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By Dr. Vincent A. Ani

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STRATEGIESFORMODELINGANDSIMULATIONOFALTERNATIVEENERGYSYSTEMSFORPOWERINGHEALTHFACILITIESUSINGHOMERAPPLICATION

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Strategies for Modeling and Simulation of Alternative Energy Systems for Powering Health Facilities using HOMER Application

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I. INTRODUCTION

Health facilities are community institutions where reliable and sustainable energy requires particular attention. Energy in health facilities is a critical enabler of access to many medical technologies, and thus to health services access. Studies conducted by World Health Organization (WHO) indicate that electricity access have a significant impact on some key health service indicators, such as: prolonging night-time service provision; attracting and retaining skilled health workers to a facility; and providing faster emergency response, including for childbirth emergencies. Without energy, many life-saving interventions cannot be undertaken (WHO, 2014).Modern energy provision is therefore a critical enabler of universal access to health care and universal health coverage.

The problems that health facilities encounter in Nigeria based on power supply are found throughout much of the world. Where there is a central power system, it is unreliable. Bringing power from the central grid to rural health facilities is not economically feasible in many cases. Hybrid systems designed with Hybrid Optimization Model for Electric Renewables (HOMER) can be cost effective and robust, solving both these issues simultaneously. Many studies throughout the world have used HOMER software to investigate the optimal design of proposed hybrid energy systems (HESs). Halabi et al. (2017), Ansong et al. (2017), Sigarchian et al. (2015), Rezzouk and Mellit (2015), and Madziga et al. (2018) used HOMER to analyze the performance of suggested HESs to find the optimal configurations. Each study proposed certain components that differed from others and the simulation was conducted for a specific area. Ani (2014) used HOMER to model energy map for off-grid health clinics in Nigeria. The author found that the most ideal solutions for the sites were hybrid systems (PV/diesel; PV/wind/diesel) with a battery backup. Malika (2016) also used HOMER to model renewable energy systems for rural health clinics in Algeria. The study focused on the optimization and the cost analysis of renewable energy hybrid systems for electricity production at rural health clinics situated in coastal, high plains and desert regions of Algeria, represented by Algiers, Ghardaia and Djanet. Regarding the cost of fuel in different regions of Algeria, the optimized renewable energy systems found for Algiers and Ghardaia are composed of PV systems, wind generators and batteries, while for Djanet it is a PV system and batteries. Ani and Emetu (2013) used the HOMER software to model robust, reliable energy systems for a rural health service facility in the southern part of Nigeria. Although HOMER is increasingly used for state-of-the-art microgrid design, these examples go back to HOMER's roots as a tool for electrification. The benefits of electrifying rural health clinics can literally mean the difference between the health clinics standards of the "dark ages" compared to that of the modern world. By having electricity, a health clinic will have prolonged opening hours. With more electricity, health clinics could access basic medical devices and appliances, such as vaccine refrigerators, as well as general equipment such as water sterilization, heating, cooling, and ventilation.

An international donor agency United States Agency for International Development (USAID) (2016)has been working with a health clinic in the Kalahari Desert of Botswana to improve local health care service delivery. The health clinic is not connected to the grid and currently utilizes a diesel generator to partially meet its energy needs. The donor agency

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decided to explore different options for upgrading the clinic's power generation systems, by comparing costs for a variety of different energy generation systems that can meet 100% of the clinic's load using HOMER program. Evaluating the energy generation options, the resulting cost estimates show that the lowest cost system is a PV/diesel-battery hybrid system. A diesel-battery system costs 13% more than this hybrid system because the added fuel cost over the life of the system is more than the savings in initial PV investment, and a PV-battery system costs about 28% more than the least-cost design. In diesel only system, the cost of energy from a diesel system with no batteries is over twice the cost from a diesel-battery system. The calculations demonstrate that because of fuel and maintenance costs, the system with the lowest capital cost is not the system with the lowest lifetime cost of energy.

World health organization (2016) conducted a simulation to compare the costs of different stand-alone power supply technologies to a hypothetical health clinic in rural Kenya, using HOMER Power System Design tool. The simulation tested and compared power supply arrays reliant upon a fuel-based generator, PV and generator combinations, and PV only, with and without battery backup; and looked at costs of the different supply options (both initial and long-term), as well as the pollution and climate emissions. The simulation further explored these supply options for two demand scenarios: one using conventional medical devices and one using more energy-efficient medical devices that reduce the clinic's overall energy demand. The simulation provides an interesting example of how optimal combinations of photovoltaic and diesel generation with appropriate energy storage can yield multiple gains: lower overall cost of energy, a shift to renewable energy, and a reliable supply for all health facility energy needs. The simulation also demonstrates how investments in more energy-efficient medical devices, can help reduce the required capital investment in energy supply for a rural health clinic. The results of the simulation demonstrate that the best combination remains energy efficiencies + more efficient supply configurations.

a) Description of HOMER Software

HOMER is a computer model developed by the United States (U.S.) National Renewable Energy Laboratory (NREL) to assist in the design of power systems; evaluate technical (power system's physical behavior) and financial (power system's life-cycle cost, which is the total cost of installing and operating the system over its life span) options for on-grid and off-grid power systems, for distributed generation and stand-alone applications. This software application (HOMER) helps to facilitate the comparison of power generation technologies across a wide range of applications. It allows one to model the performance of a power system configuration and determine its technical feasibility and life-cycle cost; compare many different design options based on the satisfied technical constraints at the lowest life-cycle cost; and assists in understanding and quantifying the effects of uncertainty or changes in the inputs. In 1993, NREL developed the first version of HOMER for the U.S. Department of Energy (DOE) for renewable energy programs. The developed design tool (HOMER) was used in predicting the long-term performance of hybrid power systems and to understand the tradeoffs between different energy production configurations. HOMER has a user-friendly windows-based interface with a library of input data files and users can readily model new applications. HOMER simulate different system configurations, or combinations of components, and generates results that can be viewed as a list of feasible configurations sorted by net present cost. It displays simulation results in a wide variety of tables and graphs that help one compare configurations and evaluate them on their economic and technical merits (Getting Started Guide, 2005).

b) Literature Review

Based on literature search, many case studies concentrate on the use of HOMER at the national, regional, and rural communities for households scale (Olubayo et al., 2019; Shahinzadeh et al., 2016; Cristian et al., 2017; Budes et al., 2020; Acakpovi et al., 2015; Razmjoo and Davarpanah, 2018; Farid et al., 2017; Nagger et al., 2018; Bahramara et al., 2016; Adetunji et al., 2018; Al-Hamdani et al., 2016; Hassan et al., 2016; Rajbongshi et al., 2017; Ronad and Jangamshetti, 2015; Jamalaiah et al., 2017; Rohit and Subhes, 2014; Deshmukha and Singha, 2019; Al Garni et al., 2018; Zahboune et al., 2016; Mohammed et al., 2013; Shahinzadeh et al., 2015a; Shahinzadeh et al., 2015b) with only a few research efforts directed at healthcare facilities. Furthermore, the strategies for modelling and simulation of alternative energy systems for powering health facilities have not been comprehensively studied. Razmjoo and Davarpanah (2018) studied four different models of hybrid renewable energy systems with a combination of photovoltaic panels, wind turbine, and diesel generators for residential application in Damghan city. Simulation, optimization, and modeling procedures were done by HOMER software. The simulation results show that among three hybrid systems investigated, PV-wind system has the highest value of electrical production with 18,478 kWh/yr and the PV-diesel system has the lowest value of electrical production with 9,876 kWh/yr. Moreover, from the environmental view, the PV-Diesel system is highest with2,402 kg/yr and the PV-wind system has the lowest pollution rate, i.e., 0%.Shezan et al (2016) carried out a research to analyze the performance of an off-grid PV (photovoltaic)-wind-diesel-battery hybrid energy system for a remote area located in the state of Selangor, Malaysia. The system was designed as well as simulated to support a small community considering an average load demand of 33 kWh/day with a peak load of 3.9 kW. The simulation and optimization of operations of the system was done by HOMER application using the real time field data of solar radiation and wind speed of that area. The simulation ensures that the system is suitably feasible with respect to net present cost (NPC) and carbon dioxide (CO2) emission reduction purpose. The result shows that NPC and CO2emission can be reduced about 29.65% and 16 tons per year respectively compared to the conventional power plants. The NPC of the optimized system has been found about USD 288,194.00 having the per unit Cost of Energy (COE) about USD 1.877/kWh. The analyzed hybrid energy system might be applicable for other region of the world where the climate conditions are similar. Similar research was conducted in Shezan and Ping (2017) which uses the HOMER to design an off-grid Hybrid PV-Wind-Biomass-Diesel Energy Systemin order to support a small community having an average load demand of 80kWh/d with a peak load of 8.1 kW. The simulation ensures that the system is economically and environmentally feasible with respect to NPC and CO2 emission limitations. The result shows that the NPC of the optimized system has been found to be about USD 160,626.00, having the per unit COE of USD 0.431/kWh. In a related research, a PV–wind–diesel system was designed by Bernal-Agustín et al. (2006) to minimize the total cost of system installation and to reduce the pollutant emissions by using HOMER software. The results demonstrated the practical utilization of the method used. Bekelea and Boneya (2011) designed a wind-PV hybrid power system for supplying electricity for a community living in Ethiopian remote area using HOMER. Moreover Kusakana and Vermaak (2013) used HOMER to investigate the possibility of using hybrid PV–wind renewable systems to supply mobile telephone stations in remote areas of Congo. Li et al. (2013) presented a techno-economic feasibility study of an autonomous hybrid wind/PV/battery power system for a household in Urumqi, China using Hybrid Optimization Model for Electric Renewable (HOMER) simulation software. They recommended a hybridwind/PV/battery system with 5 kW of PV arrays (72% solar energy penetration), with a one wind turbine of 2.5 kW (28% wind energy penetration), 8 unit batteries each of6.94 kWh and 5 kW sized power converters for the household. Furthermore Ngan and Tan (2012) analyzed the implementation of hybrid photovoltaic (PV)/wind turbine/diesel system in JohorBahru, Malaysia and used "HOMER" software. Bad awe et al. (2012) integrated and optimized a hybrid wind and solar energy system to an existing diesel generator with a battery backup to supply power to telecommunication towers using HOMER software. Their results indicated that the hybrid renewable energy system is a cost effective solution.

HOMER software is one of the tools being used by WHO for designing renewable energy health facilities. HOMER can evaluate a range of equipment options over varying constraints to optimize small power systems for health facilities. HOMER's flexibility makes it useful in the evaluation of design issues in the planning and early decision-making phase of health facility electrification projects. Therefore, the aim of this paper is to design energy system options that can optimize health services delivery, using HOMER software and demonstrates in detail the depth of the software application; teach health workers step by step on how to model renewable energy health facilities. The objective of this research is to ensure the uninterrupted power supply to the health facilities in the remote and decentralized areas, to ensure environmentally safe energy system, to reduceCO2 and other greenhouse gas (GHG) emissions, to reduce the COE and improving the NPC.

II. METHODS AND MATERIALS

a) Modeling of Alternative Energy System Components

Before going to the computer simulation, modeling of alternative energy system components is done step by step as described below. The proposed system contains wind energy sub-system, PV sub-system, diesel generators unit and battery storage sub-system.

Step One: Defining the Power System

This schematic (Add/Remove Equipment to Consider) shown in Figure 1 represents all of the technology options for a power system design. The power system design can be defined by clicking the Add/Remove button. For this exercise, we selected a number of different components as shown in Figure 1 by clicking the check box of each of the following: Primary Load 1 (Health Facility Load), PV, Wind Turbine 1 (BWC Excel-R), Converter, Generator 1 (diesel generator) and Battery 1 (Surrette 6CS25P). At the bottom of the window select 'do Not Model Grid', and Click OK to return to the Main window.

Step Two: Defining the Facility Load and its Location

The load inputs describe the electrical demand that the power system must be served according to a particular schedule. In this case, clinic personnel must examine their facility's specific needs and discuss them with energy design experts. The needs assessment will include an inventory of the types of equipment used in the facility, the power required to operate each device, and the average "daily load", or the amount of power required to operate equipment under normal working conditions. Therefore, in this study, the hourly load profile of each load [shown in Table A1 of the supplementary data] needs to be entered into primary load according to the setup defined in the schematic and model. To find wattage information for a given

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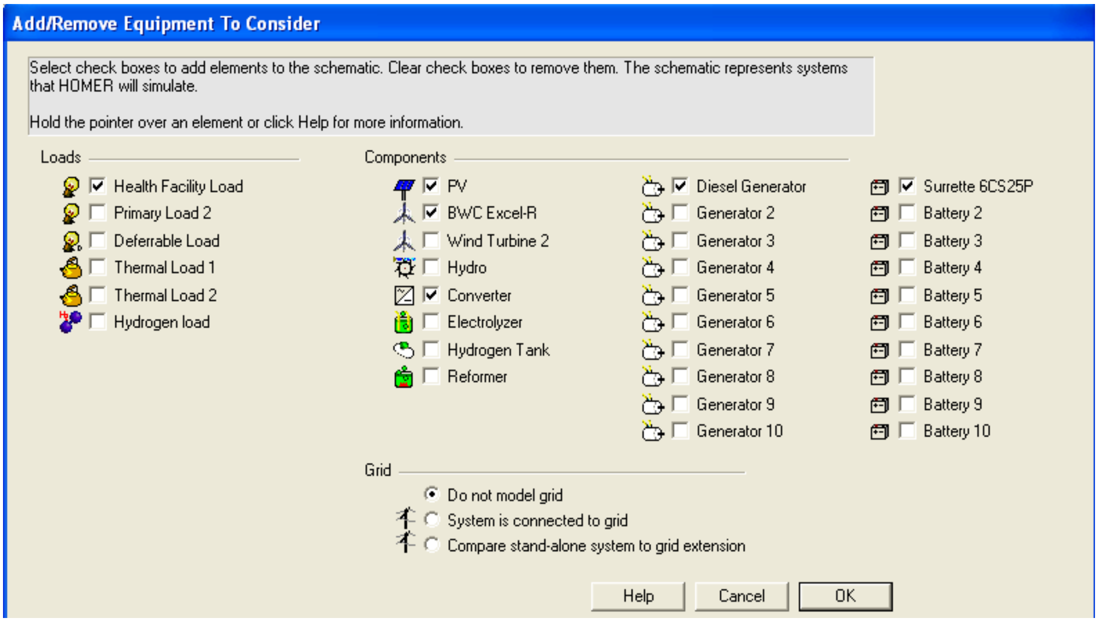


Add/Remove Equipment To Consider

Select check boxes to add elements to the schematic. Clear check boxes to remove them. The schematic represents systems that HOMER will simulate.

Hold the pointer over an element or click Help for more information.

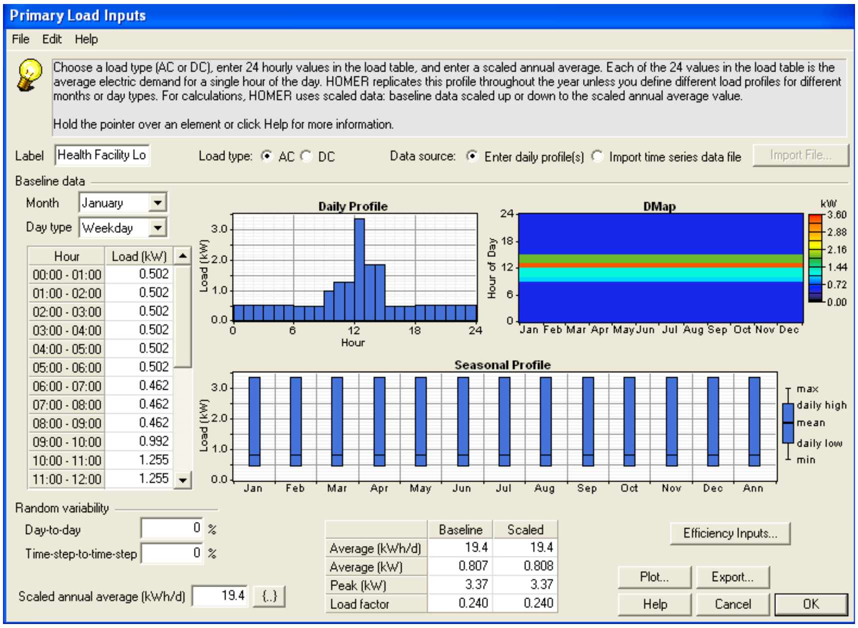
Loads
- ☑ Health Facility Load
- ☐ Primary Load 2
- ☐ Deferrable Load
- ☐ Thermal Load 1
- ☐ Thermal Load 2
- ☐ Hydrogen load

Components
- ☑ PV
- ☑ BWC Excel-R
- ☐ Wind Turbine 2
- ☐ Hydro
- ☑ Converter
- ☐ Electrolyzer
- ☐ Hydrogen Tank
- ☐ Reformer
- ☑ Diesel Generator
- ☐ Generator 2
- ☐ Generator 3
- ☐ Generator 4
- ☐ Generator 5
- ☐ Generator 6
- ☐ Generator 7
- ☐ Generator 8
- ☐ Generator 9
- ☐ Generator 10
- ☑ Surrette 6CS25P
- ☐ Battery 2
- ☐ Battery 3
- ☐ Battery 4
- ☐ Battery 5
- ☐ Battery 6
- ☐ Battery 7
- ☐ Battery 8
- ☐ Battery 9
- ☐ Battery 10

Grid
- ● Do not model grid
- ○ System is connected to grid
- ○ Compare stand-alone system to grid extension

Figure 1: Add/Remove window of different components

device, check the user's manual or it may be written on the back of the device. A Health facility load profile depends on multiple parameters including lighting for child delivery and emergency night-time care, refrigeration for blood and vaccines, sterilization facilities, electricity for simple medical devices, etc., and for this reason, it is important to outline an accurate power profile in order to dimension correctly the renewable components for the facility. The adoption of energy efficiency can reduce energy consumption and increase renewable energy penetration (Babatunde et al., 2019; Olubayo et al., 2019). It can also reduce cost of energy and emissions. The simulation concerns a standard health facility described by (Ani and Emetu, 2013). Obviously, many rural health clinics in Nigeria have the same electrical load data with that of Ani and Emetu (2013) which can be used in the establishment of a general case study for the electrical load data; therefore it was used by Ani (2014)to study three hypothetical off-grid remote health clinics at various geographical locations in Nigeria; which will be use here as an example to the study. The electrical load (Power supply requirements) data for a Health facility is shown in Table A1 of the supplementary data, which was used to define the hourly profile, and the random variability parameters was set to 0% for accurate power load measurements as indicated in Figure 2.



Primary Load Inputs

Choose a load type (AC or DC), enter 24 hourly values in the load table, and enter a scaled annual average. Each of the 24 values in the load table is the average electric demand for a single hour of the day. HOMER replicates this profile throughout the year unless you define different load profiles for different months or day types. For calculations, HOMER uses scaled data: baseline data scaled up or down to the scaled annual average value.

Hold the pointer over an element or click Help for more information.

Label: Health Facility Lo
Load type: ● AC ○ DC
Data source: ● Enter daily profile(s) ○ Import time series data file

Baseline data
Month: January
Day type: Weekday

Hour	Load (kW)
00:00 - 01:00	0.502
01:00 - 02:00	0.502
02:00 - 03:00	0.502
03:00 - 04:00	0.502
04:00 - 05:00	0.502
05:00 - 06:00	0.502
06:00 - 07:00	0.462
07:00 - 08:00	0.462
08:00 - 09:00	0.462
09:00 - 10:00	0.992
10:00 - 11:00	1.255
11:00 - 12:00	1.255

Random variability
Day-to-day: 0 %
Time-step-to-time-step: 0 %

Scaled annual average (kWh/d): 19.4

	Baseline	Scaled
Average (kWh/d)	19.4	19.4
Average (kW)	0.807	0.808
Peak (kW)	3.37	3.37
Load factor	0.240	0.240

Figure 2: HOMER output for the Primary load

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Strategic Thinking and Adjusting for Change

Once a facility has comprehensively analyzed the energy requirements of its daily operations, it must be determined whether those demands are likely to change. One must think strategically about the possibility that energy demands may increase due to the addition of new services or extended operating hours.

b) *Power Generation Options*

After determining the facility's typical daily energy usage as described above, it is time to evaluate the energy technologies available to electrify the facility. Rural health clinics have a number of options available to supply reliable electricity. The best option for a given application depends on energy technology drivers such as the capital cost, operating cost, reliability, and durability.

Capital Cost is the initial cost to purchase and install the equipment. Power equipment – including generators (PV panels, wind turbine, and diesel), inverters, charge controllers, and batteries – can vary greatly in cost and quality. In many cases, higher-quality models will cost more, but can have a greater return on investment in terms of greater reliability of power and longer system lifetimes. Costs also vary considerably based on the local market.

Operating Cost includes the cost of fuel (where applicable), operations and maintenance, and parts purchased for repairs. Operating costs will vary more than capital costs, due to differences in:

- Fuel prices over time and from location-to-location.
- Use patterns - systems will experience more or less stress in a given day, based on the number of hours they operate, the amount of power they provide, and the type of equipment drawing loads (e.g., high intensity equipment such as sterilizer oven (laboratory autoclave), as opposed to low-intensity equipment such as lighting); and
- Environmental conditions.

Reliability is expressed as a fraction of time the equipment is available to provide power. Generators need to be taken off-line for service periodically; wind and solar power systems require optimal weather conditions to operate at maximum efficiency. Systems can generally achieve greater reliability by adding backup components; hybrid systems (include photovoltaic panels and/or a wind turbine, batteries, and a generator) which has the ability for one system to support the other provide greater flexibility, although this generally increases cost and complexity.

Durability is the typical system lifetime, expressed either in years or in hours of run-time (for engine generators).

Facility Location - The Case Study Sets of Locations in Nigeria

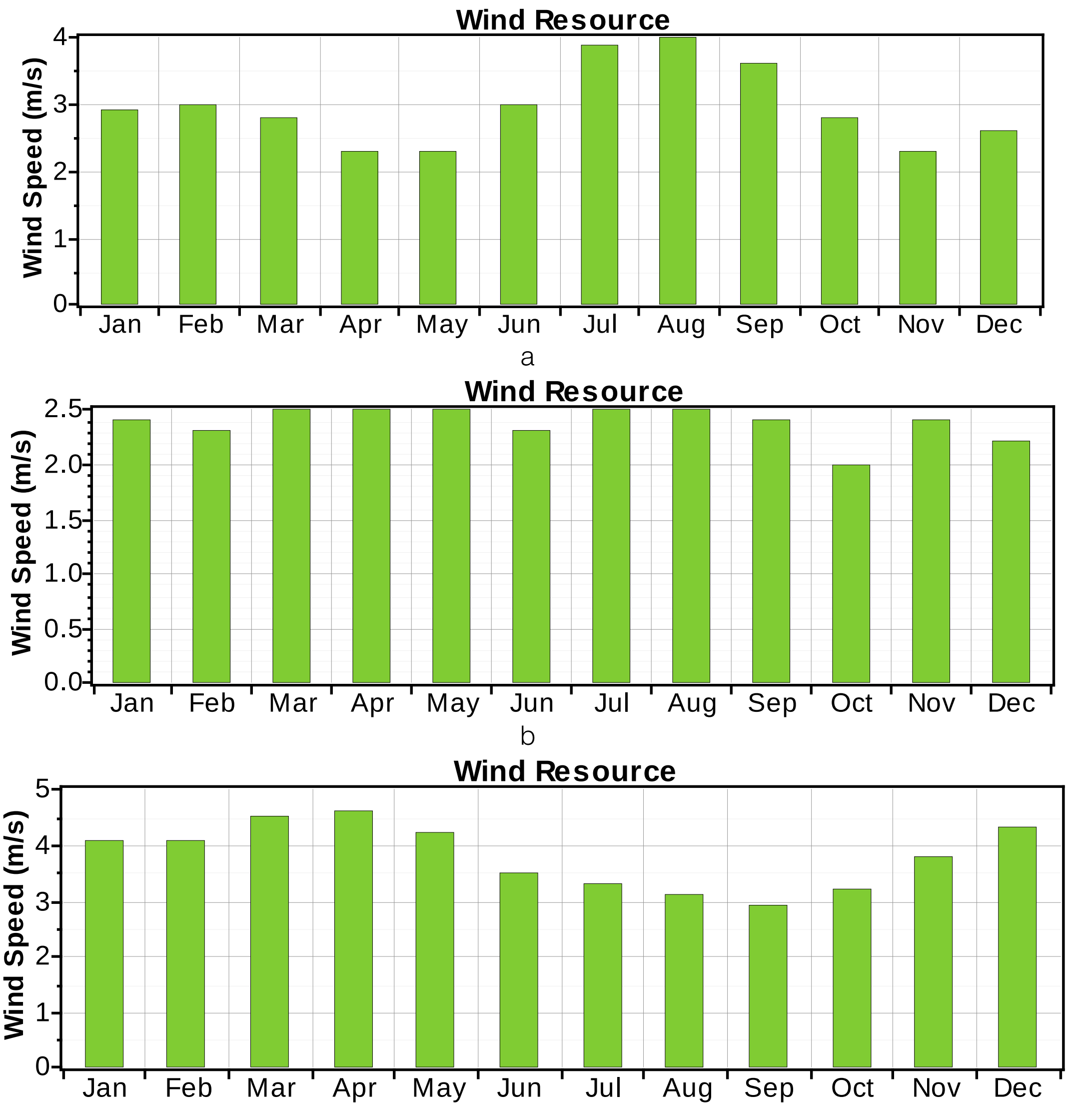
The locations of the hypothetical health facility are chosen to reflect the various geographical and climatic conditions in Nigeria. Nigeria is divided into three main climatic regions: the equatorial climatic region where the global solar radiation ranges from 4.1 to 4.9 kWh/m^2/day, the tropical climatic region where the global solar energy is around 5kWh/m^2/day, and finally the arid climatic region where the global solar radiation is higher than 5kWh/m^2/day, while the wind is characterized by a moderate speed (2.4 to 5.4m/s) as can be seen in (Ani, 2014). These locations for the hypothetical health facility are: Nembe (Bayelsa State) in the equatorial climatic region, Abaji (Abuja, FCT) in the tropical climatic region, and Guzamala (Borno State) in the arid climatic region.

Step Three: Renewable Energy (Wind and Solar) Resources

The availability of renewable energy system (RES) at a location differs considerably from location to location. This is a vital aspect in the development of the power system. The performances of solar and wind energy components are influenced by the geographical location and climatic conditions. As RES (solar and wind) are naturally available and intermittent, they are the best option to be combined into a hybridized diesel system. These resources (solar and wind) depend on different factors such as the amount of solar energy available is dependent on climate and latitude (your specific location on the Earth's surface), the wind resource is influenced by atmospheric circulation patterns and geographic aspects; in turn influences when and how much power can be generated. The specific geographical locations (latitude and longitude) of the health facility based on solar and wind resources are discussed below.

c) *Wind Resources*

Wind resources can be determined by using the National Aeronautics and Space Administration (NASA) Surface Meteorology and Solar Energy database. Therefore, to determine the wind resources of a location, log into the NASA Meteorology website (http://eosweb.larc.nasa.gov/) and enter the coordinates and select the annual wind speed average, which (the annual wind speed average) is a good indicator of the suitability of the installation of a wind turbine in any given location. Generally, values above 7m/s with few months below 5m/s are considered adequate for satisfactory results (Kassam, 2011). Once the data is received, click on the wind resource icon in HOMER and click on the "enter monthly averages" and enter the monthly wind data, then fill the Altitude and Anemometer Height with the appropriate information. For this exercise, a hypothetical site coordinates of 4° 17' N latitude and 6° 25' E longitude for Nembe (Bayelsa State), of 9° 00' N latitude and 7° 00' E longitude for Abaji (Abuja, FCT), and latitude 11° 05' N, longitude 13° 00' E for Guzamala (Borno State), were used as indicated in Figure 3.



a

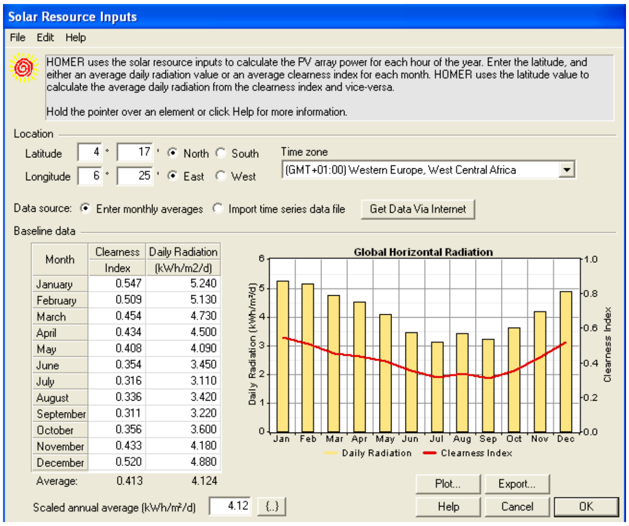
b

c

Figure 3: HOMER output graphic for wind speed profile in (a) Nembe, (b) Abaji, and (c) Guzamala

d) Solar Resource

Solar resources can be obtained directly via internet by HOMER from the NASA Surface Meteorology and Solar Energy database by entering the GPS coordinates. NASA provides extensive information on solar resources by month for any location in the world (http://eosweb.larc.nasa.gov/sse/). Using the coordinates from the wind resources above, the annual solar radiation of these areas are4.12kWh/m²/d for Nembe (Bayelsa State), 5.45 kWh/m²/d for Abaji (Abuja, FCT), and 5.90 kWh/m²/d for Guzamala (Borno State) which can be seen from Figure 4. Kassam (2011) advised that the average radiation should have a constant trend and that the annual radiation should be above 5kWh/m²/d in order to have a reliable source of power coming from the photovoltaic panels.



HOMER uses the solar resource inputs to calculate the PV array power for each hour of the year. Enter the latitude, and either an average daily radiation value or an average clearness index for each month. HOMER uses the latitude value to calculate the average daily radiation from the clearness index and vice-versa.

Hold the pointer over an element or click Help for more information.

Location

Latitude 4 ° 17 ' ● North ○ South

Longitude 6 ° 25 ' ● East ○ West

Time zone (GMT+01:00) Western Europe, West Central Africa

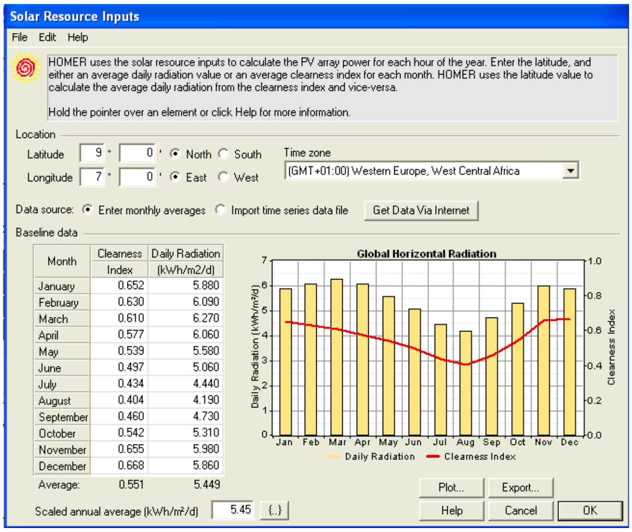
Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.547	5.240
February	0.509	5.130
March	0.454	4.730
April	0.434	4.500
May	0.408	4.090
June	0.354	3.450
July	0.316	3.110
August	0.336	3.420
September	0.311	3.220
October	0.356	3.600
November	0.433	4.180
December	0.520	4.880
Average:	0.413	4.124

Scaled annual average (kWh/m²/d) 4.12

a



HOMER uses the solar resource inputs to calculate the PV array power for each hour of the year. Enter the latitude, and either an average daily radiation value or an average clearness index for each month. HOMER uses the latitude value to calculate the average daily radiation from the clearness index and vice-versa.

Hold the pointer over an element or click Help for more information.

Location

Latitude 9 ° 0 ' ● North ○ South

Longitude 7 ° 0 ' ● East ○ West

Time zone (GMT+01:00) Western Europe, West Central Africa

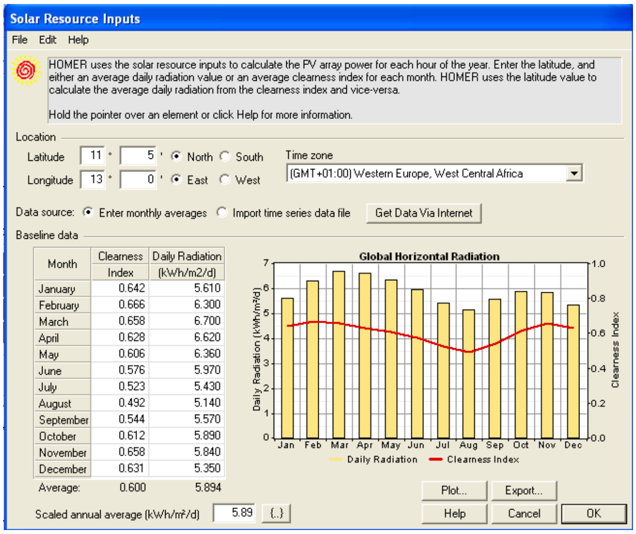
Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.652	5.880
February	0.630	6.090
March	0.610	6.270
April	0.577	6.060
May	0.539	5.580
June	0.497	5.060
July	0.434	4.440
August	0.404	4.190
September	0.460	4.730
October	0.542	5.310
November	0.655	5.980
December	0.668	5.860
Average:	0.551	5.449

Scaled annual average (kWh/m²/d) 5.45

b



HOMER uses the solar resource inputs to calculate the PV array power for each hour of the year. Enter the latitude, and either an average daily radiation value or an average clearness index for each month. HOMER uses the latitude value to calculate the average daily radiation from the clearness index and vice-versa.

Hold the pointer over an element or click Help for more information.

Location

Latitude 11 ° 5 ' ● North ○ South

Longitude 13 ° 0 ' ● East ○ West

Time zone (GMT+01:00) Western Europe, West Central Africa

Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.642	5.610
February	0.666	6.300
March	0.658	6.700
April	0.628	6.620
May	0.606	6.360
June	0.576	5.970
July	0.523	5.430
August	0.492	5.140
September	0.544	5.570
October	0.612	5.890
November	0.658	5.840
December	0.631	5.350
Average:	0.600	5.894

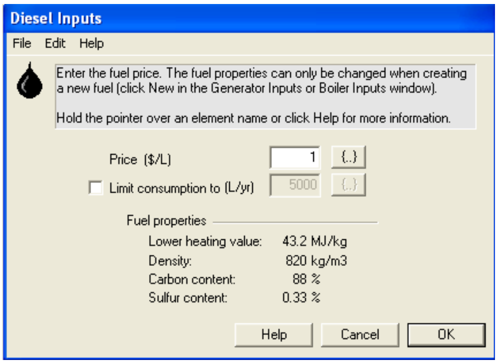
Scaled annual average (kWh/m²/d) 5.89

c

Figure 4: HOMER output graphic for Solar (clearness index and daily radiation) profile in (a) Nembe, (b) Abaji, and (c) Guzamala

Step Four: Diesel Price

Diesel price has a significant impact on the running costs of a system equipped with a diesel generator (Kassam, 2011).The diesel price can be added by clicking the diesel icon in HOMER, then click on the "Diesel Inputs" and enter the diesel price.In the exercise,1$US/L for Nembe, 1.5$US/L for Abaji and 1.8$US/L for Guzamala, were considered as reference price for the diesel as shown in Figure 5.



Enter the fuel price. The fuel properties can only be changed when creating a new fuel (click New in the Generator Inputs or Boiler Inputs window).

Hold the pointer over an element name or click Help for more information.

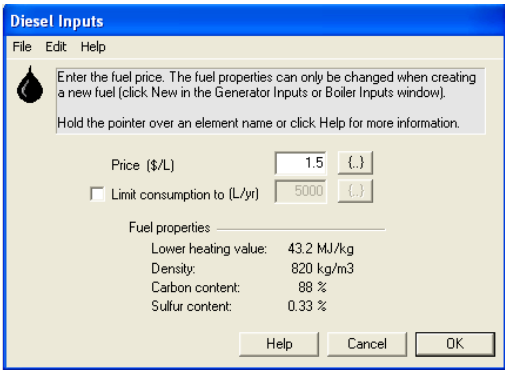
Price ($/L) 1

☐ Limit consumption to (L/yr) 5000

Fuel properties

Lower heating value: 43.2 MJ/kg
Density: 820 kg/m3
Carbon content: 88 %
Sulfur content: 0.33 %

a



Enter the fuel price. The fuel properties can only be changed when creating a new fuel (click New in the Generator Inputs or Boiler Inputs window).

Hold the pointer over an element name or click Help for more information.

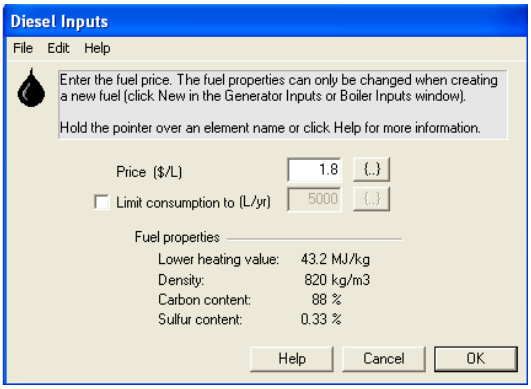
Price ($/L) 1.5

☐ Limit consumption to (L/yr) 5000

Fuel properties

Lower heating value: 43.2 MJ/kg
Density: 820 kg/m3
Carbon content: 88 %
Sulfur content: 0.33 %

b



Enter the fuel price. The fuel properties can only be changed when creating a new fuel (click New in the Generator Inputs or Boiler Inputs window).

Hold the pointer over an element name or click Help for more information.

Price ($/L) 1.8

☐ Limit consumption to (L/yr) 5000

Fuel properties

Lower heating value: 43.2 MJ/kg
Density: 820 kg/m3
Carbon content: 88 %
Sulfur content: 0.33 %

c

Figure 5: HOMER input for diesel price profile in (a) Nembe, (b) Abaji, and (c) Guzamala

Step Five: Economics

The economic factors of the project shown in Figure 6 can all be defined by clicking on the Economics icon in HOMER .In this exercise, a real annual interest rate of 6% was assumed. The real interest rate is equal to the nominal interest rate minus the inflation rate. The appropriate value for this variable depends on current macroeconomic conditions, the financial strength of the implementing entity, and concessional financing or other policy incentives. Also, the project lifetime was set to 20 years – inline with the expected life span of the renewable equipment (wind turbine, photovoltaic system). Diesel generators and batteries have usually a much lower lifetime, which largely depends on the

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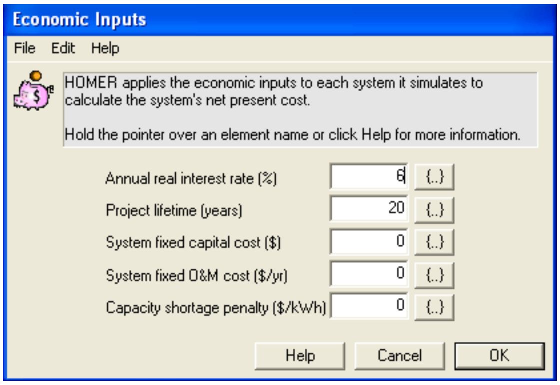
conditions where the equipment operates and the maintenance performed (Kassam, 2011).



Economic Inputs

File Edit Help

HOMER applies the economic inputs to each system it simulates to calculate the system's net present cost.

Hold the pointer over an element name or click Help for more information.

Annual real interest rate (%)	6
Project lifetime (years)	20
System fixed capital cost ($)	0
System fixed O&M cost ($/yr)	0
Capacity shortage penalty ($/kWh)	0

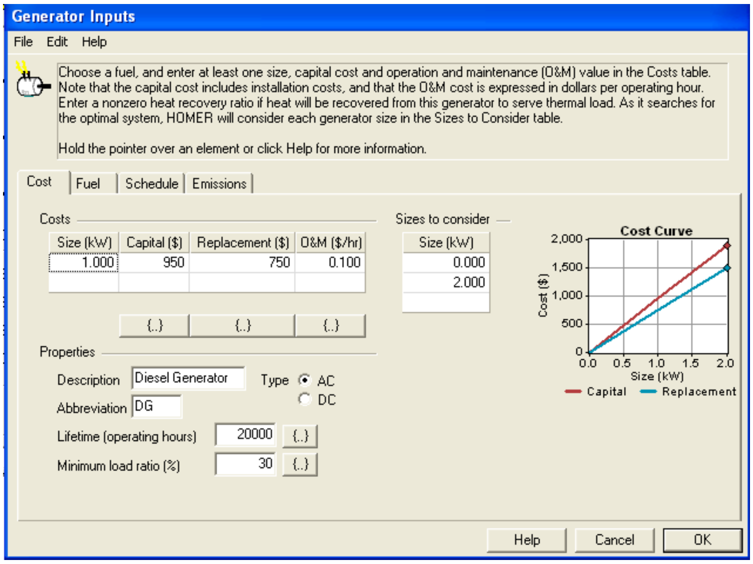
Figure 6: HOMER input for economics

Step Six: Equipment

Diesel Generator

The Generator in the power system can be defined by considering the Size, Cost, Replacement Cost, Operating Lifetime, and Operations & Maintenance (O & M) expenditure of the generator. In generator-only systems, the generator must be sized to handle the peak expected load, but the system frequently runs at lower loads at reduced efficiency. Therefore, in such situation, a battery bank can be added to a generator-based system to reduce run time and save fuel costs. The addition of batteries to a diesel system are often a good investment in terms of fuel savings.

In this exercise, by clicking on the Generator icon, a2.5kVA diesel generator has been considered. The minimum allowable load on the generator has been set as 30% of its rated capacity and has 20,000 operating hours life time. The default efficiency curve present in HOMER was used, as often vendors do not provide comprehensive details to design a specific efficiency curve. Generators typically have low capital cost compared to other alternatives, but higher operating costs due to the need for fuel(USAID, 2016). Initial capital cost will vary with the size and type of generator, while the Operating costs will vary depending on the level of usage. Generators have several maintenance requirements; and maintenance checks will vary depending on the design of the engine and its duty cycle (whether it is a primary energy source or a back-up/emergency unit). Engine oil and the oil filter should be changed after approximately 1,000 hours of operation. Meanwhile, it is often difficult to determine the generator hourly maintenance cost (the expense and transport associated with acquiring diesel) due to many health facilities have contract with companies or individuals to supply diesel to the generator at the facility and also manage the generator's O&M services. In the exercise, an hourly O&M cost of 0.1 US$ were assumed as indicated in Figure 7.



Generator Inputs

File Edit Help

Choose a fuel, and enter at least one size, capital cost and operation and maintenance (O&M) value in the Costs table. Note that the capital cost includes installation costs, and that the O&M cost is expressed in dollars per operating hour. Enter a nonzero heat recovery ratio if heat will be recovered from this generator to serve thermal load. As it searches for the optimal system, HOMER will consider each generator size in the Sizes to Consider table.

Hold the pointer over an element or click Help for more information.

Costs

Size (kW)	Capital ($)	Replacement ($)	O&M ($/hr)
1.000	950	750	0.100

Sizes to consider

Size (kW)
0.000
2.000

Properties

Description: Diesel Generator

Abbreviation: DG

Type: ● AC ○ DC

Lifetime (operating hours): 20000

Minimum load ratio (%): 30

Figure 7: HOMER input for fuel generator

e) *Mathematical Model of Diesel Generator*

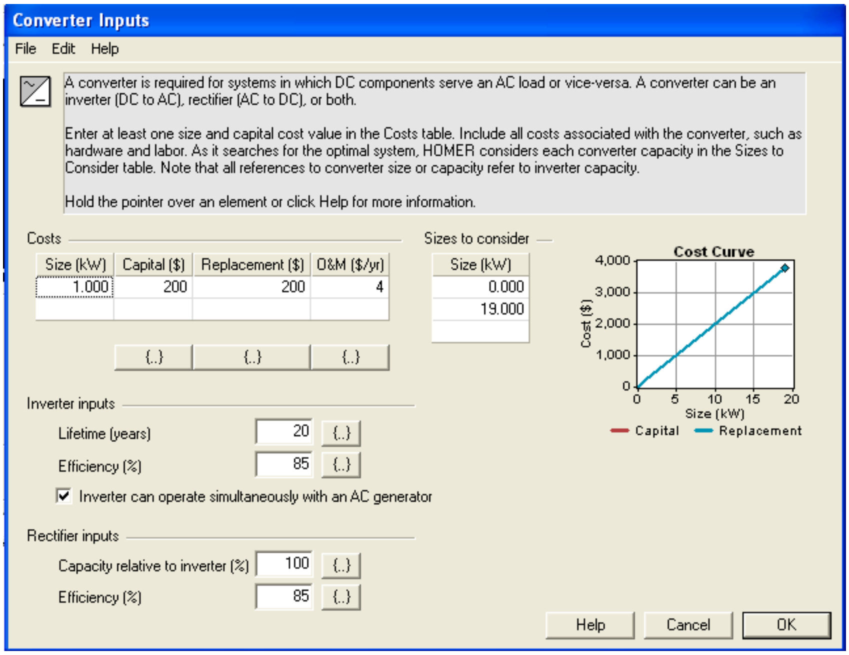
Hourly energy generated by diesel generator (E_{DEG}) with rated power output (P_{DEG}) is defined by the following expression (Deepak et al, 2011):

$$E_{DEG}(t) = P_{DEG}(t) \times \eta_{DEG} \text{ ----------------------------------- } (1)$$

For better performance and higher efficiency the diesel generator will always operate between 80 and 100% of their kW rating, where η_{DEG} is the diesel generator efficiency.

f) *Converter*

Converter in the power system represents both an inverter (for the conversion of generated direct current (DC) power into required alternating current (AC) power; both for energy flowing directly to the load from the PV and for energy transiting through the battery), and a rectifier (for the conversion of generated AC power in order to charge the battery).It is a device that can convert electrical power from ac to dc in a process called rectification and from dc toac in a process called inversion (Shezan et al., 2016). When defining the converter, the key parameters to consider are the energy conversion efficiencies, Size, Cost, and O&M Cost as shown in Figure 8.



A converter is required for systems in which DC components serve an AC load or vice-versa. A converter can be an inverter (DC to AC), rectifier (AC to DC), or both.

Enter at least one size and capital cost value in the Costs table. Include all costs associated with the converter, such as hardware and labor. As it searches for the optimal system, HOMER considers each converter capacity in the Sizes to Consider table. Note that all references to converter size or capacity refer to inverter capacity.

Hold the pointer over an element or click Help for more information.

Costs

Size (kW)	Capital ($)	Replacement ($)	O&M ($/yr)
1.000	200	200	4

Sizes to consider

Size (kW)
0.000
19.000

Inverter inputs

Lifetime (years): 20

Efficiency (%): 85

☑ Inverter can operate simultaneously with an AC generator

Rectifier inputs

Capacity relative to inverter (%): 100

Efficiency (%): 85

Figure 8: HOMER input for converter

g) Mathematical Model of Converter

In the proposed scheme converter contains both rectifier and inverter. PV, wind energy generator and battery sub-systems are connected with DC bus while diesel generating unit sub-system is connected with AC bus. The electric loads connected in this scheme are DC loads (Ani, 2015).

The rectifier is used to transform the surplus AC power from the diesel electric generator to DC power of constant voltage. The diesel electric generator will be powering the load and at the same time charging the battery. The rectifier model is given below(Ani, 2015):

$$E_{REC-OUT}(t) = E_{REC-IN}(t) \times \eta_{REC} \text{ -------------------------(2)}$$

$$E_{REC-IN}(t) = E_{SUR-AC}(t) \text{ ----------------------------------(3)}$$

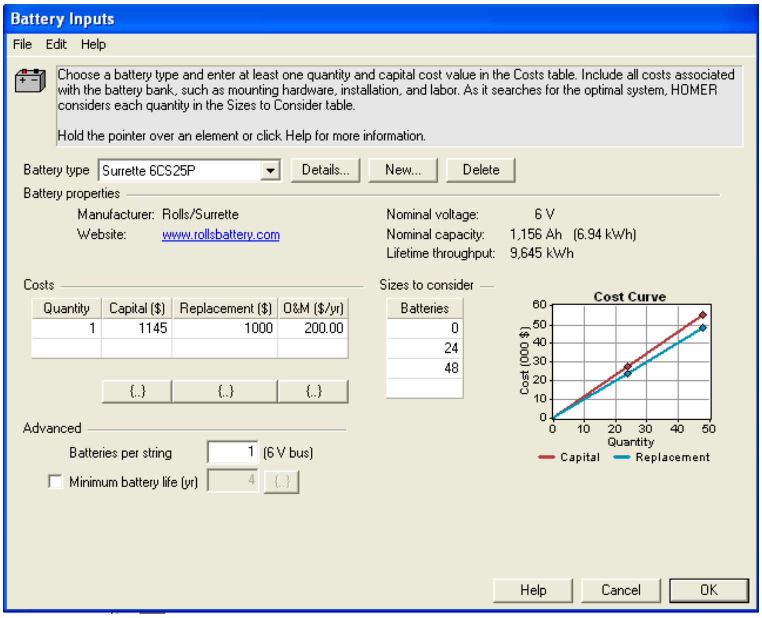
At any time t,

$$E_{SUR-AC}(t) = E_{DEG}(t) - E_{Load}(t) \text{ ------------------------(4),}$$

where $E_{REC-OUT}(t)$ is the hourly energy output from rectifier, kWh, $E_{REC-IN}(t)$ is the hourly energy input to rectifier, kWh, η_{REC} is the efficiency of rectifier, $E_{SUR-AC}(t)$ is the amount of surplus energy from AC sources, kWh, $E_{DEG}(t)$ is the hourly energy generated by diesel generator.

h) Storage System - Battery

Battery is a device that stores energy and makes it available in an electrical form. Batteries are not a power technology, but a means of storing the power produced by other systems, such as photovoltaic and/or wind systems, hybrid systems. The battery stores the generated electricity during the availability of the renewable energy sources and the stored energy supplied to the consumer whenever required (Partha and Nitai, 2020). For some renewable energy clinics, batteries can be used to provide backup power during surges and outages. However, if renewable energy is absent for a lengthy period of time, some other system (generator) would be useful to recharge the batteries. Batteries' lifetimes are partly dependent on the cycling (charging and discharging) they experience. HOMER provides a library of several predefined batteries, and users can add to the library if necessary. When choosing from the library, the key parameters to consider or include are the Nominal Capacity, Voltage, Round Trip Efficiency, Minimum State of Charge, Capacity Curve and Lifetime Curve (User Manual, 2016). By clicking on the battery icon (selected or created) in HOMER we are able to define the battery bank used in the power system by entering the cost of the battery, the number of batteries per string and the number of strings of batteries. Therefore, in this exercise, a single string of Surrette 6CS25P battery, 6V/1,156Ah sealed lead-acid batteries were considered as indicated in Figure 9.


Battery Inputs

File Edit Help

Choose a battery type and enter at least one quantity and capital cost value in the Costs table. Include all costs associated with the battery bank, such as mounting hardware, installation, and labor. As it searches for the optimal system, HOMER considers each quantity in the Sizes to Consider table.

Hold the pointer over an element or click Help for more information.

Battery type: Surrette 6CS25P

Battery properties

Manufacturer: Rolls/Surrette
Website: www.rollsbattery.com
Nominal voltage: 6 V
Nominal capacity: 1,156 Ah (6.94 kWh)
Lifetime throughput: 9,645 kWh

Costs

Quantity	Capital ($)	Replacement ($)	O&M ($/yr)
1	1145	1000	200.00

Sizes to consider

Batteries
0
24
48

Advanced

Batteries per string: 1 (6 V bus)
☐ Minimum battery life (yr): 4

Figure 9: HOMER input for storage battery

i) Mathematical Model of Storage Battery

HOMER uses the Kinetic Battery Model (Manwell and McGowan, 1993) to determine the amount of energy that can be absorbed by or withdrawn from the battery bank each time step. HOMER determines the total amount of energy stored in the battery at any time as the sum of the available (energy that is readily available for conversion to DC electricity) and bound energy (energy that is chemically bound and therefore not immediately available for withdrawal) by the following equation(HOMER help, 2015;User Manual, 2016):

$$Q = Q_1 + Q_2 \text{ --(5),}$$

where:

Q_1 is the energy in kWh that is readily available for conversion to DC electricity.

Q_2 is the energy in kWh that is chemically bound and therefore not immediately available for withdrawal.

Each hour of the simulation, the maximum amount of power that the battery bank can withdraw (or absorb) is being calculated using maximum discharge (or charge) power. The maximum discharge (or charge) power varies from hour to hour according to its state of charge and its recent charge and discharge history, as determined by the kinetic battery model.

Using the kinetic battery model, the maximum amount of power that the battery can discharge over a specific length of time Δt is given by the following equation(User Manual, 2016):

$$P_{batt,d\max,kbm} = \frac{-kcQ_{\max} + kQ_1 e^{-k\Delta t} + Qkc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c\left(k\Delta t - 1 + e^{-k\Delta t}\right)} \text{ -- --- (6),}$$

where:

Δt is the length of the time step [h].

P is the power [kW] into (positive) or out of (negative) the battery bank using kinetic battery model.

$Q_{\max}$ is the total capacity in kWh of the battery bank.

Q is the total amount of energy in kWh in the battery at the beginning of the time step

k is the rate constant [h^{-1}] which is a measure of how quickly the battery can convert bound energy to available energy or vice-versa.

c is the battery capacity ratio [unitless].

Likewise, the maximum amount of power that the battery can absorb over a specific length of time Δt is given by the following equation(User Manual, 2016):

$$P_{batt,c\max,kbm} = \frac{kQ_1 e^{-k\Delta t} + Qkc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c\left(k\Delta t - 1 + e^{-k\Delta t}\right)} \text{ ------------(7)}$$

j) Mathematical Model of Charge Controller

To prevent overcharging of a battery, a charge controller is used to sense when the batteries are fully charged and to stop or decrease the amount of energy flowing from the energy source to the batteries. The

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model of the charge controller is presented below (User Manual, 2016):

$$E_{CC-OUT}(t) = E_{CC-IN}(t) \times \eta_{CC} \text{ ----------------------------- } (8)$$

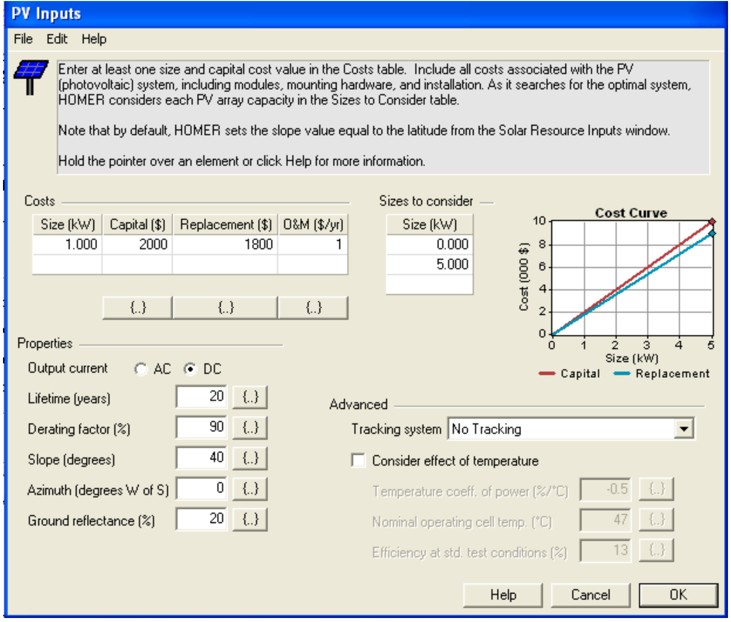
$$E_{CC-IN}(t) = E_{REC-OUT}(t) + E_{SUR-DC}(t) \text{ ---------------- } (9),$$

where $E_{CC-OUT}(t)$ is the hourly energy output from charge controller, kWh, $E_{CC-IN}(t)$ is the hourly energy input to charge controller, kWh, η_{CC} is the efficiency of charge controller, $E_{REC-OUT}(t)$ is the hourly energy output from rectifier, kWh, $E_{SUR-DC}(t)$ is the amount of surplus energy from DC sources, kWh (Ani, 2015).

k) Photovoltaic (PV) System

Photovoltaic (PV) Systems generate electricity from sunlight collected by solar panels. Solar panels are available in different shape and size. For instance, the size of the PV system depends on the power requirement of the health facility and its location. PV systems are highly modular, so the system can be customized to cover power demand of the health facility and add units if the power demand increases. PV systems typically have higher capital costs, but lower operating costs when compared to other energy generation options. Solar panels has the lowest O&M cost due to it does not require extensive maintenance; only to remove dust from the panels twice a year (Kassam, 2011).

For the facility under analysis we assumed for the photovoltaic panels a derating factor of 90% and expected lifetime of twenty years as indicated in Figure 10. The cost of PV panels was estimated as US$ 0.600/Wp based on prices cited by Nigerian suppliers (Solar Power Systems Components, 2015). This was adjusted upward to US$ 2/Wp (US$ 2,000 per kWp) to account for other support components that are required, also known as balance of system (BOS) parts, such as cables, charge controller with Maximum Power Point Tracker, lightening protection, as well as delivery/labour and installation costs.



Enter at least one size and capital cost value in the Costs table. Include all costs associated with the PV (photovoltaic) system, including modules, mounting hardware, and installation. As it searches for the optimal system, HOMER considers each PV array capacity in the Sizes to Consider table.

Note that by default, HOMER sets the slope value equal to the latitude from the Solar Resource Inputs window.

Hold the pointer over an element or click Help for more information.

Costs

Size (kW)	Capital ($)	Replacement ($)	O&M ($/yr)
1.000	2000	1800	1

Sizes to consider

Size (kW)
0.000
5.000

Properties

Output current ○ AC ● DC

Lifetime (years) 20

Derating factor (%) 90

Slope (degrees) 40

Azimuth (degrees W of S) 0

Ground reflectance (%) 20

Advanced

Tracking system No Tracking

☐ Consider effect of temperature

Temperature coeff. of power (%/°C) -0.5

Nominal operating cell temp. (°C) 47

Efficiency at std. test conditions (%) 13

Figure 10: HOMER input for solar photovoltaic

l) Mathematical Model of the Monthly Average Clearness Index andSolar Photovoltaic Generator

HOMER uses the *extraterrestrial horizontal radiation* ($H_{o,ave}$) to calculate either *the monthly average clearness index* (K_T) or *the monthly average global solar radiation* (H_{ave}). For instance, when you enter H_{ave}, HOMER divides it by $H_{o,ave}$ to find K_T. If you enter K_T, HOMER multiplies it by $H_{o,ave}$ to find H_{ave} (User Manual, 2016).

The monthly average clearness index can be calculated using the equation (HOMER help, 2015; User Manual, 2016):

$$K_T = \frac{H_{ave}}{H_{o,ave}} \text{ -- } (10),$$

where:

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H_{ave} is the monthly average radiation on the horizontal surface of the earth (kWh/m^2/day)

$H_{o,ave}$ is the *extraterrestrial horizontal radiation*, meaning the radiation on a horizontal surface at the top of the earth's atmosphere (kWh/m^2/day)

Mathematically, the output of the PV array are calculated by HOMER using the following equation(Help Manual, 2015):

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) \left[1 + \alpha_P \left(T_c - T_{c,STC} \right) \right] \qquad \text{------ (11),}$$

where

Y_{PV} is the rated capacity of the PV array, meaning its power output under standard test conditions [kW]

f_{PV} is the PV derating factor [%]

$\bar{G}_T$ is the solar radiation incident on the PV array in the current time step [kW/m^2]

$\bar{G}_{T,STC}$ is the incident radiation at standard test conditions [1 kW/m^2]

α_P is the temperature coefficient of power [%/°C]

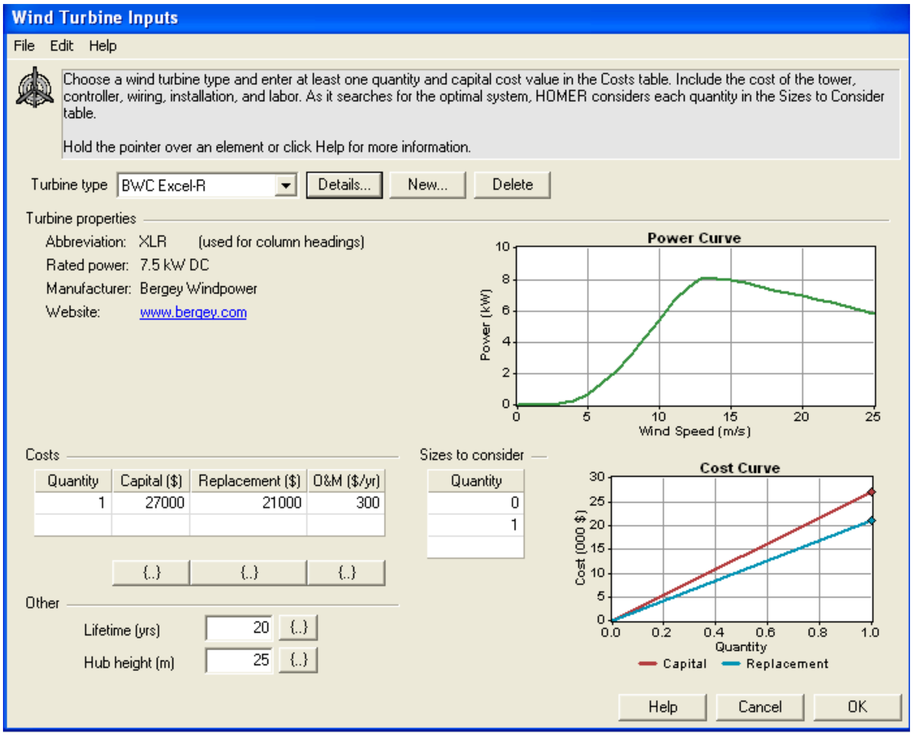
T_c is the PV cell temperature in the current time step [°C]

$T_{c,STC}$ is the PV cell temperature under standard test conditions [25 °C]

III. WIND TURBINE

Wind Turbine converts the wind energy to the mechanical torque, which rotates the shaft of an electrical generator to generate electrical energy (Hur, 2018; Zammit et al., 2017).The wind turbine in the power system generation can be defined by considering the wind turbine power curve, cut-in speed, and cut-out speed of the wind turbine. HOMER provides a library of several wind turbines already defined to choose from (select), but the wind turbine of ones interest (not found in the library)can be defined (create) based on the manufacturer specifications. By clicking on the wind turbine icon (selected or created) in HOMER, we are able to define the wind turbine used in the power system by entering the quantity (number of wind turbine), Capital Cost, Replacement Cost, Operations & Maintenance (O&M) expenditure, Operating Lifetime, and Hub height of the wind turbine. Full details of the chosen wind turbine can be seen by clicking the 'Details' button.

For the health facility in this exercise, a BWC Excel-R 7.5kW wind turbine (mounted on a standalone monopole) was considered as shown in Figure 11using the default model present in HOMER library. Due to the moving parts, maintenance for wind turbines is somewhat higher than for PV systems.



Choose a wind turbine type and enter at least one quantity and capital cost value in the Costs table. Include the cost of the tower, controller, wiring, installation, and labor. As it searches for the optimal system, HOMER considers each quantity in the Sizes to Consider table.

Hold the pointer over an element or click Help for more information.

Turbine type: BWC Excel-R

Turbine properties

Abbreviation: XLR (used for column headings)
Rated power: 7.5 kW DC
Manufacturer: Bergey Windpower
Website: www.bergey.com

Costs

Quantity	Capital ($)	Replacement ($)	O&M ($/yr)
1	27000	21000	300

Sizes to consider

Quantity
0
1

Other

Lifetime (yrs): 20
Hub height (m): 25

Figure 11: HOMER input for wind turbine

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a) Mathematical Model of Wind Energy Generator

Wind speed increases with height above ground. This is because; the ground-level obstacles such as vegetation, buildings, and topographic features tend to slow the wind near the surface. Since the effect of these obstacles decreases with height above ground, wind speeds tend to increase with height above ground. This variation of wind speed with height is called *wind shear*. HOMER uses wind shear to calculate the wind speed at the hub height of the wind turbine. Wind energy engineers typically models wind shear using the logarithmic profile mathematical model.

The logarithmic profile (or log law) assumes that the wind speed is proportional to the logarithm of the height above ground. The following equation gives the ratio of the wind speed at hub height to the wind speed at anemometer height(HOMER help, 2015):

$$\frac{v(z_{hub})}{v(z_{anem})} = \frac{\ln(z_{hub}/z_o)}{\ln(z_{anem}/z_o)} \text{ -------------------------------- (12),}$$

where:

z_{hub} = the hub height of the wind turbine [m]

z_{anem} = the anemometer height [m]

z_o = the surface roughness length [m]

$v(z_{hub})$ = wind speed at the hub height of the wind turbine [m/s]

$v(z_{anem})$ = wind speed at anemometer height [m/s]

$\ln(...)$ = the natural logarithm

The surface roughness length is a parameter that characterizes the roughness of the surrounding terrain. The representative surface roughness lengths taken from Manwell, McGowan, and Rogers (2002) are shown in Table A2 of the supplementary data.

Step Seven: Calculate Results

HOMER model can be used to compare costs for a variety of different energy generation systems that can meet 100% of this clinic's load. By clicking the Calculate button, the program runs the simulation of different permutations of all possible configurations of system types based on the inputs provided. After the design system had completely simulated, the best possible system configurations will be determined under optimization process. HOMER sorts the feasible cases in order of increasing net present (or lifecycle) cost. This cost is the present value of the initial, component replacement, operation, maintenance, and fuel costs(User Manual, 2016). HOMER lists the optimal system configuration, defined as the one with the least net present cost, for each system type.

In this investigation, and by Ani (2014)an attempt was made to determine for each region and regarding the selected components, which of the mix renewable energy (PV/wind/battery) or hybrid system (PV/wind/diesel/battery; PV/diesel/battery; wind/diesel/battery) is the optimal power system. A 60% renewable fraction was used as criteria for the energy solution. The components needed to satisfy the health facility centre's annual load of 7,082kWh are shown in Figure 12.

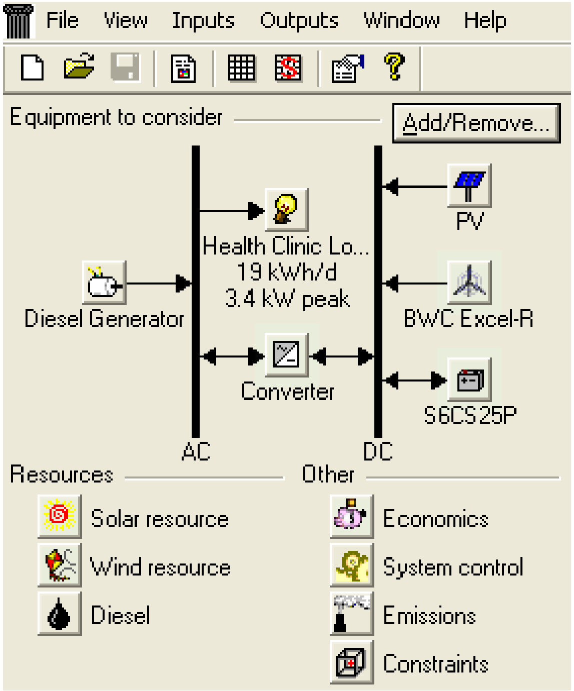

Figure 12: The network architecture (HOMER simulator) for the hybrid energy system of the health facility centre

b) Mathematical Cost Model (Economic & Environmental Costs) of Energy Systems

The equation for estimating the level of optimization of any energy solution being considered for a health clinic and location is derived as below:

c) The Annualized Cost of a Component

The annualized cost of a component includes annualized capital cost, annualized replacement cost, annual O&M cost, emissions cost and annual fuel cost (generator). Operation cost is calculated hourly on daily basis (Ani, 2015):

d) Annualized Capital Cost

The annualized capital cost of a system component is equal to the total initial capital cost multiply by the capital recovery factor. Annualized capital cost is calculated using (Ani, 2015):

$$C_{acap} = C_{cap} \cdot CRF(i, R_{proj}) \text{ ---------------------------- (13),}$$

where:

C_{cap} =initial capital cost of the component

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$CRF(i, R_{proj})$ =capital recovery factor

e) Annualized Replacement Cost

The annualized replacement cost of a system component is the annualized value of all the replacement costs occurring throughout the lifetime of the project, minus the salvage value at the end of the project lifetime. Annualized replacement cost is calculated using (Ani, 2015):

$$C_{arep} = C_{rep} \cdot f_{rep} \cdot SFF(i, R_{comp}) - S \cdot SFF(i, R_{proj}) \tag{14}$$

f_{rep}, a factor arising because the component lifetime can be different from the project lifetime, is given by(Ani, 2015):

$$f_{rep} = \begin{cases} CRF(i, R_{proj}) / CRF(i, R_{rep}), & R_{rep} > 0 \\ 0 \qquad , & R_{rep} = 0 \end{cases} \tag{15}$$

R_{rep}, the replacement cost duration, is given by(Ani, 2015):

$$R_{rep} = R_{comp} \cdot INT\left(\frac{R_{proj}}{R_{comp}} \right) \tag{16}$$

where $INT(\ )$ is the integer function, returning the integer portion of a real value.

$SFF(\ )$, the sinking fund factor is a ratio used to calculate the future value of a series of equal annual cash flows, is given by(User Manual, 2016):

$$SFF(i, N) = \frac{i}{(1+i)^N - 1} \tag{17}$$

The salvage value of the component at the end of the project lifetime is proportional to its remaining life. Therefore the salvage value S is given by(User Manual, 2016):

$$S = C_{rep} \cdot \frac{R_{rem}}{R_{comp}} \tag{18}$$

where R_{rem}, the remaining life of the component at the end of the project lifetime is given by(User Manual, 2016):

$$R_{rem} = R_{comp} - (R_{proj} - R_{rep}) \tag{19}$$

where:

C_{rep} = replacement cost of the component

$SFF(\ )$= sinking fund factor

i = interest rate

R_{comp} = lifetime of the component

R_{proj} = project lifetime

N = number of years

f) Annualized Operating Cost

The operating cost is the annualized value of all cost and revenues other than initial capital costs and is calculated using (Ani, 2015):

$$C_{aop} = \sum_{t=1}^{365} \left\{ \sum_{t=1}^{24} [C_{oc}(t)] \right\} \tag{20}$$

where $C_{oc}(t)$ is the Cost of operating component.

g) Cost of Emissions

HOMER uses the following equation to calculate the cost of emissions (Ani, 2015; User Manual, 2016):

$$C_{emissions} = \frac{c_{CO_2} M_{CO_2} + c_{CO} M_{CO} + c_{UHC} M_{UHC} + c_{PM} M_{PM} + c_{SO_2} M_{SO_2} + c_{NO_x} M_{NO_x}}{1000} \tag{21}$$

where:

c_{CO_2} = cost for emissions of CO_2 [\$/t]

c_{CO} = cost for emissions of CO [\$/t]

c_{UHC} =cost for emissions of unburned hydrocarbons (UHC) [\$/t]

c_{PM} =cost for emissions of particulate matter (PM) [\$/t]

c_{SO_2} =cost for emissions of SO_2 [\$/t]

c_{NO_x} =cost for emissions of NO_x [\$/t]

M_{CO_2} =annual emissions of CO_2 [kg/yr]

M_{CO} =annual emissions of CO [kg/yr]

M_{UHC} =annual emissions of unburned hydrocarbons (UHC) [kg/yr]

M_{PM} =annual emissions of particulate matter (PM) [kg/yr]

M_{SO_2} =annual emissions of SO_2 [kg/yr]

M_{NO_x} =annual emissions of NO_x [kg/yr]

Total cost of a component = Economic cost + Environmental cost

Where:

Economic cost = Capital cost + Replacement cost + Operation & Maintenance cost + Fuel cost (Generator)

Environmental cost = Emissions cost

Annualized cost of a component is calculated using (Ani, 2015):

$$C_{ann} = C_{acap} + C_{arep} + C_{aop} + C_{emissions} \text{ -- } (22)$$

Annualized total cost of a component is calculated using (Ani, 2015):

$$C_{ann,tot,c} = \sum_{c=1}^{N_c} \left(C_{acap,c} + C_{arep,c} + C_{aop,c} + C_{emissions} \right) \text{ -- } (23),$$

where:

$C_{acap,c}$ = Annualized capital cost of a component

$C_{arep,c}$ = Annualized replacement cost of a component

$C_{aop,c}$ = Annualized operating cost of a component

From equation (23), the Economic and Environmental cost model of running Hybrid (Wind & Solar) + Diesel Generator + Batteries+ Converter is calculated as(Ani, 2015):

$$\begin{aligned} C_{ann,tot,w+s+g+b+c} = {} & \sum_{w=1}^{N_w} \left(C_{acap,w} + C_{arep,w} + C_{aop,w} + C_{emissions} \right) + \sum_{s=1}^{N_s} \left(C_{acap,s} + C_{arep,s} + C_{aop,s} + C_{emissions} \right) + \\ & \sum_{g=1}^{N_g} \left(C_{acap,g} + C_{arep,g} + C_{aop,g} + C_{emissions} + C_{afg} \right) + \sum_{b=1}^{N_b} \left(C_{acap,b} + C_{arep,b} + C_{aop,b} + C_{emissions} \right) + \\ & \sum_{c=1}^{N_c} \left(C_{acap,c} + C_{arep,c} + C_{aop,c} \right) \text{ ------------------------------------ } (24), \end{aligned}$$

where:

$C_{acap,w}$ = Annualized Capital Cost of Wind Power

$C_{arep,w}$ = Annualized Replacement Cost of Wind Power

$C_{aop,w}$ = Annualized Operating Cost of Wind Power

$C_{emissions}$ = Cost of Emissions

$C_{acap,s}$ = Annualized Capital Cost of Solar Power

$C_{arep,s}$ = Annualized Replacement Cost of Solar Power

$C_{aop,s}$ = Annualized Operating Cost of Solar Power

$C_{acap,g}$ = Annualized Capital Cost of Diesel Generator

$C_{arep,g}$ = Annualized Replacement Cost of Diesel Generator

$C_{aop,g}$ = Annualized Operating Cost of Diesel Generator

$C_{af,g}$ = Annualized Fuel Cost for Diesel Generator

$C_{acap,b}$ = Annualized Capital Cost of Batteries Power

$C_{arep,b}$ = Annualized Replacement Cost of Batteries Power

$C_{aop,b}$ = Annualized Operating Cost of Batteries Power

$C_{acap,c}$ = Annualized Capital Cost of Converter Power

$C_{arep,c}$ = Annualized Replacement Cost of Converter Power

$C_{aop,c}$ = Annualized Operating Cost of Converter Power

The mathematical model derived estimates the life-cycle cost of the system, which is the total cost of installing and operating the system over its lifetime. The output when run with HOMER software/tool will give us the optimal configuration of the energy system that takes into account technical and economic performance of supply options (rated power characteristics for solar Photovoltaic (PV), power curve characteristics for wind turbine (WT), fuel consumption characteristics for diesel generators (DG) and minimum and maximum state of charge (SOC) of a battery bank), the 20-year life cycle cost (LCC) of equipment, locally available energy

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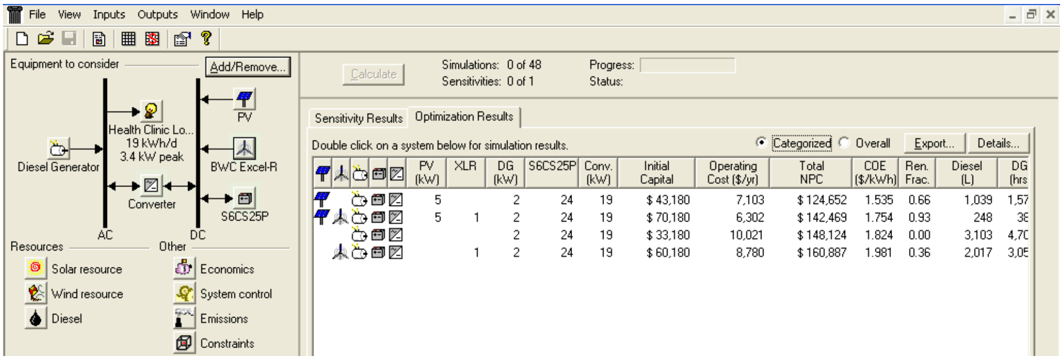
resources (hourly solar insolation data (W/m^2), hourly wind speed (m/s), as well as cost of fossil fuels), environmental costs, and system reliability.

IV. Simulation

Simulation process determines how a particular system configuration, a combination of system components of specific sizes, and an operating strategy that defines how those components work together, would behave in a given setting over a long period of time. HOMER simulates the operation of a system by making energy balance calculations for each of the 8,760 hours in a year(User Manual, 2016). For each hour, HOMER compares the electric demand of the health facility in the hour to the energy that the system (energy option) can supply in that hour, and calculates the flows of energy to and from each component of the system.

After running the simulations, HOMER sorts the feasible cases in order of increasing NPC (or lifecycle cost). This cost is the present value of the initial, component replacement, operation, maintenance, and fuel costs. HOMER lists the optimal system configuration, defined as the one with the least net present cost, for each system type. It is possible to display the overall (entire) list of configurations or to show the categorized lists (the best solutions from an economic perspective) per system design. Overall list of configuration is the simulation results, while the categorized lists is the optimization results.In this exercise, the optimization result panels in Figure 13 show the categorized list displayed four (a,b) to five (c) different configurations, ordered by most effective NPC.

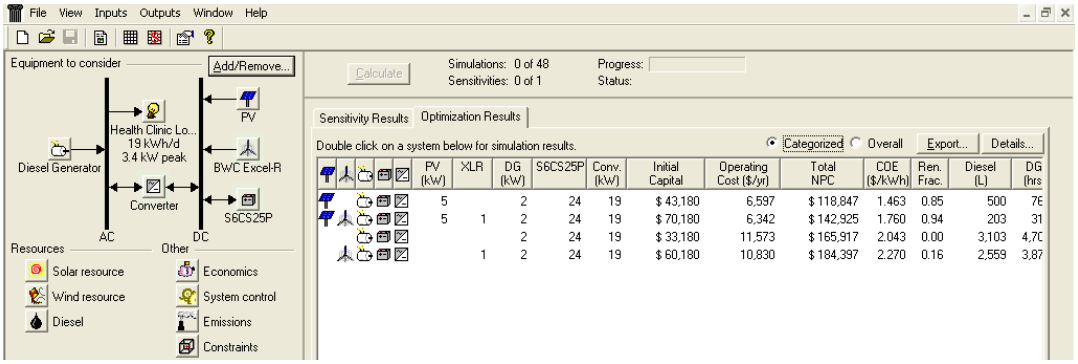


Simulations: 0 of 48
Sensitivities: 0 of 1

Double click on a system below for simulation results.

PV (kW)	XLR	DG (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs
5		2	24	19	$ 43,180	7,103	$ 124,652	1.535	0.66	1,039	1,57
5	1	2	24	19	$ 70,180	6,302	$ 142,469	1.754	0.93	248	38
		2	24	19	$ 33,180	10,021	$ 148,124	1.824	0.00	3,103	4,70
	1	2	24	19	$ 60,180	8,780	$ 160,887	1.981	0.36	2,017	3,05

a

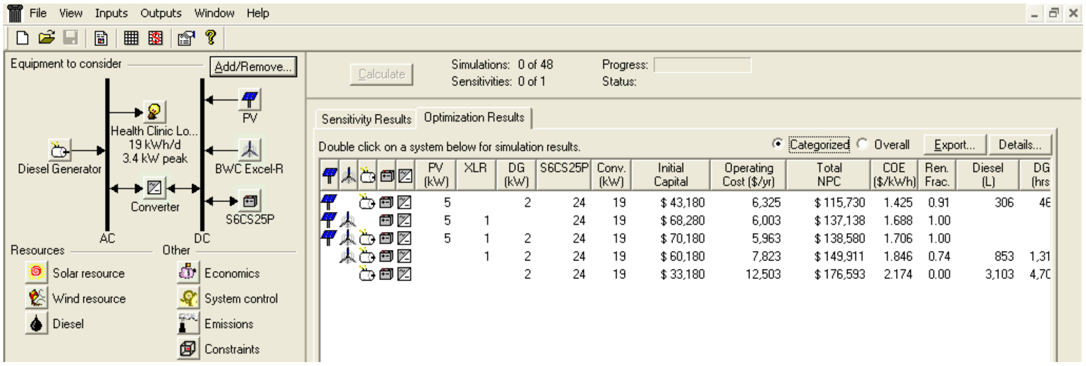


Simulations: 0 of 48
Sensitivities: 0 of 1

Double click on a system below for simulation results.

PV (kW)	XLR	DG (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs
5		2	24	19	$ 43,180	6,597	$ 118,847	1.463	0.85	500	76
5	1	2	24	19	$ 70,180	6,342	$ 142,925	1.760	0.94	203	31
		2	24	19	$ 33,180	11,573	$ 165,917	2.043	0.00	3,103	4,70
	1	2	24	19	$ 60,180	10,830	$ 184,397	2.270	0.16	2,559	3,87

b



Simulations: 0 of 48
Sensitivities: 0 of 1

Double click on a system below for simulation results.

PV (kW)	XLR	DG (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs
5		2	24	19	$ 43,180	6,325	$ 115,730	1.425	0.91	306	46
5	1		24	19	$ 68,280	6,003	$ 137,138	1.688	1.00		
5	1	2	24	19	$ 70,180	5,963	$ 138,580	1.706	1.00		
	1	2	24	19	$ 60,180	7,823	$ 149,911	1.846	0.74	853	1,31
		2	24	19	$ 33,180	12,503	$ 176,593	2.174	0.00	3,103	4,70

c

Figure 13: Optimization result panel for (a) Nembe, (b) Abaji, and (c) Guzamala

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By clicking on each of the displayed solution we can access a comprehensive set of data providing high level of detail on each system component such as economical information essential to run a thorough business case. HOMER's main financial output is the total NPC and COE of the examined system(s) configurations (Farid et al., 2017). The Cost summary and Cash Flow details represent a practical starting point for developing a customized business case, including financial indicators such as ROI (Return on Investment), payback period and NPV (Net Present Value), in comparison to the diesel generator only base case that will enable decision makers within health organizations to make accurate investment decisions. In addition it is possible to display many other relevant data concerning renewable (PV and wind turbine) equipment details (i.e. electrical production, hours of operation, etc.), diesel generator (i.e. diesel generator hours of operation, fuel consumption), batteries performances (battery state of charge histogram, etc.), and emissions, etc. These data were organized and presented in the supplementary data.

V. RESULTS AND DISCUSSION

Results in the supplementary data (Tables A3 – A14) show that the study of electrification options for the hypothetical health facility at various geographical locations (Nembe (Bayelsa State) in the south, Abaji (Abuja, FCT) in the centre, and Guzamala (Borno State) in the north) in Nigeria illustrate that the percentage of energy generated by both the solar and the wind renewable energy components of each of the hybrid system types tends to vary with the locations of the health facility; and that both the lifetime costof different energy system and the environmental impact of the hybrid energy system types studied vary significantly with the locations of the health facilities due to availability of the renewable energy resources and climatic conditions. Therefore in setting up power system for off-grid rural health facility in Nigeria, the following options were to be chosen based on different regions as this depends on climatic conditions and available renewable energy resources.

- Equatorial Region has two options (PV/diesel, and PV/wind/diesel)
- Tropical Region has also two options (PV/diesel, and PV/wind/diesel)
- Arid Region has four options (PV/diesel, PV/wind, PV/wind/diesel, and wind/diesel)

VI. CONCLUSION

This paper is a resource for health professionals seeking to electrify health facilities that currently lack power. A case study of a hypothetical off-grid health facility at various geographical locations in Nigeria was used to illustrate the stepwise approach to electrification of health facilities and demonstrate the utility of a modeling tool to assist in the critical task of system design. Information was provided to help the health professionals weigh the pros and cons of various energy systems with a focus on appropriate solutions and special considerations for off-grid rural health clinics. When considering the lifetime cost of different system designs, a modeling program HOMER is a valuable tool. HOMER simplifies the task of determining the most suitable combination of renewable source to supply a given load, and is, therefore, a useful tool in systems load sizing. The product could be used during the process of design, energy analysis and simulation of electrical power process in hybrid and stand-alone systems for energy supply of daily needs and technological processes in health clinics.

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Supplementary Data

Electrical Load Data

Table A1: The electrical load (Power supply requirements) data for a Health facility

S. No.	Power Consumption	Power (Watts)	Qty	Load (watt x qt)	Hours/day	On-Time (Time in Use)
1	Vaccine Refrigerator/Freezer	60	1	60	24	(0.00hr – 23.00hr)
2	Small Refrigerator (non-medical use)	300	1	300	5	(10.00hr – 15.00hr)
3	Centrifuge	575	1	575	2	(12.00hr – 14.00hr)
4	Hematology Mixer	28	1	28	2	(10.00hr – 12.00hr)
5	Microscope	15	1	15	5	(09.00hr – 14.00hr)
6	Security light	10	4	40	12	(18.00hr – 6.00hr)
7	Lighting	10	2	20	7	(09.00hr – 16.00hr)
8	Sterilizer Oven (Laboratory Autoclave)	1,564	1	1,564	1	(12.00hr – 13.00hr)
9	Incubator	400	1	400	24	(0.00hr – 23.00hr)
10	Water Bath	1,000	1	1,000	1	(14.00hr – 15.00hr)
	Communication via VHF Radio		1			
11	Stand-by	2		2	24	(0.00hr – 23.00hr)
12	Transmitting	30		30	4	(09.00hr – 13.00hr)
13	Desktop Computer	200	2	400	5	(09.00hr – 14.00hr)
14	Printer	65	1	65	3	(09.00hr – 10.00hr; 13.00 – 15.00hr)

Table A2: Surface roughness lengths (Manwell, McGowan, and Rogers, 2002)

Terrain Description	z_0
Very smooth, ice or mud	0.00001 m
Calm open sea	0.0002 m
Blown sea	0.0005 m
Snow surface	0.003 m
Lawn grass	0.008 m
Rough pasture	0.010 m
Fallow field	0.03 m
Crops	0.05 m
Few trees	0.10 m
Many trees, few buildings	0.25 m
Forest and woodlands	0.5 m
Suburbs	1.5 m
City center, tall buildings	3.0 m

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Power System Configurations

Table A3: Power system configurations for *Equatorial region (Nembe)*

Configurations	PV	BWC Excel-R Wind turbine	Diesel Generation	Surrette 6CS25P Battery	Converter	Renewable fraction (%)
PV/Diesel/Batt/Conv	5kW		2kW	24 units	19kW	66*
PV/Wind/Diesel/Batt/Conv	5kW	7.5kW	2kW	24 units	19kW	93*
Diesel/Batt/Conv			2kW	24 units	19kW	0
Wind/Diesel/Batt/Conv		7.5kW	2kW	24 units	19kW	36

*Significant renewable fraction exceeding 60%

Table A4: Power system configurations for *Tropical region (Abaji)*

Configurations	PV	BWC Excel-R Wind turbine	Diesel Generation	Surrette 6CS25P Battery	Converter	Renewable fraction (%)
PV/Diesel/Batt/Conv	5kW		2kW	24 units	19kW	85*
PV/Wind/Diesel/Batt/Conv	5kW	7.5kW	2kW	24 units	19kW	94*
Diesel/Batt/Conv			2kW	24 units	19kW	0
Wind/Diesel/Batt/Conv		7.5kW	2kW	24 units	19kW	16

*Significant renewable fraction exceeding 60%

Table A5: Power system configurations for *Arid region (Guzamala)*

Configurations	PV	BWC Excel-R Wind turbine	Diesel Generation	Surrette 6CS25P Battery	Converter	Renewable fraction (%)
PV/Diesel/Batt/Conv	5kW		2kW	24 units	19kW	91*
PV/Wind/Batt/Conv	5kW	7.5kW		24 units	19kW	100*
PV/Wind/Diesel/Batt/Conv	5kW	7.5kW	2kW	24 units	19kW	100*
Wind/Diesel/Batt/Conv		7.5kW	2kW	24 units	19kW	74*
Diesel/Batt/Conv			2kW	24 units	19kW	0

*Significant renewable fraction exceeding 60%

Simulation Results of Economic Cost

Table A6: Simulation results of Economic cost for *Equatorial region (Nembe)*

Parameter	PV/Diesel/ Batt/Conv	PV/Wind/Diesel/ Batt/Conv	Diesel/ Batt/Conv	Wind/Diesel/ Batt/Conv
Initial Cost	$43,180	$70,180	$33,180	$60,180
Operating Cost ($/yr)	7,103	6,302	10,021	8,780
Total NPC	$124,652	$142,469	$148,124	$160,887

Table A7: Simulation results of Economic cost for *Tropical region (Abaji)*

Parameter	PV/Diesel/ Batt/Conv	PV/Wind/Diesel/ Batt/Conv	Diesel/ Batt/Conv	Wind/Diesel/ Batt/Conv
Initial Cost	$43,180	$70,180	$33,180	$60,180
Operating Cost ($/yr)	6,597	6,342	11,573	10,830
Total NPC	$118,847	$142,925	$165,917	$184,397

Table A8: Simulation results of Economic cost for *Arid region (Guzamala)*

Parameter	PV/Diesel/ Batt/Conv	PV/Wind/ Batt/Conv	PV/Wind/Diesel/ Batt/Conv	Wind/Diesel/ Batt/Conv	Diesel/ Batt/Conv
Initial Cost	$43,180	$68,280	$70,180	$60,180	$33,180

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Operating Cost ($/yr)	6,325	6,003	5,963	7,823	12,503
Total NPC	$115,730	$137,138	$138,580	$149,911	$176,593

Simulation Results of Electricity Production

Table A9: Simulation results of Electricity production for *Equatorial region (Nembe)*

Parameter	PV/Diesel	PV/Wind/Diesel	Diesel	Wind/Diesel
PV	(6,220) 66%	(6,220) 60%	0%	0%
Wind	0%	(3,385) 33%	0%	(3,385) 36%
Diesel	(3,146) 34%	(750) 7%	(9,402) 100%	(6,112) 64%
Total	(9,366) 100%	(10,355) 100%	(9,402) 100%	(9,497) 100%

Table A10: Simulation results of Electricity production for *Tropical region (Abaji)*

Parameter	PV/Diesel	PV/Wind/Diesel	Diesel	Wind/Diesel
PV	(8,493) 85%	(8,493) 80%	0%	0%
Wind	0%	(1,502) 14%	0%	(1,502) 16%
Diesel	(1,512) 15%	(614) 6%	(9,402) 100%	(7,756) 84%
Total	(10,005) 100%	(10,608) 100%	(9,402) 100%	(9,258) 100%

Table A11: Simulation results of Electricity production for *Arid region (Guzamala)*

Parameter	PV/Diesel	PV/Wind	PV/Wind/Diesel	Wind/Diesel	Diesel
PV	(9,138) 91%	(9,138) 55%	(9,138) 55%	0%	0%
Wind	0%	(7,490) 45%	(7,490) 45%	(7,490) 74%	0%
Diesel	(925) 9%	0%	0%	(2,568) 26%	(9,402) 100%
Total	(10,062) 100%	(16,628) 100%	(16,628) 100%	(10,058) 100%	(9,402) 100%

Simulation Results of Environmental Impact

Table A12: Simulation results of Environmental impact for *Equatorial region (Nembe)*

Parameter	PV/Diesel	PV/Wind/Diesel	Diesel	Wind/Diesel
Fuel Consumption (L)	1,039	248	3,103	2,017
Hour of diesel consumption (hrs)	1,578	380	4,701	3,056
Carbon dioxide (kg/yr)	2,736	654	8,170	5,311
Carbon monoxide (kg/yr)	6.75	1.61	20.2	13.1
Unburned hydrocarbon (kg/yr)	0.748	0.179	2.23	1.45
Particulate matter (kg/yr)	0.509	0.122	1.52	0.988
Sulphur dioxide (kg/yr)	5.49	1.31	16.4	10.7
Nitrogen oxides (kg/yr)	60.3	14.4	180	117

Table A13: Simulation results of Environmental impact for *Tropical region (Abaji)*

Parameter	PV/Diesel	PV/Wind/Diesel	Diesel	Wind/Diesel
Fuel Consumption (L)	500	203	3,103	2,559
Hour of diesel consumption (hrs)	764	311	4,701	3,878

Carbon dioxide (kg/yr)	1,317	535	8,170	6,740
Carbon monoxide (kg/yr)	3.25	1.32	20.2	16.6
Unburned hydrocarbon (kg/yr)	0.36	0.146	2.23	1.84
Particulate matter (kg/yr)	0.245	0.0996	1.52	1.25
Sulphur dioxide (kg/yr)	2.65	1.07	16.4	13.5
Nitrogen oxides (kg/yr)	29	11.8	180	148

Table A14: Simulation results of Environmental impact for *Arid region (Guzamala)*

Parameter	PV/Diesel	PV/Wind	PV/Wind/Diesel	Wind/Diesel	Diesel
Fuel Consumption (L)	306	0	0	853	3,103
Hour of diesel consumption (hrs)	466	0	0	1,318	4,701
Carbon dioxide (kg/yr)	805	0	0	2,246	8,170
Carbon monoxide (kg/yr)	1.99	0	0	5.54	20.2
Unburned hydrocarbon (kg/yr)	0.22	0	0	0.614	2.23
Particulate matter (kg/yr)	0.15	0	0	0.418	1.52
Sulphur dioxide (kg/yr)	1.62	0	0	4.51	16.4
Nitrogen oxides (kg/yr)	17.7	0	0	49.5	180