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Article

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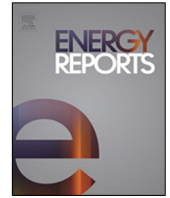
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Research paper

Optimization of energy performance with renewable energy project sizing using multiple objective functions



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HIGHLIGHTS

- A new architectural energy audit software is design using Qt development framework.
- Multiple objective functions are used for the optimization of different energy stock.
- The regression model for each method shows the important variable, considering $p > 0.05$ the independent variable is which not a key contributor to the function.
- The predicted values include lighting, cooling load, annual energy production for solar PV and wind energy projects.

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ABSTRACT

Energy demand profiling of varied stocks within the Faculty of Engineering is investigated, comprising of audit activities like the performance optimization of air-conditioners and other energy appliances. Using a newly-developed renewable energy (RE) calculator, standard energy performance methodologies, including cooling load analysis, energy audit and rating exercises, thermal comfort analysis, distributed power generation from wind turbine and solar photovoltaic module, are adopted. Based on a comprehensive energy audit exercise, areas of energy saving potential are observed. Also, the minimum energy performance standard of energy appliances for maximum human thermal comfort is assessed. Towards the possibility of integrating different sources of renewable energy into the Faculty of Engineering for alternative power supply, an open source widget toolkit based on Qt development environment is used to design a new renewable energy (RE) calculator, known as **EnergixPlus**. A multiple objective function approach is proposed to properly evaluate all the key performance indicators simultaneously, thereby unveiling the existing gaps and identifying possible synergies and strategies in the estimation of the building life cycle. The regression of the data obtained from the segregated optimization approach shows a strong linear relationship (i.e., for the appliance audit, the coefficient of determination is approximately 84%; while the correlation coefficient is 0.92). It is anticipated that the application of the proposed methodologies to the multi-scale and multi-objective nature of the challenges in the optimization of energy demand in the built environment will address the uncertainties in previous modelling strategies.

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1. Introduction

Increasing energy demand profile is fast outpacing the available supply in the sub-Saharan region, including the existing reality in most of the developing nations of Africa. Notwithstanding, the role of energy as the major driver of every nation's

economy cannot be over emphasized. For example, Nigeria has an installed electricity capacity of about 12,500 MW, while the country's available capacity of about 4500 MW (due to weak evacuation capacity of the nation's transmission lines [Olawoyin, 2017](#)) is barely enough to meet the needs of a population of more than 170 million. This shortage in electricity supply has led to widespread self-generation of power in the commercial, industrial and residential sectors. Many individuals and businesses have opted for diesel generators in order to compensate for the shortage in energy supply ([Idemudia and Nordstrom, 2016](#)). The mounting gap between electricity generation and demand side of power would not be abridged, even in the near future,

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Nomenclature

A	Open glass area m^2
CLF	Cooling load factor
C_p	Power constant of the wind turbine
EC	Energy consumed daily [kWh]
ES	Total Energy Saving [kWh]
ET	Effective temperature index
f_{temp}	Temperature de-rating factor, dimensionless
f_{man}	de-rating factor for manufacturing tolerance, dimensionless
f_{dirt}	de-rating factor for dirt, dimensionless
LCC	Life cycle cost [€]
N	Number of occupants.
OH	Total operating hours of operation [Hour]
per	Power constant of the wind [J/kg]
U	Number of unit lamps
W	Power consumed by lamp [kW]
β	Blade incline angle
ρ	Air density [kg/m^3]
l	Rotor radius [m]
v	Wind speed [m/s]
$\eta_{inverter}$	Inverter efficiency
$\eta_{DCcables}$	DC cable efficiency
$\eta_{ACcables}$	AC Cable efficiency
λ	Blade speed ratio

unless necessary alternative measures are taken. Therefore, it is projected that commercial facilities, like the University of Lagos, must effectively utilize the amount of energy it receives from the grid. Also, the University is seeking other means of meeting its energy demand, in order to maintain its leading role in Nigeria's higher institutions of learning. Energy profiling, in existing buildings, involves an analysis of the actual or predicted energy performance of the buildings (O'Donnell et al., 2004). It is used to analyse the energy demand of the buildings and suggests the measures that building managers, owners or occupants can use to improve energy efficiency in the running of those buildings on a daily basis. For some buildings, a quick option is to seek alternative or additional means of meeting its energy demand.

In most developed countries, government invests significantly in the promotion of sustainable power generation through the most conservative measures. By putting certain standards in place, energy consuming appliances are regulated in order to reduce the use of low energy-efficient appliances, leading to a reduction in energy demand. In some other areas, the development of solar photovoltaic energy systems and wind turbine systems are recommended. Solar energy provides a compelling solution for all societies to meet their needs for clean and abundant sources of energy in the future, especially in the tropics with abundant solar irradiation. Moreover, solar PV systems can operate with little or no operating cost, fuel costs are non-existent, and they require minimal maintenance. Hussam (2004) designed a solar photovoltaic system for a school and health centre in Petit-Anse, Haiti. The system was meant to power fluorescent and incandescent bulbs, and a cool box for medical refrigeration at the health centre. Eshita et al. (2010) designed a grid connected solar PV system for the BRAC University campus. In 2011, Barman (2011) carried out the design and feasibility study of photovoltaic systems in Kenya. The project involved presenting one backup

energy system for a grid connected facility (based on existing but non-operational solar panels) and a cost-effective autonomous energy system with a good reliability, for an upcoming school. An investigation on the feasibility of attaching reflectors to solar panels was also carried out. Kumi and Brew-Hammond (2013) developed a standard procedure for the design of large-scale institutional grid-connected solar PV systems using the roofs of buildings and car parks. The standard procedure developed was validated in the design of a 1-MW grid-connected solar PV system for Kwame Nkrumah University of Science and Technology (KNUST), Ghana. They also simulated the performance of the 1-MW grid-connected solar PV system over the guaranteed life of the system using RETScreen Clean Energy Project Analysis software, designed by the Natural Resources Canada. However, a detailed energy audit of facilities within a system often precede the design of a reliable renewable energy project.

Energy audit exercises in educational institutions, which have resulted in several recommendations, have been conducted in different tropic regions. Alajmi (2012) conducted an audit of an educational building in a hot climate State of Kuwait. Although the heating, ventilation, and air conditioning (HVAC) system consumes the most energy within that building (87%), a similar energy audit technique was used where they gathered the information regarding its initial usage and compared it with the potential energy reduction that can be made. It is observed that 6.5% of energy can be saved from the non-retrofitting recommendations, which are mainly changes in the schedule of the lighting and equipment usages. A change in the type of lighting has been observed to save a further 2.3% of their energy usage. Ultimately, 52% of energy can be saved if all of the recommendations are implemented, including energy conservation opportunities that require additional costs. Dall'O and Sarto (2013) conducted a study on 49 school complexes, consisting of 77 buildings for various usages. Energy savings of 15%, 67%, and 81% were respectively recommended as a possibility from the implementation of these energy conservation measures.

Previous methods of minimizing energy usage and optimal energy conservation measures in schools from different climates have singular objective function among different energy systems, such as heating, ventilation, and air-conditioning (Dall'O et al., 2013; Roslizar et al., 2014; Bernardo and Oliveira, 2018). Butala and Novak (1999) conducted an energy audit for 24 schools in Slovenia that targets heat losses from air and water heating systems. The study revealed the heat losses of about 89% in the school buildings, being higher than the recommended values. In another study conducted in high schools from central Italy, Desideri and Proietti (2002) showed that there are potential energy savings of 46% when implementing some energy conservation measures. Also, Perez and Capeluto (2009) conducted a study for school buildings in hot-humid climates, where simulation techniques were used to identify the potential energy savings; while focussing on the thermal energy conservation measures. A high-performance design for school buildings shows that there is a potential energy consumption reduction of more than 50%.

The prevailing optimization strategies aim at transforming multi-objective problems into a single-objective challenge, through a weighted compound of several objective functions (Diakaki et al., 2008). Whereas, alternative approaches, like *physical programming*, have been preferred to linear weighting of objective functions, through the use of conditions and non-linear mathematical relations and constraints. Population-based search methods, based on populations of coexisting solutions, pursue different objectives in parallel, so as to define the Pareto non-dominated solutions without requiring an explicit weighting of objective functions. Optimization of the building involves multiple criteria and the goal is to find a single solution that minimizes

the combined criteria or objectives (i.e., wind power, annual energy, cooling load, and life cycle costs). Wright et al. (2002) optimized the building thermal comfort by using the predicted mean vote (PMV) index. While energy consumption may include total facility energy use, subsystem energy use, peak demand, and seasonal or annual consumption, life cycle cost considers the costs of manufacturing and disposal of different components or materials in the building (Djuric et al., 2007). Energy consumption. Kolokotsa et al. (2009) reviewed decision methodologies for energy efficiency in buildings and, as a result of this study, specified that it is possible to make evaluations in the following six different areas, including (a) energy-related: basic energy consumption, heating-cooling load, and electricity consumption; (b) cost-related: initial investment cost, direct cost, net present value, and life cycle cost; (c) environment-related: annual emissions, global warming, and lifelong environmental potential; (d) comfort-related: internal ambient temperature and humidity, CO₂(equivalent) rate, ventilation rate, and sunlight and noise levels; (e) miscellaneous: construction time and safety.

Diakaki et al. (2008) developed a multi-objective optimization model by considering energy consumption and initial investment cost. In their work, window type, insulation material, and wall thickness were used as decision variables. Furthermore, they improved the model and added energy systems and heat layers to the model, using energy consumption, initial investment cost, and CO₂(equivalent) emissions in the objective function. Juan et al. (2009) developed a genetic algorithm-based decision support system and researched the balance of cost and quality in home renovations. Chantrelle et al. (2011) developed a software with an interface that employed the genetic algorithm for the renovation of buildings and contained energy consumption, thermal comfort, cost, and environmental impact. Hamdy et al. (2011) developed a three stage multi-objective optimization model based on simulation, seeking to minimize the cost and environmental effects of an air conditioning system and a house. Fesanghary et al. (2012) used life cycle cost and CO₂(equivalent) emissions in the objective function and reached a solution with the harmony search algorithm. Asadi et al. (2012) used energy saving maximization and minimization of renovation cost as the objective function in their study. Evins (2013) reviewed computational optimization methods used in building design and, as a result of the study, demonstrated that optimization methods, especially the use of multi-objective optimization methods, had increased noticeably. In addition, the study found that the most widely used method was the genetic algorithm, and that energy consumption and the cost of initial investment were mostly included in the objective function. Malatji et al. (2013) studied the minimization of the payback period and the maximization of energy saving by using the genetic algorithm with a sensitivity analysis. Nguyen et al. (2014) explored studies conducted that were related to building performance analysis in detail, and they specified that the biggest challenges experienced in simulation-based optimization studies used in building design were the complexity of problems, calculation difficulties, and parameter uncertainties. Karmellos et al. (2015) developed a multi-objective non-linear model to increase energy efficiency in new and existing buildings. They chose the minimization of energy consumption and cost of initial investment as the objective function. They also developed software for the solution of this problem and used it in two different case studies.

The energy demand profiling challenges within the University of Lagos campus and the country at large, especially the direct access to open source tool for a detailed development of the balance between local energy demand and the integration of alternative sources of power, have necessitated the ongoing investigation. Using multiple objective optimization techniques, the study is

aimed at developing a renewable energy (RE) calculator that will be capable of analysing the building energy demand through the identification of heavy energy consuming appliances. Also, the developed tool (**EnergHxPlus 1.0**) aimed at establishing the minimum energy performance standards of energy consuming appliances in different types of buildings. Consequently, it is anticipated that the outcome of the investigation will recommend energy-saving measures that can be used in order to improve the energy efficiency of these buildings on a daily basis, including (a) energy audit exercise, (b) sizing and integration of solar panels as an alternative source of energy, and (c) the integration of different software methods (i.e., **SunCalc 1.0**, and **AirCalc 1.0** in **EnergHxPlus 1.0** Ogedengbe et al., 2017), towards the design and development of renewable power generation and commercial energy efficiency technologies within the University. Therefore, the next section of this paper (i.e., Section 2) details the design architecture of **EnergHxPlus 1.0** and the adopted system optimization techniques; while Section 3 provides the observed results of the predicted models and the discussion on the performances of the proposed optimization techniques.

2. Design architecture and optimization

2.1. Design architecture

Fig. 1 presents the layout of the Faculty of Engineering, University of Lagos. The proposed design methodology of the RE calculator (released as **EnergHxPlus 1.0**) for the audit of the Faculty of Engineering, University of Lagos, is capable of data collection, data verification, and deploing of real time calculation of energy consumption. Fig. 2 shows the four layers of the software's design architecture, including the data layer, the algorithms and software layer, the method layer, and the output layer. The data layer includes the weather data, the benchmark data, the GIS, the building data (utility data etc.). These data represent the inputs into the software; and enable the identification of the areas of energy wastage that create energy conservation measures (ECMs), through a guided support of the backend by the constituting methods. The algorithm and software layer are built on Qt software and python API which enables the development of the GUI framework and the processing of the specific input towards solving a problem. The method architecture shows the various theoretical formulae and techniques used in approaching results, such as area method for solar PV sizing. The output layer constitutes different results, including the energy efficiency ratings of the audited energy stocks, and the recommended energy conservation measures, through the platform for post-processing of the results for potential applications, including the energy benchmarking comparison, energy conservation measures such as energy retrofit, ratings and certifications, as well as the performance visualization. The flat-roofed Engineering Lecture Theatre (ELT), which is located at the central location within the Faculty plan (see Fig. 3), is proposed as the installation site for the integration of the solar photovoltaic project (see in the inset at the right corner of the map). Apart from the flat roofed ELT at the centre of the space, all other buildings appear to be solar-ready built with arrays of about 22-degree flipped-wings.

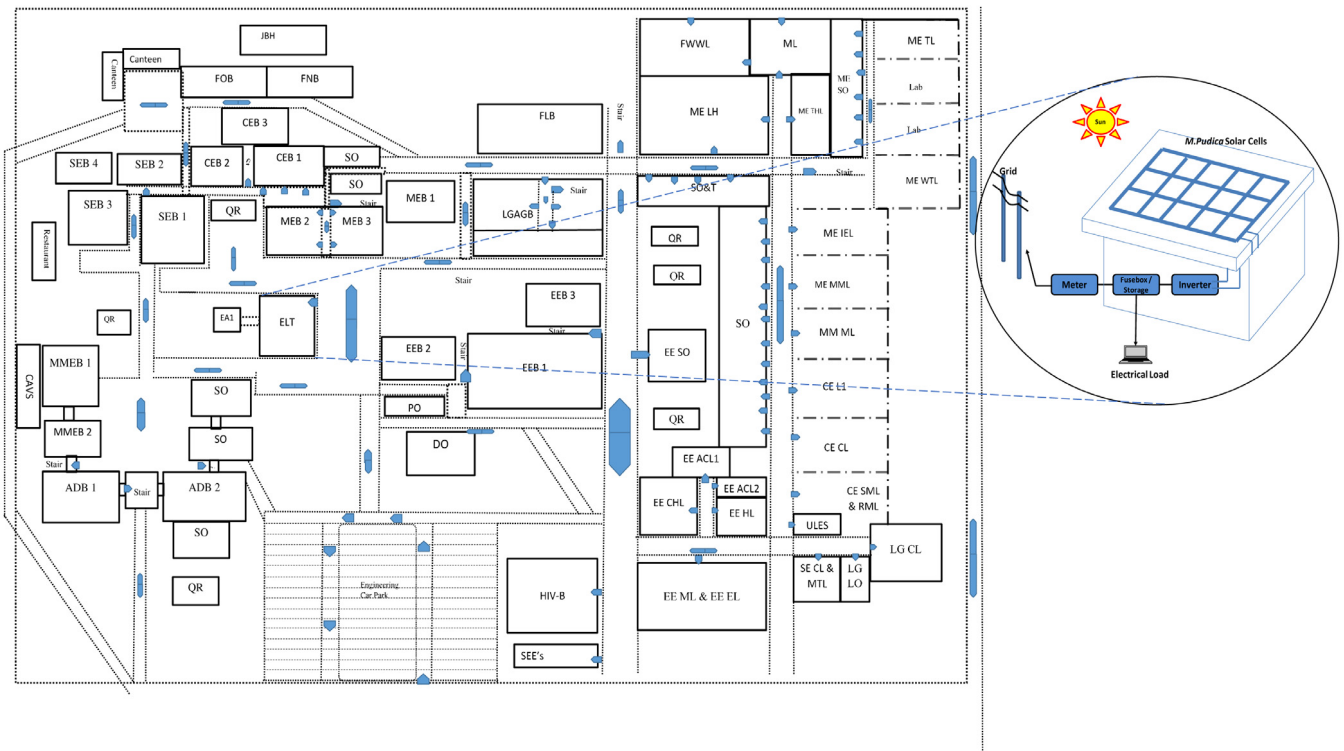


Fig. 1. Layout of the Faculty of Engineering with the proposed integration of solar energy technology.

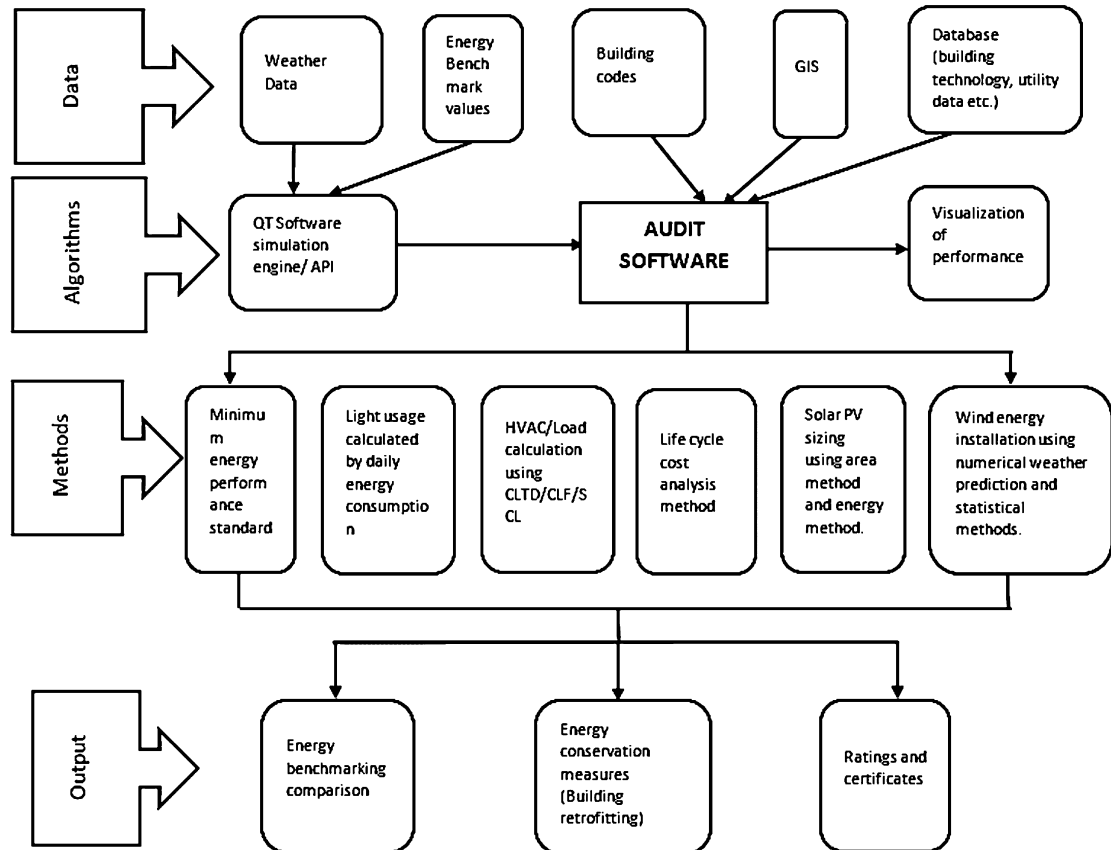


Fig. 2. Proposed design architecture.

2.2. System optimization

The global optimization technique in the Mathematica built-in library enables the use of NMinimize and NMaximize functions. The constraints to NMaximize or NMinimize allow linear programming with logical combination of inequalities. Otherwise, the use of the Nelder–Mead method is recommended.

2.2.1. Lighting

Lighting represents one of the energy consuming fittings in residential buildings, commercial buildings and workspaces that requires system optimization. Eq. (1) provides the life cycle cost of using lighting as the dependent variable of the objective function for optimization.

Objective function: Optimize

$$LCC = 365 \times Op \times U(P_1 - P_2) \left(\frac{P_1}{2P_1 - P_2} \right)^{\frac{365P_1}{P_1 - P_2}} + (Op \times U \times P_2) \quad (1)$$

where;

LCC - Life cycle cost

Op - Operating hours

U - Number of units

P_1 - Rated power of light

P_2 - Retrofit power of light

Constrain: $P_1 - P_2 > 0, P_1 > 0, P_2 > 0$

2.2.2. Cooling load

Houghten et al. (1923) introduced the effective temperature index (ET) which was originally established to provide a method of determining the relative effects of air temperature and humidity on thermal comfort (Houghten and Yagloglou, 1923). Gagge et al. (1971) defined a new effective temperature which was based on the temperature of an environment at 50% relative humidity. This new ET results in the same total heat loss from the skin as in the actual environment. ASHRAE defines the standard effective temperature (SET) as the equivalent air temperature of an isothermal environment at 50% relative humidity in which a subject, while wearing clothing standardized for the activity concerned, has the same heat stress (skin temperature) and thermoregulatory strain (skin wettedness) as in the actual environment. ASHRAE also states that the SET is an environmental index that combines temperature and humidity, so two environments with the same effective temperature should evoke the same thermal response, even though they have different temperatures and humidity at the same air velocities. Total skin heat loss is used as a measure of the thermal environment; two combinations of parameters that yield the same total heat loss for a given set of body conditions (i.e., Skin temperature and wettedness) are considered to be approximately equivalent. The fully expanded skin heat loss equation, showing each parameter that must be known or specified, as shown in Table 1 (ASHRAE, 2013):

However, the optimization of the cooling load (CL) depends on different independent variables or performance factors including the solar cooling factor (SCL) and the cooling load temperature difference (CLTD). The CLTD/ SCL method uses predetermined set of data from the audited energy stocks in order to simplify the process of approximating the cooling load. Therefore, the different variables in the optimization technique include the building material of the envelope, thicknesses of the building materials, day of the year, time of day, orientation of the surface, and wall face orientation, e.t.c (see Eq. (2))

Table 1

Standard effective temperatures.

Standard effective temperature	Sensation
>37.5	Very hot, great discomfort
37.5–34.5	Hot, very unacceptable
34.5–30	Warm, uncomfortable, unacceptable
30–25.6	Slightly warm, slightly unacceptable
25.6–22.2	Comfortable, acceptable
22.2–17.5	Slightly cool, slightly unacceptable
17.5–14.5	Cool, unacceptable
14.5–10	Cold, very unacceptable

Objective function: Optimize

$$CL = \frac{121a_c \times dT \times V}{6} + \frac{301a_c \times dW \times V}{6} + 130n_{\text{people}} + (1210a_r \times dT \times n_{\text{people}}) + (3010a_r \times dW \times n_{\text{people}}) + SC_{\text{glass}}(A_{\text{ge}}SCL_e + A_{\text{gn}}SCL_n + A_{\text{gs}}SCL_s + A_{\text{gw}}SCL_w) + (A_{\text{ge}} + A_{\text{gn}} + A_{\text{gs}} + A_{\text{gw}})CLTD_{\text{glass}}U_{\text{glass}} + A_{\text{roof}}CLTD_{\text{roof}}U_{\text{roof}} + (A_{\text{we}}CLTD_{\text{we}} + A_{\text{wn}}CLTD_{\text{wn}} + A_{\text{ws}}CLTD_{\text{ws}} + A_{\text{ww}}CLTD_{\text{ww}})U_{\text{walls}} \quad (2)$$

where

a_c = Air change

dT = difference in outdoor temp and indoor temp

V = Volume of Space

dW = difference in indoor humidity and outdoor humidity

a_r = Air Rate Flow

n_{people} = Maximum Number of Person in room

SC_{glass} = SC of Glass

$CLTD_{\text{glass}}$ = CLTD of glass

$CLTD_{\text{roof}}$ = CLTD of roof

$CLTD_{\text{wn}}$ = CLTD of Northern wall

$CLTD_{\text{we}}$ = CLTD of Eastern wal

$CLTD_{\text{ws}}$ = CLTD of Southern wal

$CLTD_{\text{ww}}$ = CLTD of Western wall

U_{glass} = U of glass

U_{roof} = U of roof

U_{walls} = U of Walls

SCL_n = SCL of Northern Glass

SCL_e = SCL of Eastern Glass

SCL_s = SCL of Southern Glass

SCL_w = SCL of Western Glass

A_{gn} = Area of Northern glass of the room

A_{ge} = Area of Eastern glass of the room

A_{gs} = Area of Southern glass of the room

A_{gw} = Area of Western glass of the room

A_{wn} = Area of Northern Wall of the room

A_{we} = Area of Eastern Wall of the room

A_{ws} = Area of Southern Wall of the room

A_{ww} = Area of Western Wall of the room

A_{roof} = Area of Roof

Constrain:

$$A_{\text{gn}}, A_{\text{ge}}, A_{\text{gs}}, A_{\text{gw}}, A_{\text{wn}}, A_{\text{we}}, A_{\text{ws}}, A_{\text{ww}}, A_{\text{roof}} > 0$$

2.2.3. Solar PV

The steps for the design and development of photovoltaic systems on the roofs of the Faculty of Engineering buildings include the following three (3) sections: site analysis, design and sizing of PV systems, and development of software to aid system integration. Site analysis involved obtaining the physical

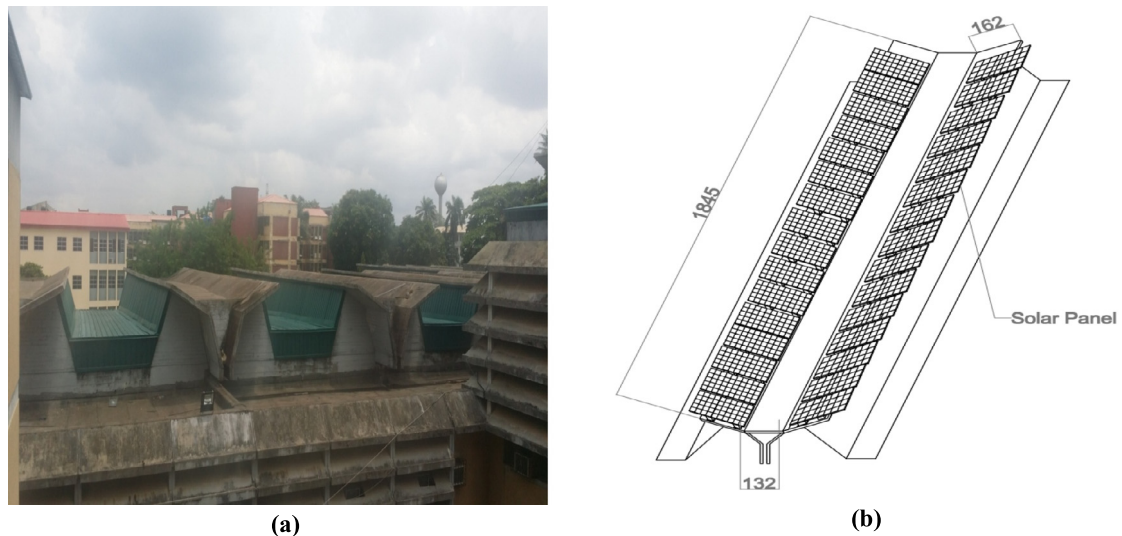


Fig. 3. Proposed solar PV installation site, showing (a) the solar-ready roof of buildings at the Faculty of Engineering with wings; and (b) the dimension of one of the wings.

layout of the roof space suitable for panel placement, decision on what type of system (grid- or off-grid) would be suitable, and relevant climatic data needed for energy calculations. The design and sizing of solar PV systems (inverter inclusive) are carried out based on relevant data collated from the site analysis. The Area Method is adopted for the PV design and sizing due to the limited space available for PV installation. The total energy output is obtained through the following steps:

- (1) Selection of a specific solar module for installation;
- (2) Collection of the dimensions and area of the solar module;
- (3) Calculation of the number of PV modules to be installed by dividing the total area available for installation by the area of the selected PV module; and
- (4) Calculation of the total energy output of PV module by multiplying the Number of PV modules x System Efficiency x PV power rating x Peak Sun-Hours.

The Peak Sun-Hour (PSH) used in the design is the minimum daily peak sun-hours throughout the year. The PSH enables the calculation of the minimum possible solar output throughout the year, i.e., it serves as a lower limit for the design. However, the PSH as used in the design is the minimum daily peak sun-hours of the worst month of solar irradiation. The main parameters needed for the inverter sizing include (a) the power rating of the inverter; (b) the inverter efficiency; (c) the output power of the inverter; and (d) the input power to the inverter. Therefore, Eq. (3) provides the objective function for the optimization of the annual energy production from the solar PV project.

Objective function: Optimize

$$\text{EnergyAnnual} = n_{\text{wings}} \times \frac{28.29}{\text{area}_{\text{mod}}} \times P_{\text{actual}} \times 0.72 \quad (3)$$

where

n_{wings} = number of wings on the roof of the target buildings in the Faculty of Engineering (see Fig. 3)

P_{actual} = actual power produced

area_{mod} = area of the module

Constraints: $\text{EnergyAnnual}, \text{eff} > 0.2, n_{\text{wings}} > 0, \text{area}_{\text{mod}} > 0, P_{\text{modulated}} > 0, T_{\text{modcoeff}} < 1$

2.2.4. Wind turbine

The energy harvest performance of a wind turbine is dependent on different variables, including the density of the air,

the diameter of the turbine blades, the local wind speed, and a dynamic power constant. The need for optimized energy harvest within the campus is driven the design of a vertical-axis wind turbine blades, using the combination of experimental technique in a subsonic wind tunnel and the development of numerical tool (Obiji et al., 2017). Eq. (4) provides the objective function for the optimization of dependent variable for the predicted power in the wind.

Objective function: Optimize

$$P_{\text{wind}} = \frac{\text{per} \times \rho \times \pi \times l^2 \times v^3}{2} \quad (4)$$

where

v – speed of wind

per – the power constant of the wind

ρ – air density

l – rotor radius

Constraints: $l > 0$

2.3. Regression analysis and modelling

Regression models for four methods were developed using MS Excel. This tool was used in determining the multiple regression for the wind power, annual energy, cooling load, and life cycle costs. The data used were generated using PyCharm. The process in generating data is shown in Fig. 4:

3. Results and discussion

Having performed the minimum energy performance standard, and the sizing of the proposed renewable energy power alternative, the results obtained from **EnerghxPlus** provide useful feasibility report for possible investment towards project implementation. Fig. 5 shows the daily energy consumption pattern in all the departments within the Faculty of Engineering.

The results obtained shows that total daily energy consumption of the Faculty of Engineering is 8690 kWh. The department with highest energy consumption is observed to be Mechanical Engineering; with an average daily energy demand of 2380 kWh (27%). While the department with the least energy demand is Surveying & Geoinformatics and other general offices within the Faculty of Engineering, with an average daily energy consumption of 363 kWh (4%). Based on these results, it is recommended

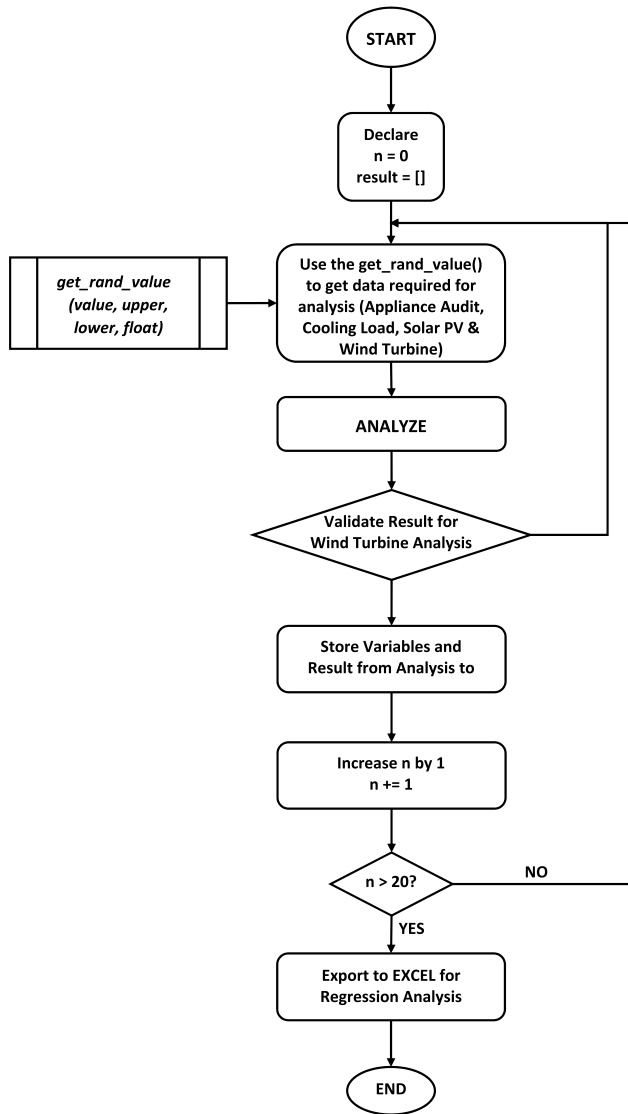


Fig. 4. Flowchart of data generating code for regression analysis.

that solar photovoltaic systems should be installed to meet the energy demands of the Faculty of Engineering. Table 2 shows

Table 2
Specifications of the PV system and inverter sizing for the Faculty of Engineering.

PV model: Tabuchi electric EPW-T250P6-US	
Inverter model: Eclipsal NRG72 310M	
Installed capacity (kWp)	409.2
Specific energy (kWh per kWp)	1252.27
Performance ratio	0.723
Minimum number of pv modules per inverter	15
Maximum number of PV modules per inverter	22
Maximum number of PV modules per wing	15
Minimum daily energy output (MWh)	1.14
Annual energy yield (MWh)	512

the specification of the solar PV system and the inverter for the Faculty of Engineering, University of Lagos.

The results of the optimization study are segregated (based on the built-in symbols of Mathematica Wolfram, 2019) into four different profiles, including lighting, cooling load, solar PV, and wind turbine. Given that $Op = 10$ and $U = 6$ for the lighting system at the Faculty of Engineering, the optimization function becomes

$$NMinimize[\{60(365(P_1 - P_2) \left(\frac{P_1}{2P_1 - P_2} \right)^{\frac{365P_1}{P_1 - P_2}} + P_2), \\ P_1 - P_2 > 1, P_1 > 0, P_2 > 0\}, \{P_1, P_2\}]$$

with a plot function of

$$Plot3D[60(365(P_1 - P_2) \left(\frac{P_1}{2P_1 - P_2} \right)^{\frac{365P_1}{P_1 - P_2}} + P_2), \\ \{P_1, 0, 9\}, \{P_2, 0, 9\}]$$

The predicted results underscore a linear relationship between P_2 and LCC given other constant values. It implies that, given the minimum value for P_2 is highly dependent on the constraint, the minimal value for P_2 approximates 60 and a minimum LCC of 3600.

For the cooling load, Eq. (5) gives the optimization function

$$Q = 96413. + 2671.6150000000002V + 55.7632A_{ge} \\ + 55.7632A_{gn} + 47.3582A_{gs} \\ + 80.6174A_{gw} + 80.68211A_{roof} + 10.77A_{we} + 10.77A_{wn} \\ + 153.293A_{ws} \\ + 153.293A_{ww} \quad (5)$$

subject to

$$NMinimize[\{Q, A_{ge} > 0, A_{gn} > 0, A_{gs} > 0, A_{gw} > 0, A_{roof} > 0,$$

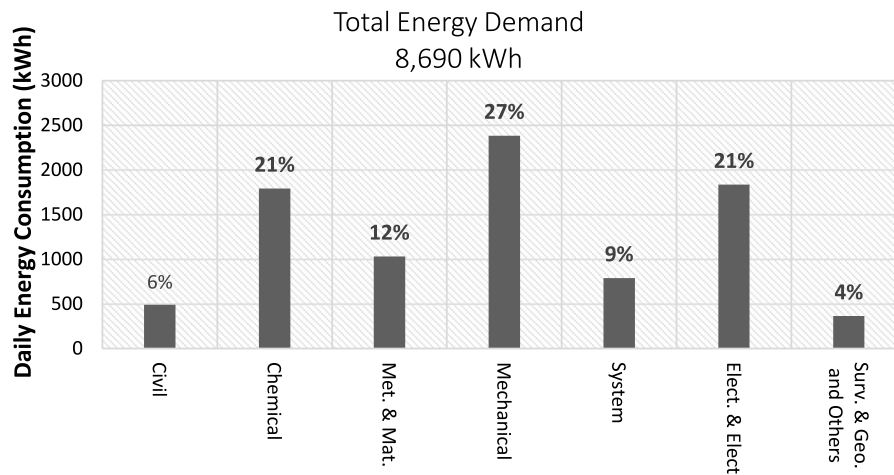


Fig. 5. Daily energy consumption in the Faculty of Engineering, University of Lagos.

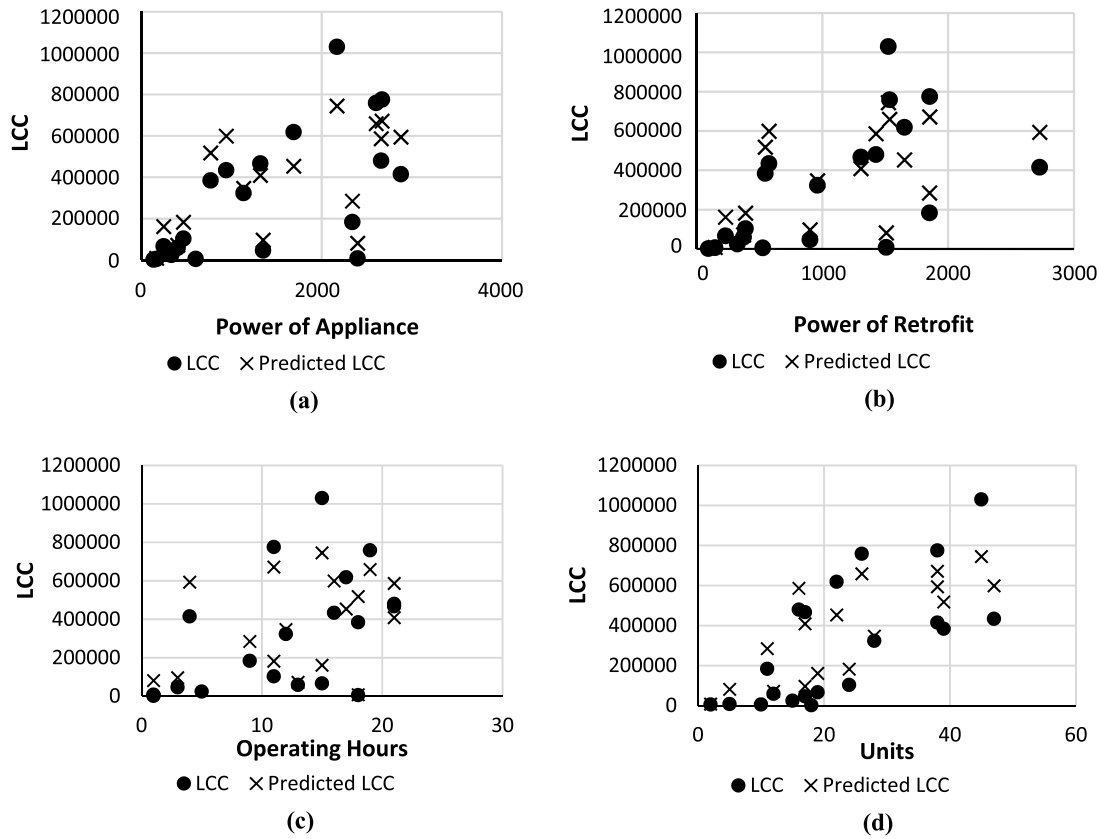


Fig. 6. Correlation between the actual LCC and the predicted LCC, based on the (a) power of the lighting appliance; (b) power of retrofit; (c) operating hours; and (d) number of units.

$$\begin{aligned}
 &A_{we} > 0, A_{ws} > 0, A_{wn} > 0, A_{ww} \\
 &> 0 \}, \{A_{ge}, A_{gn}, A_{gs}, A_{gw}, A_{roof}, A_{we}, A_{ws}, A_{wn}, A_{ww}\} \\
 &\{1180447.5024, \{A_{ge} \rightarrow 0., A_{gn} \rightarrow 0., A_{gs} \rightarrow 0., A_{gw} \rightarrow 0., \\
 &A_{roof} \rightarrow 0., A_{we} \rightarrow 0., A_{ws} \rightarrow 0., A_{wn} \rightarrow 0., A_{ww} \\
 &\rightarrow 0.\}\}
 \end{aligned}$$

As expected, a linear relationship between cooling load, Q , and the volume of space, V , is observed. Comparison of the correlation coefficients for the different orientations of the area of the walls and windows shows that the thermal load on the southern and western walls are greater than the demand from the other walls. Based on the output of the appliance audit, the minimized function of the areas is given value the lower bound constraint. And since the lower bound is set to zero, the values are minimized to zero.

Eq. (6) gives the actual power produced from the solar PV.

$$P_{actual} = P_{modulated} \times f_{temp} \times f_{dirt} \times eff_{ac} \times eff_{dc} \times eff_{inverter} \quad (6)$$

subject to

$$f_{temp} = 35 \times \frac{T_{modcoeff}}{100}$$

$$f_{man} = 0.95$$

$$f_{dirt} = 0.95$$

$$eff_{ac} = 0.99$$

$$eff_{dc} = 0.97$$

$$eff_{inverter} = \frac{eff}{100}$$

While Eq. (7) gives the predicted annual production of electricity from the solar PV project

$$EnergyAnnual = n_{wings} \times \frac{28.29}{area_{mod}} \times P_{actual} \times 0.72 \quad (7)$$

resulting in an optimized function as:

$$\begin{aligned}
 &NMinimize[\{EnergyAnnual, eff > 0.2, n_{wings} > 0, area_{mod} > 0, \\
 &P_{modulated} > 0, T_{modcoeff} \\
 &< 1\}, \{n_{wings}, area_{mod}, P_{modulated}, T_{modcoeff}, eff\}]
 \end{aligned}$$

and

$$\begin{aligned}
 &\{-3.312801107988637 \\
 &\times 10^{10}, \{eff \rightarrow 1.1044483104240013, area_{mod} \\
 &\rightarrow 1.199212894829227 \times 10^{-9}, n_{wings} \\
 &\rightarrow 5.61227739172741, P_{modulated} \rightarrow 12.745036575173138, \\
 &T_{modcoeff} \\
 &\rightarrow -7.732181156656196\}
 \end{aligned}$$

The result of the optimization of the solar PV function considering four variables, including the number of wings, n_{wings} , the area of the module, $area_{mod}$, the rated power of the module, $P_{modulated}$, the temperature, $T_{modcoeff}$. The $T_{modcoeff}$ is observed to be negative, which corresponds to the standard values.

For the wind turbine, the predicted wind power is given by Eq. (8).

$$P_{wind} = \frac{0.541 \times \rho \times \pi \times l^2 \times v^3}{2} \quad (8)$$

subject to

$$NMinimize[\{P_{wind}, l > 20\}, \{l\}]$$

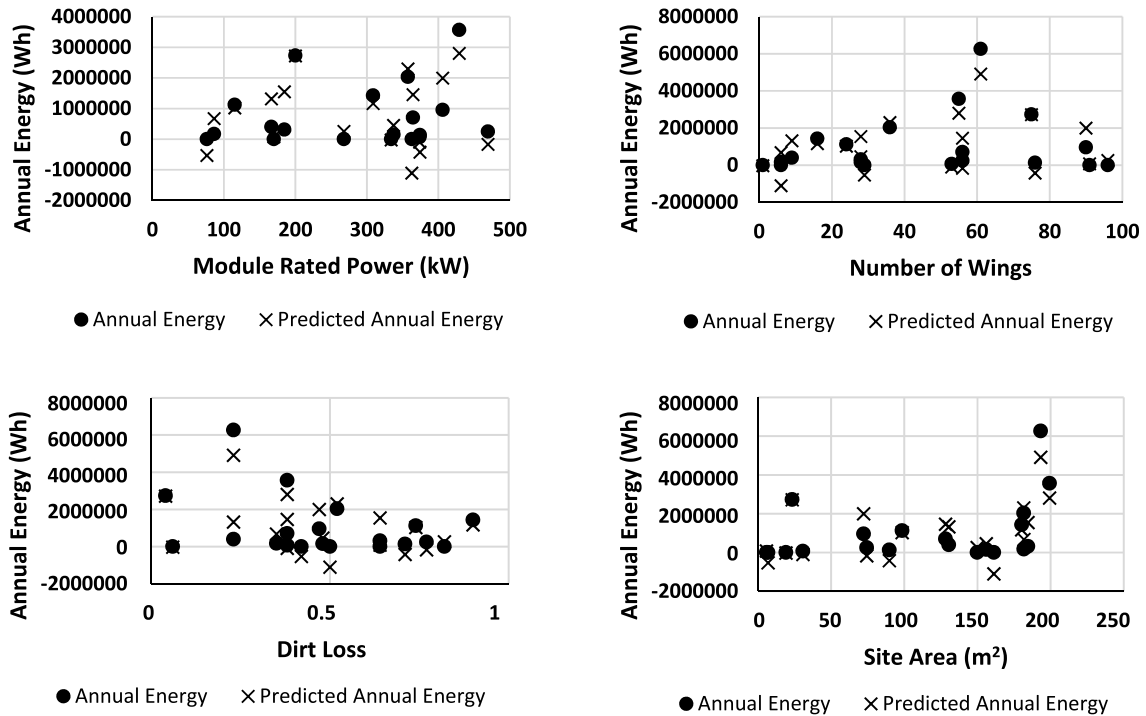


Fig. 7. Predicted annual energy from the solar PV project with different performance variables.

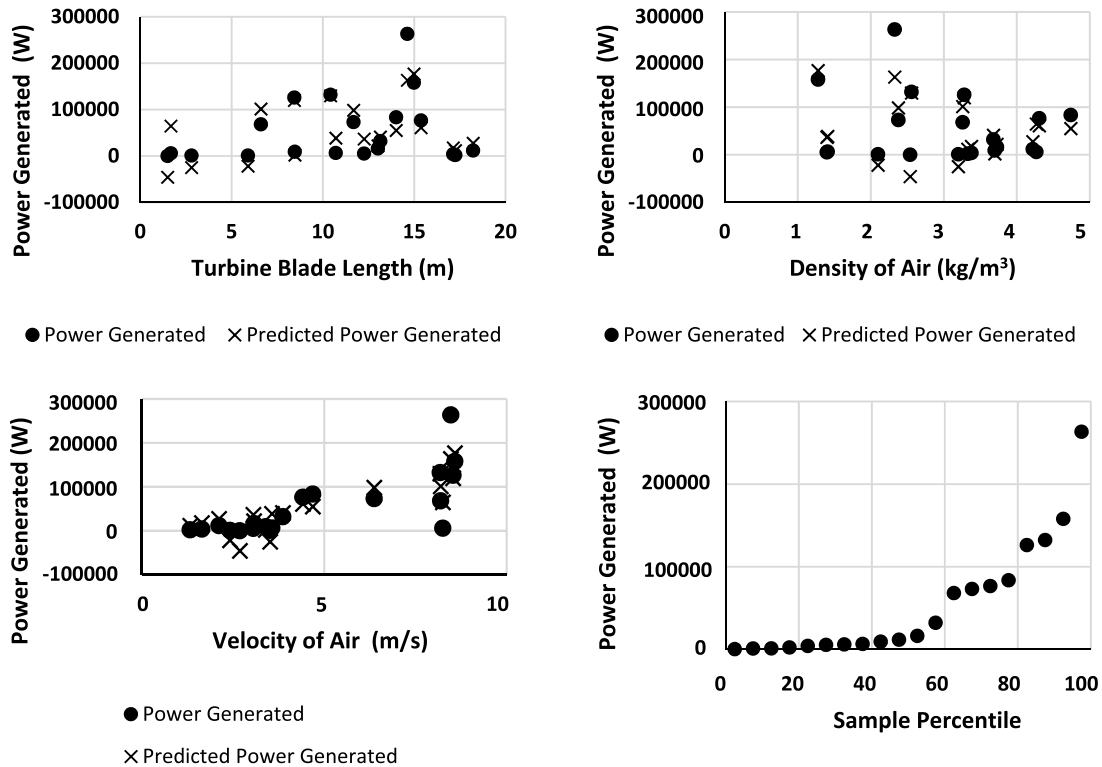


Fig. 8. Predicted power generation from the wind energy project with different performance variables.

$$\rho = 1.2205 \text{ kg/m}^3$$

$$v = 4.3 \text{ m/s}$$

and

$$\{32985.28827545624, \{l \rightarrow 20.\}\}$$

Eq. (9) shows the proposed regression model for the life cycle cost (LCC) from the appliance audit of the Faculty of Engineering using the data generated from the PyCharm codes. The regression of the data obtained from the segregated optimization approach shows that for the appliance audit, the coefficient of determination is approximately 84%; while the correlation coefficient is 0.92; showing a strong linear relationship. Fig. 6 shows the

relationship between the dependent and independent variables and also the predicted values.

$$LCC = -350735.32 + 139.53 P_1 + 15.56 P_2 + 17224.97 OP + 11343.69 U \quad (9)$$

The performance fits of the actual LCC from the comprehensive audit of the lighting system at the Faculty of Engineering is compared with the predicted LCC based on the regression analysis, based on the different indices, including the power of appliance, operating hours, power of retrofits, and the number of units (see Fig. 5). The relative fitness suggests the relative reliability of the proposed model for comparative energy savings from the choice of different lighting systems (for example, the options of common 60 W incandescent bulb, common 14 W CFL bulb, and Phillips 12.5 W ambient LED bulb) for the same output of 800 lumens.

Eq. (10) provides the regression model from the segregated optimization approach for the cooling load. Significant influence of the unit of the air-conditioners, based on the weighting of the correlation coefficient on AC_{units} , appears to dominate the predicted cooling load. The influences of the glass on both the south and west and the roof tend to be cancelled by the contributions from the glass and wall at the other orientations. The coefficient of determination is approximately 48% with reasonable level of accuracy; while the correlation coefficient is 0.69.

$$CL = 157953.05 + 27627.93 AC_{units} - 1560.78 A_{NG} - 113.52 A_{EG} + 379.85 A_{SG} + 2249.73 A_{WG} - 1627.34 A_{NW} - 10.61 A_{EW} - 1576.18 A_{SW} - 1187.31 A_{WW} + 901.78 A_{Roof} + 0.0897 E_C \quad (10)$$

Eq. (11) presents the regression model for the segregated optimization approach for the predicted solar power. The model embraces the performance study of different independent variables involved in the solar PV project, including the size of the module, the rated power specification, the number of the installation wings, the ambient temperature, the coefficient of temperature for power, and the dirt loss, among other performance variables. The coefficient of determination is approximately 76% while the correlation coefficient is 0.87; showing a strong linear relationship. Fig. 7 shows the relationship between the dependent and independent variables and also the predicted values.

$$Annual_{energy} = 3700965.89 + 16359.54 N_{wings} + 47914.69 L_{mod} - 279494.73 B_{mod} + 10232.12 A_{site} + 570.38 P_{mod} - 2503.78 T_{amb} - 8420.48 T_{coeff} - 1375518.91 T_e - 3297182.18 D_l + 8321.94 eff - 128308644 DC_{loss} - 735438.86 AC_{loss} \quad (11)$$

Based on the favourable correlation of the actual annual energy and the predicted energy production from the solar PV project, the model appears to propose the production of about 6000 kWh of power at just 60 wings and 200 sq.(m) of solar panel.

Eq. (12) shows the regression of the data obtained from the segregated optimization approach for the wind turbine analysis. The coefficient of determination is approximately 93% while the correlation coefficient is 0.96; showing a strong linear relationship. Fig. 8 shows the relationship between the dependent and independent variables, including the density of air velocity of the air, and the length of the turbine blade. While the correlation

confidence of the profile of the turbine blade and the density of the air appears consistent, the influence of the velocity of the air on the power generation from the wind energy conversion project is dominant. Notwithstanding, a linearly steady power generation of 80 kW is observed within the percentile of about 60–80.

$$P_{WIND} = 93213.01 - 8400.71 \rho_{AIR} + 2226.76 V_{AIR} + 5979.22 L_{BLADE} \quad (12)$$

4. Conclusions

Energy conservation principles for effective energy management of existing buildings at the University of Lagos is adopted. Using an energy audit software (**EnerghxPlus 1.0**), several methods are developed for quick assessment of the energy demand–supply balance at the Faculty of Engineering, such as the minimum energy performance standards (MEPS) for appliances, cooling load, and the renewable energy (RE) calculator for solar PV and wind turbine projects. The Qt developmental framework was adopted based on its flexibility and favourable compatibility with a wide range of operating systems. The regression model for each method shows the important independent variables, subject to reliable constraints (e.g., p -value > 0.05). Also, the predicted values are compared with each of the dependent variables. Segregated optimizations on Mathematica are carried out and the results are observed for the various methods. For each of the methods, the predicted solutions provide the necessary design for the optimal harvest of renewable energy potentials on campus. Considering the observed favourable correlation of the actual with predicted variables, the proposed model for each of the different dependent variables with the MEPS for the energy stock (Faculty of Engineering) promises a reliable tool for the ongoing energy audit of the entire Akoka campus of the University of Lagos.

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