO	UH	PM	SO_2	NO
DG	-	969,129	6,109	267	37	2373	5739
DG-WTG	60	294,058	1,945	80.9	9.02	720	688

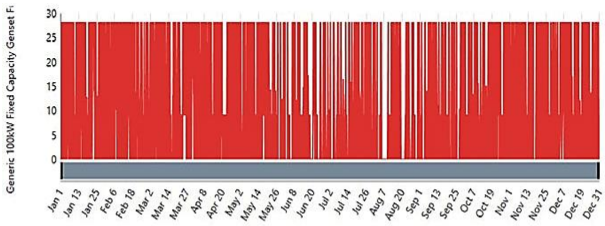

Figure 15. The 100kW fixed capacity of the hybrid DG-WTG powered black start

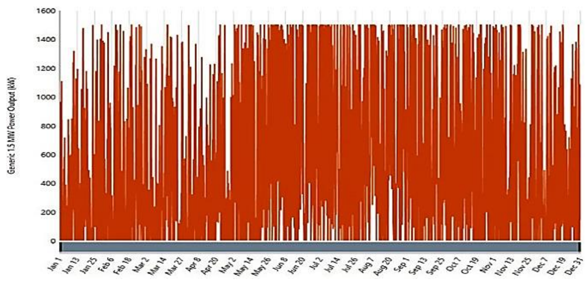

Figure 16. The 1.5MW WTG output of the hybrid DG-WTG powered black start

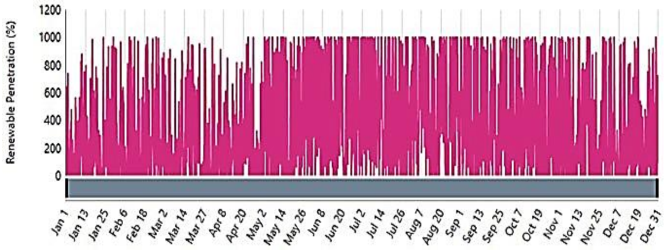

Figure 17: The percentage of renewable penetration of the hybrid DG-WTG powered black start

44.4 Sensitivity analysis results

The sensitivity analysis results of DG-WTG powered black start at varying WTG heights is presented in this section. Figure 17 shows the comparison of electrical production with the variation of WTG height for 100kW, 50kW, and 1.5MW. According to the Figure 17, the electrical production of 50kW and 100kW DGs decreases with an increase in the WTG height. This suggests that at a higher height, the WTG can produce more electrical energy, thereby reducing the energy demand from the DGs. The figure shows that the electrical production of 1.5MW WTG increases with WTG height, implying that at a greater height, there are more wind resources and, hence, WTG generates greater electrical energy. Generally, it can be inferred that while the electrical production of DGs decreases with an increase in WTG height, the electrical production of WTG increases with an increase in WTG height.

The comparison of the variation of hub height with the unmet electrical load and fuel summary of the hybrid DG-WTG powered black start is presented in Figure 18. The figure reveals that the unmet electricity of the hybrid DG-WTG powered black start decreases with an increase in the WTG height, which attests to the availability of more wind resources at a higher height, thereby resulting in reduced unmet electricity. In addition, Figure 19 shows that the fuel summary of the hybrid DG-WTG-powered black start decreases with an increase in WTG height. This shows that as a result of more energy produced by WTG at higher heights due to the availability of more wind resources, the DGs are not running at full capacity leading to a decrease in fuel summary.

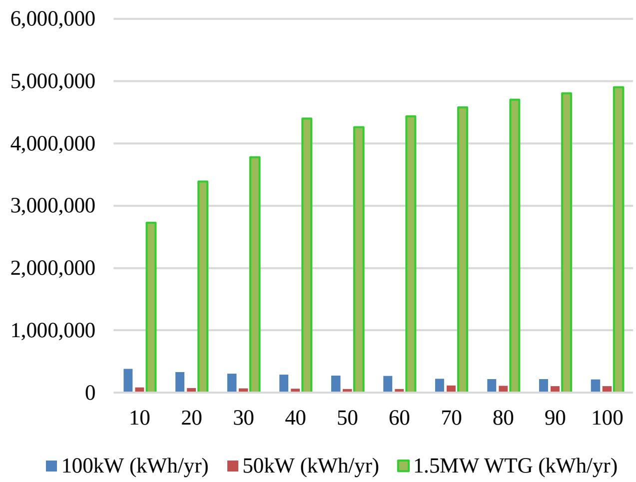

Figure 18. Comparison of electrical production of 100kW DG, 5kW DG, and 1.5MW WTG at different heights

Table 9 presents the summary of emissions by the hybrid DG-WTG powered black start at different heights from which six gases namely carbon dioxide (CO_2), carbon-monoxide (CO), unburned hydrocarbon (UH), particulate matter (PM), sulphur dioxide, SO_2, and nitrate-oxide (NO) were emitted into the environment.

Table 9 shows that a large amount of gas was released at a lower WTG height (10m), whereas less was released at the maximum WTG height (100m), which is consistent with the fuel summary stated before. 100m because greater electricity is produced with less diesel fuel at a reduced emission quantity.

Table 9. Summary of emissions by the hybrid DG-WTG-powered black start at different heights

Height (m)	Emissions (kg/yr)					
	CO_2	CO	UH	PM	SO_2	NO
10	362,953	2,431	99.9	10.6	889	564
20	314,843	2,109	86.7	9.17	771	486
30	289,987	1,942	79.8	8.45	711	446
40	274,162	1,826	75.5	7.98	672	421
50	262,537	1,729	72.3	7.64	643	402
60	253,356	1,697	69.7	7.38	621	388
70	258,088	1,702	71.0	8.00	632	648
80	253,022	1,671	69.6	7.81	602	619
90	247,811	1,637	68.2	7.64	607	602
100	242,332	1,600	66.7	7.48	594	592

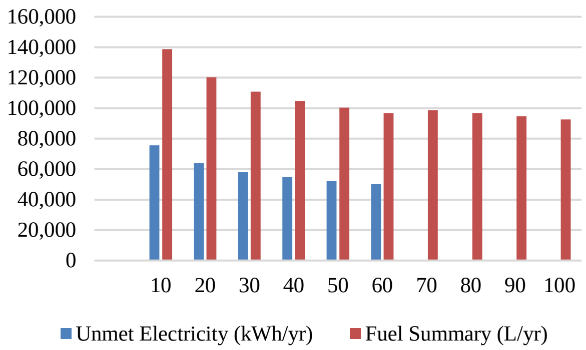

Figure 19. Comparison of unmet electricity and fuel summary with WTG height

A general study of the Table 9 shows that the higher the WTG height, the smaller the quantity of gases emitted into the environment. Finally, it can be concluded from this section that the optimal WTG height for this work is

5. CONCLUSIONS AND FUTURE DIRECTIONS

The use of renewable energy to provide the needed power for various applications is constantly on the rise. The use of wind energy is gaining acceptance due to its ability to power inductive loads. However, its high variability limits the reliability. According to the literature review conducted for this study, wind energy has mostly been employed in the generation of general electricity, healthcare, and telecommunications industry. It was further revealed that wind energy system was mostly used in the hybrid mode to improve the overall system reliability. Consequently, the possibility of harnessing the abundant offshore wind energy to power the black start load of an oil rig in place of DG was presented in this work. It was shown through HOMER Pro simulations that though the WTG provides clean energy to power the black start of the oil rig, it exhibits some unmet electrical load which necessitates the need for the hybrid DG-WTG. Furthermore, it was established that while DG had a relatively high emission profile compared to zero emissions of the WTG, the DG-WTG had a lower emission profile with no unmet electrical loads. Hence, it can be concluded from this work that the hub height of the WTG plays a significant role in the performance of the system. Moreover, the more the WTG height, the more energy produced by the WTG. Moreover, the greater the WTG height, the less the fuel summary and, hence, the less the emissions released into the atmosphere. Finally, it was demonstrated that the optimal WTG height for this work was 100m. This work opened up the possibility of harnessing the abundant offshore wind energy for offshore applications. Future studies will investigate the feasibility of harnessing the offshore wind energy for onshore applications and usage.

6. ACKNOWLEDGEMENT

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NOMENCLATURE

DG	Diesel Generators
WTG	Wind Turbine
CO_2	Carbon Dioxide
CO	Carbon Monoxide
UH	Unburn Hydrocarbon
PM	Particulate Matter
SO_2	Sulphur Dioxide
NO	Nitrae-oxide
MW	Mega Watts
PV	Photovoltaics
STEEP	Social, Technical, Economic, Environmental, and Policy
WECS	Wind Energy Conversion System
LCOE	Levelized Cost of Energy
MATLAB	Matrix Laboratory
PL	Penetration Level
PFC	Pitch Frequency Control
GAMS	General Algebraic Modeling System HOMER Hybrid Optimization of Multiple Energy Resource
GOA	Grasshopper Optimization Algorithm
PSO	Particle Swarm Optimization
CS	Cuckoo Search
CHAT	Cascaded Humidified Advanced Turbine
NPV	Net Present Value
BIPV	Building Integrated Photovoltaic
kWh	kilo Watt hour
USD	US dollar
L/kWh	Litre per kiloWatt hour
kWh/yr	kiloWatt hour per year
L/hr	Litre per hour
L/yr	Litre per year
Kg/yr	kilogram per year

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