Supplementary Materials

Section 1

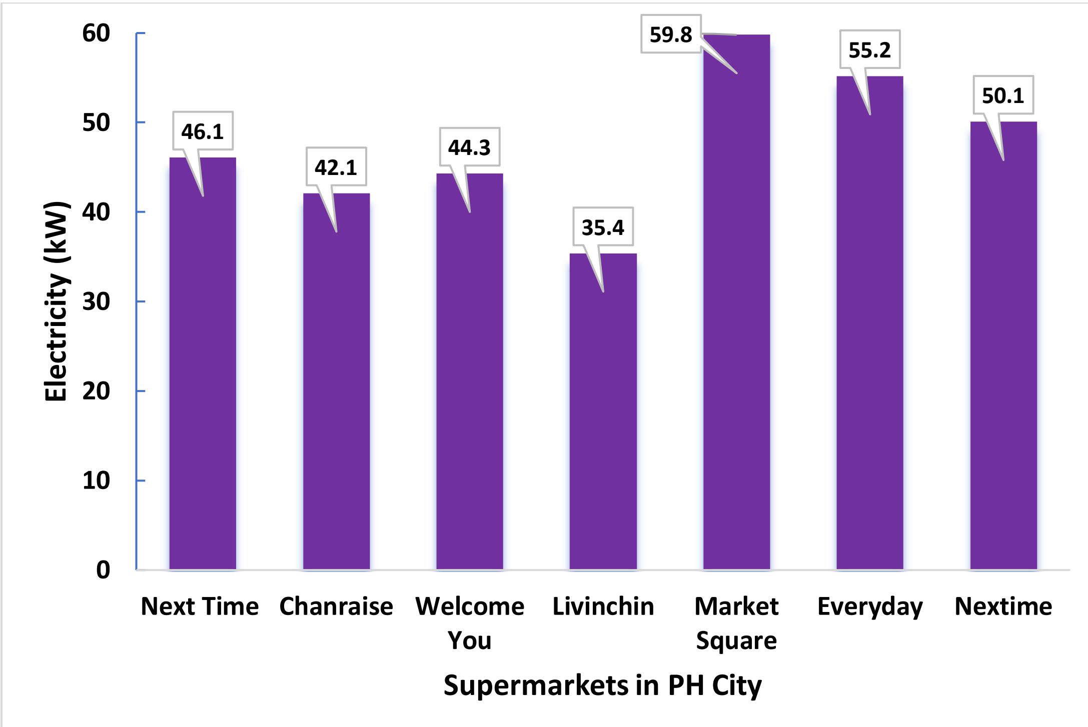
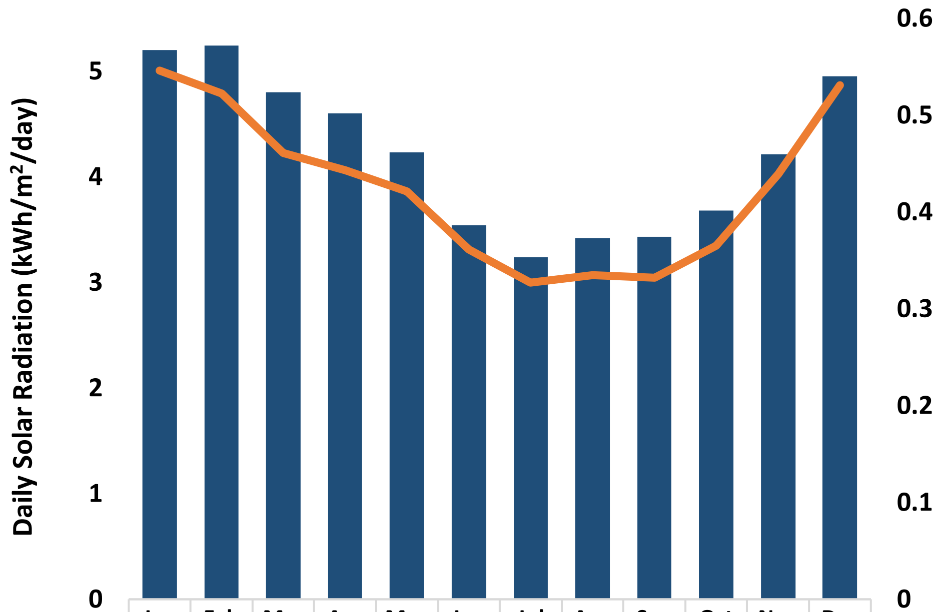


Figure 1: The power consumption of different supermarkets in Port Harcourt.

Table 1: Electrical load at Market Square Supermarket (Source: Ijeoma et. al. 2023)

Appliance	Rating (W)	Quantity	Total Power Rating (kW)	Daily Usage (h/day)	Energy (E) (kWh/day)
Refrigeration – back freezer	1125	2	2.25	24	54.0
Refrigeration – back cooler	1100	2	2.20	24	52.8
Refrigeration – store freezer closed	1100	8	8.80	2	35.2
Refrigeration – store freezer open	1300	3	3.90	2	15.6
Refrigeration – store cooler closed	1100	9	9.90	2	39.6
Lighting – Fluorescent	32	155	4.96	12	59.8
Air Conditioning	22,500		22,500	12	270
Cooking machine	1782		1.78	2	3.6
Water Heater	1100		1.10	2	2.2
ICT – ATM Machine	700	1	0.70	12	8.4
ICT – Computer, Printer	158	3	0.47	12	5.7
ICT – Register	200	6	1.20	12	14.4
TOTAL			**59.8**		**561**

Section 2



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Daily Radiation (kWh/m2/day	5.2	5.24	4.8	4.6	4.23	3.54	3.24	3.42	3.43	3.68	4.21	4.95
Clearness Index	0.546	0.522	0.461	0.443	0.421	0.361	0.327	0.335	0.332	0.365	0.439	0.531

Figure 2: The monthly average horizontal irradiance and clearness index breakdown from NASA's POWER database. This breakdown contains data from January of 1984 to December of 2013.

Provide additional information about the city's daily solar profile and temperature (1). February and July witnessed the highest and lowest levels of solar radiation, measuring 5.24 kWh/m^2/day and 3.24 kWh/m^2/day, respectively. The average amount of solar radiation is equivalent to 4.2 hours of peak sunlight daily, which indicates a considerable amount of solar energy available for conversion into electricity. The Figure also shows the clearness index of PH city.

Clearness index is the measure of the brightness and cloudiness of the sky at the site. This index is in the range of zero (0) and one (1) where zero indicates completely cloudy sky and one indicates perfectly sunny sky. The clearness index of the location shows a clear indication of the difference in the performance of solar system based on the clearness index of each month. The system could perform better from November to May, with January being the best month.

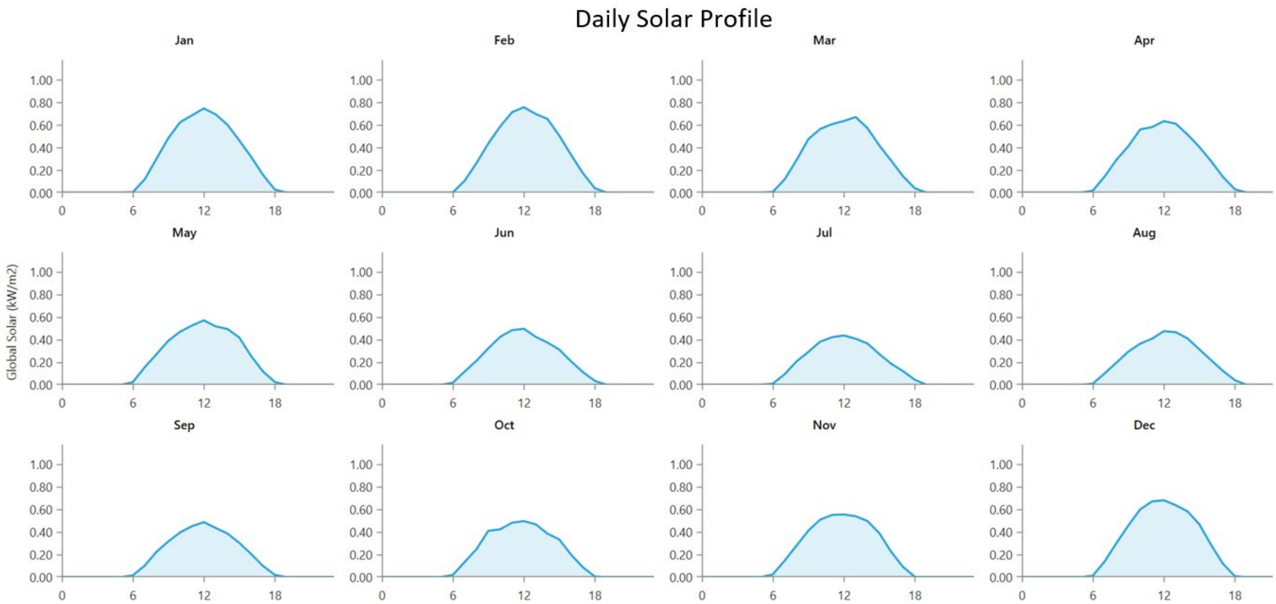


Figure 3: The average monthly daily solar profile for Port Harcourt in kW/m^2. These daily solar profile breakdowns of each month stem from data agglomerated from NASA's POWER database from January of 1984 to December of 2013.

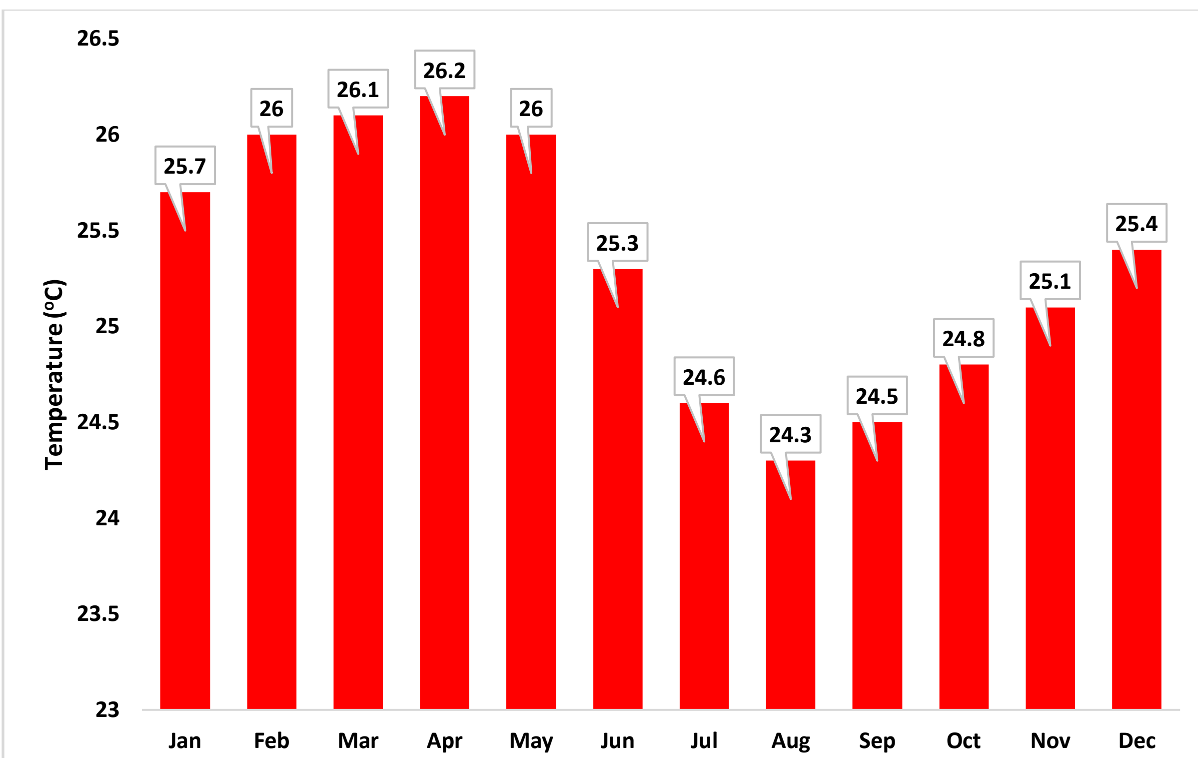


Figure 4: The monthly average temperature breakdown for Port Harcourt from NASA's Prediction of Worldwide Energy Resource (POWER) database. This breakdown contains data from January of 1984 to December of 2013.

Section 3

- Solar PV module

HOMER calculations of Power output of PV module

The power out of a PV module is evaluated using Equation 1.

$$\boldsymbol{P_{out} = P_{pv} f_{pv} \left(\frac{G_T}{G_{T_{STC}}}\right)\left[1 + \propto_p \left(T_c - T_{c_{STC}}\right)\right]} \qquad \textit{\textbf{Equation 1}}$$

Where P_{pv} is the rated power of the PV module at STC, f_{pv} is the derating factor of the PV module (%), G_T is the radiation incident on the PV module (W/m^2), $G_{T_{STC}}$ is radiation incident at STC of 1000 W/m2, T_c is the PV operating cell temperature (^{o}C), and $T_{c_{STC}}$ is the PV cell temperature at STC (25^{o}C) (2).

- Battery Storage

The battery storage bank life is calculated in HOMER using the following equations:

$$\boldsymbol{R_{batt} = \frac{N_{bat} \times Q_{lifeime}}{Q_{thrpt}}} \qquad \textit{\textbf{Equation 2}}$$

$$\boldsymbol{R_{batt} = R_{batt,f}} \qquad \textit{\textbf{Equation 3}}$$

Where R_{batt} is the storage bank life (yr.), N_{bat} is the number of batteries in the storage bank, $Q_{lifeime}$ is the lifetime throughput of a single storage (kWh) and $R_{batt,f}$ is the storage float life (yr.)

- Generator System

HOMER utilizes the following equation to compute the average total efficiency of a generator system:

$$\boldsymbol{\mu_{get\_tot} = \frac{3.6 \times E_{gen} H_{gen}}{m_{fuel} LHV_{fuel}}} \qquad \textit{\textbf{Equation 4}}$$

Where Egen is the generators total annual electrical production in kWh/yr., H_{gen} is the total generators annual thermal production in kWh/yr., m_{fuel} is total fuel consumption in kg/yr., and LVH_{fuel} is the lower heating value of the fuel (MJ/yr.). We should note that the 3.6 in the equation represents 1 kWh = 3.6 MJ (3).

Table 2: Specification of the selected components of the hybrid PV/battery/generator energy system HOMER model

Description	Specification	Remarks/References
PV modules		
PV model	Generic flat plate	Authors Selection in HOMER
Rated capacity	380 kW	Model Specification in HOMER
Capital cost	$180 USD/kW	Alibaba (4) / Ijeoma et al. 2023 (1)
Replacement cost	$60 USD/kW	Authors assumption
Operation and Maintenance	$2,084.9 (USD/year)	5% of initial investment cost / Ijeoma et al. 2023 (1)
Derating Factor	80%	Authors conservative assumption
Lifetime	25 years	Model Specification in HOMER
Inverter		
Inverter mode	Generic large plate	Authors Selection in HOMER
Rated power	354 kW	Model Specification in HOMER
Capital cost	$23 USD/kW	Ijeoma et.al. 2023 (1) /Alibaba ((5)
Replacement cost	$23 USD/kW	Authors assumption
Conversion efficiency	95%	Model Specification in HOMER
Expected lifetime	15 years	Model Specification in HOMER
Storage battery		
Battery model	Hoppecke 24 OPzS 3000	Authors Selection in HOMER
Nominal Voltage	2V	Model Specification in HOMER
Maximum state of charge	610 A	Model Specification in HOMER
Minimum state of charge	30%	Model Specification in HOMER
Round trip efficiency	86%	Model Specification in HOMER
Nominal energy capacity per battery	7.15 kWh	Model Specification in HOMER
Nominal capacity	7.15 kWh	Model Specification in HOMER
Maximum Capacity	3570 Ah	Model Specification in HOMER
Capital cost	$300 USD/battery	Ijeoma et. al. 2023(1) /Alibaba ((6))
Replacement cost	$100 USD/battery	Authors assumption
Operation and Maintenance cost	$4,950 USD/year	Authors assumption - 13 % of capital cost (Conservative)/ Ijeoma et al. 2023
Float life	15 years	Ijeoma et. al. 2023 (1)
Generator		
Generator type	Autosize Genset	Authors Selection in HOMER
Rated power	91 KW	HOMER optimization selection
Capital cost	$583 USD/kW	Ijeoma et al. 2023/Alibaba (7)
Replacement Cost	$583 USD/kW	Authors assumption
Operation and maintenance cost	$0.03 USD/operation hour	Authors assumption
Fuel Price	$0.337 USD/kW	HOMER Assumption based on $0.673/L
Expected Lifetime	15,000 hours	Ijeoma et al. (2023) (1)
Minimum load ratio	25%	Authors Assumption

Section 4

- HOMER LCOE Calculations

LCOE is calculated in HOMER Pro using Equation 5.

$$\boldsymbol{LCOE = \frac{C_{ann\_tot} - C_{boiler}H_{served}}{E_{served}}} \qquad \textbf{Equation 5}$$

Where C_{ann_tot} is the total annualized cost of the system in USD/yr., H_{served} is the total thermal load served in kWh/yr., C_{boiler} is the boiler marginal cost in USD/yr., and the E_{served} is the total electrical load served in kWh/yr. it's important to note that in wind and PV systems, that do not serve thermal load H_{served} is set to zero (8). The C_{ann_tot} is calculated using *Equation 6*.

$$\boldsymbol{C_{ann\_tot} = C_{NPC} \times CRF} \qquad \textbf{Equation 6}$$

Where C_{NPC} is the total NPC, and CRF is the capital recovery rate, and it is calculated in HOMER using *Equation 7* and *Equation 8*.

$$\boldsymbol{CRF = \frac{i\,(1+i)^n}{(1+i)^n-1}} \qquad \textbf{Equation 7}$$

$$\boldsymbol{i = \frac{r-f}{1+f}} \qquad \textbf{Equation 8}$$

Where $\boldsymbol{i}$ is the annual real discount rate (%), n is the number of years (lifetime of the project), or is the nominal discount rate, and f is the inflation rate.

- NPV calculation

NPV can be calculated using the following equations:

$$NPV = \sum \frac{E_n[kWh]}{(i+r)^n} \times Unit\ Cost - Initial\ Cost - \sum \frac{C_{o\&m} + C_{repl}}{(1+r)^n}$$

Equation 9

$$NPV = Present\ Value\ of\ Benefit - Present\ Value\ of\ total\ investment$$

Equation 10

Where En is the energy generated, r is the interest rate, Unit Cost is the tariff rate, $C_{o\&m}$ is the operation and maintenance cost, C_{repl} is the cost of replacement, and n is the discounted cash flow year.

- Salvage Value

HOMER assumes linear depreciation of components, meaning that the salvage value of a component is directly proportional to its remaining life. It also assumes that the salvage value depends on the replacement cost rather than the initial capital cost. HOMER calculates salvage value using the following equation:

$$S = C_{rep} \times \frac{R_{rem}}{R_{comp}} \qquad \textbf{Example 11}$$

Where C_{rep} is the replacement cost ($), R_{comp} is the component lifetime, R_{rem} is the remaining life of the component at the end of the project lifetime, R_{rep} is the replacement cost duration. They are calculated using the following equations:

$$R_{rem} = R_{comp} - (R_{proj} - R_{rep}) \qquad \textbf{Example 12}$$

$$R_{rep} = R_{comp} - INT(\frac{R_{proj}}{R_{comp}}) \qquad \textbf{Example 13}$$

Where R_{proj} is the project lifetime, and INT () is a function that returns the integer amount of a real number.

Section 5

Table 3: Description of pollutants from the diesel generator in HOMER

Pollutant	Description
CO_2	Nontoxic greenhouse gas
CO	Poisonous gas produced by incomplete burning of carbon in fuel. I prevent delivery of oxygen to the body's organs and tissue leading to dizziness, headache, and dexterity.
UHC	Gaseous poisoning results from the incomplete combustion of carbon in fuel. It obstructs oxygen delivery to the tissues and organs of the body, resulting in vertigo, pain, and impaired dexterity.
PM	A combination of soot, smoke, and liquid droplets that can irritate the respiratory system and create haze in the air.
SO_2	Corrosive gas is produced during the combustion of fossil-fuels, such as diesel, oil, and coal. Induce respiratory complications, acid rain, and haze in the atmosphere.
NO_2	A range of nitrogen compounds, including nitric oxide (NO) and nitrogen dioxide (NO2), are produced during the high-temperature combustion of any fuel. As a result of these compounds, acid rain, respiratory issues, and pollution ensue.

Table 4: Impact categories descriptions

Impact Category	Reference Unit	Description
Global Warming Potential (GWP)	kg CO_2 eq	Global warming, an average rise in atmospheric temperature at the Earth's surface and in the troposphere, can alter global climate patterns. Global warming has natural and human causes. Emissions of CO_2, methane, etc. contribute to GWP.
Acidification Potential (AP)	kg SO_2 eq	A local environment becomes acidified as the hydrogen ion (H+) concentration rises. Air emissions of acidifying compounds can travel hundreds of kilometers before depositing as acid rain, fog, snow, dust, or smoke particle matter on soil or water. Sulphur dioxide and nitrogen oxides from fossil fuel burning cause the most acid rain.
Eutrophication Potential (EP)	kg N eq	Eutrophication is the introduction of nutrients such as nitrates and phosphates into an aquatic environment that boosts biological production (algae and weeds) and causes algal biomass buildup.
Photochemical Smog Formation (PSP)	kg O_3 eq	Diverse chemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOCs) in sunlight generate ground-level ozone. The impact on human health can lead to various respiratory complications, such as exacerbating symptoms associated with bronchitis, asthma, and emphysema.

Human Health Particulate (HHP)	PM2.5 eq	Particulate matter is a collection of small particles in ambient air that can cause adverse human health effects, including respiratory illness and death—for example, carbon monoxide and nitrogen oxide.

Table 5: TRACI 2.1 characterization factor.

Impact Category	**Factor**	**Unit**
Global Warming Potential - Air		
Carbon dioxide	1	kg CO_2 eq/kg CO_2
Acidification Potential - Air		
Nitrogen Oxides	0.7	kg SO_2 eq/kgNO_2
Sulfur Dioxide	1	kg SO_2 eq/kg SO_2
Eutrophication Potential - Air		
Nitrogen Oxides	0.0443	kg N eq/kgNO_2
HH Particulate Air		
PM10	0.228	PM2.5 eq/kg PM
Carbon Monoxide	0.00036	PM2.5 eq/kg CO
Sulfur Oxide	0.0611	PM2.5 eq/kg SO_2
Nitrogen Oxide	0.00722	PM2.5 eq/kg NO_2
Photochemical Smog formation - Air		
Carbon Monoxide	0.0556	kg O_3 eq/kg CO
Nitrogen Oxide	24.8	kg O_3 eq/kg NO_2
Eutrophication Potential - Water		
Nitrogen Oxide	0.291	kg N eq/kg NO_2

Section 6

Component design characteristics of the optimal BL system.

Table 6: **Solar PV System Characteristics**

Flat Plate PV Characteristics		
Parameters	**Value**	**Units**
Rated Capacity	313	kW
Mean Output	44.1	kW
Mean Output	1059	kWh/d
Capacity Factor	14.1	%
Hours of Operation	4447	hrs./yr.
Maximum Output	302	kW
PV Generation	386574	kWh/yr.
PV Penetration	96.3	%

kW-kilowatt, kWh/d-Kilowatt hour per day, hrs./yr. – hours per year, %-percent

Table 7: **Converter/Inverter Characteristics**

Inverter Characteristics		
Parameters	**Value**	**Units**
Capacity	117	kW
Energy In	2117591	kW/yr.
Maximum Output	81.9	kW
Capacity Factor	19.6	%

Table 8: **Generator System Characteristics and Fuel Consumption**

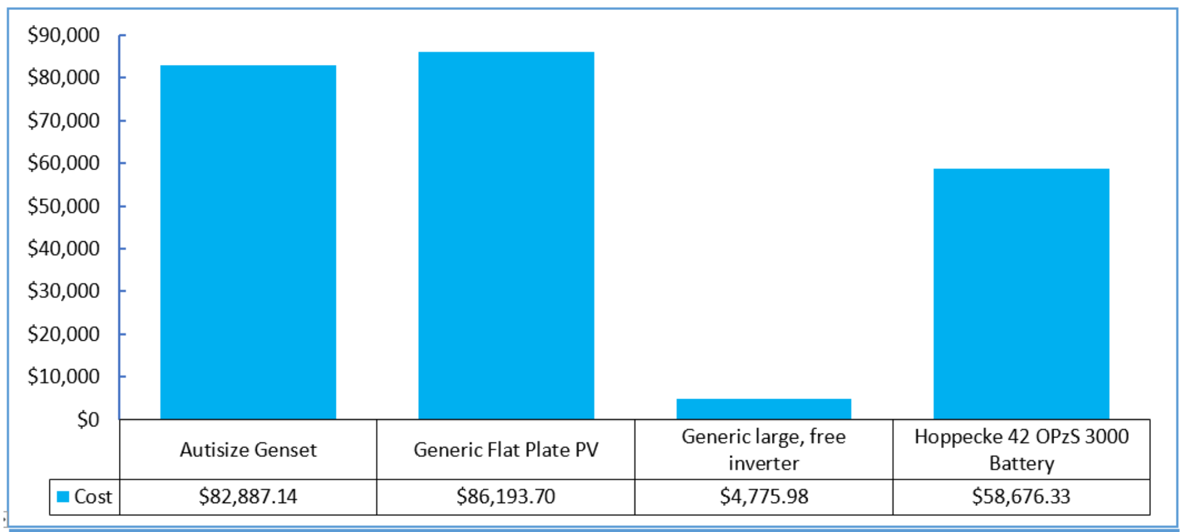
Genset Characteristics		
Parameters	**Value**	**Units**
Rated Capacity	91	kW
Hours of Operation	180	hrs./yr.
Number of Starts	28	starts/yr.
Operational Life	83.3	yr.
Capacity Factor	1.88	%
Electrical Production	15025	kWh/yr.
Mean Electrical output	83.5	kW
Mean Electricity Efficiency	36.6	%
Genset Fuel Consumption		
Fuel Consumption	4177	L
Avg fuel per day	11.4	L
Avg fuel per hour	0.477	L/hour
Fuel Specific Consumption	0.278	L/kWh

L-liter, L/kWh – liter per kilowatt hour

Table 9: **Battery Storage Characteristics**

Battery Characteristics		
Parameters	**Value**	**Units**
Rated Capacity	2/3000	V/Ah
Batteries	120	qty.
Strings Size	30	batteries
Strings in Parallel	4	strings
Bus Voltage	60	V
Nominal Capacity	858	kWh
Lifetime Throughput	1214196	kWh
Expected Life	14.5	yr.
Energy In	90279	kWh/yr.
Annual Throughput	83894	kWh/yr.

V/Ah – voltage/Hour, qty – quantity,



Component	Capital ($)	Replacement($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Autosize Genset	$53,053.00	$0.00	$5,245.59	$30,011.24	-$5,422.68	$82,887.14
Generic flat plat PV	$56,198.43	$0.00	$29,995.27	$0.00	$0.00	$86,193.70
Generic large, free inverter	$2,652.39	$836.14	$1,416.54	$0.00	-$129.10	$4,775.98
Hoppecke 24 OPzS 3000 Battery	$36,000.00	$3,939.47	$19,214.60	$0.00	-$477.74	$58,676.33
System	$147,903.82	$4,775.62	$55,871.99	$30,011.24	-$6,029.52	$232,533.15

Figure 5: economic analysis results of the BL system.

Section 7

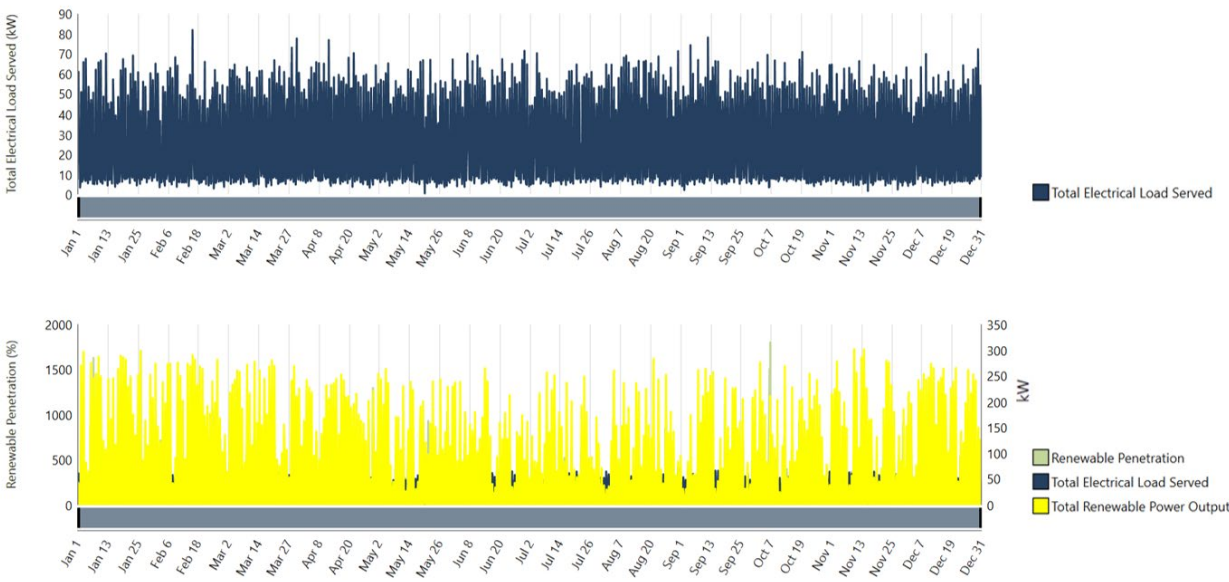


Figure 6: The annual total renewable power output for the Baseline System (BL) architecture.

Blue areas on the second graph indicate when the renewable energy output falls short of meeting the demand. These are the specific periods when the diesel generator is anticipated to activate and compensate for the unfulfilled energy requirement.

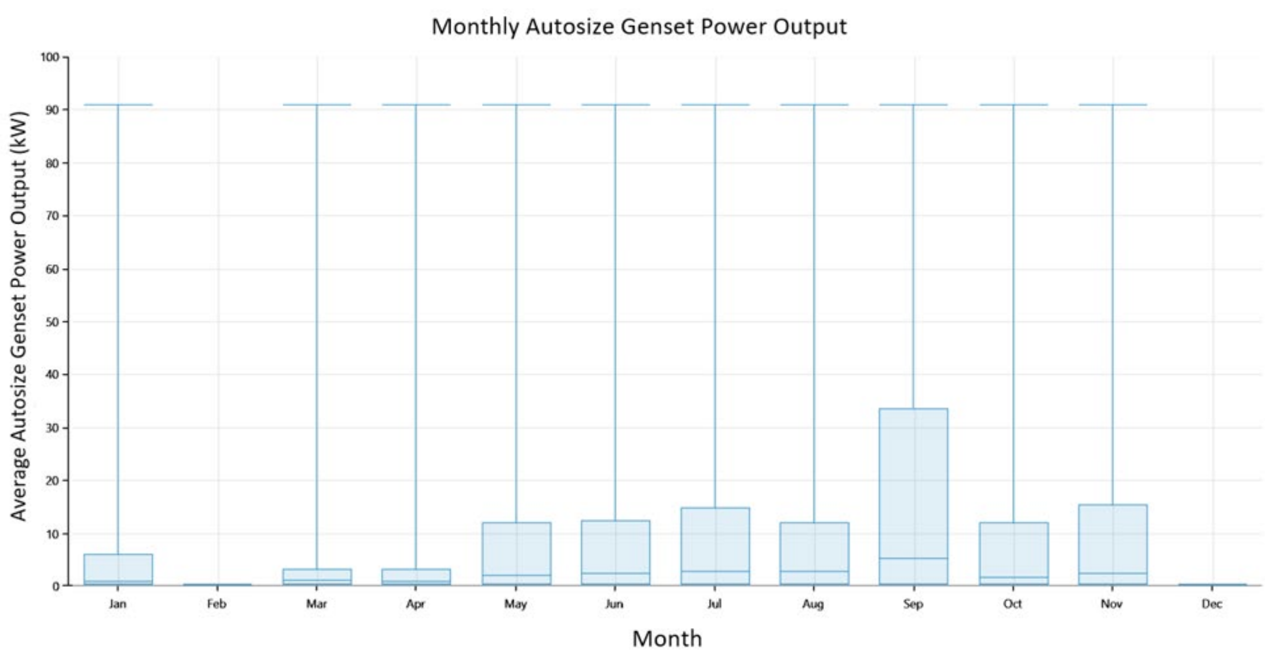


Figure 7: The mean monthly production of the diesel generator.

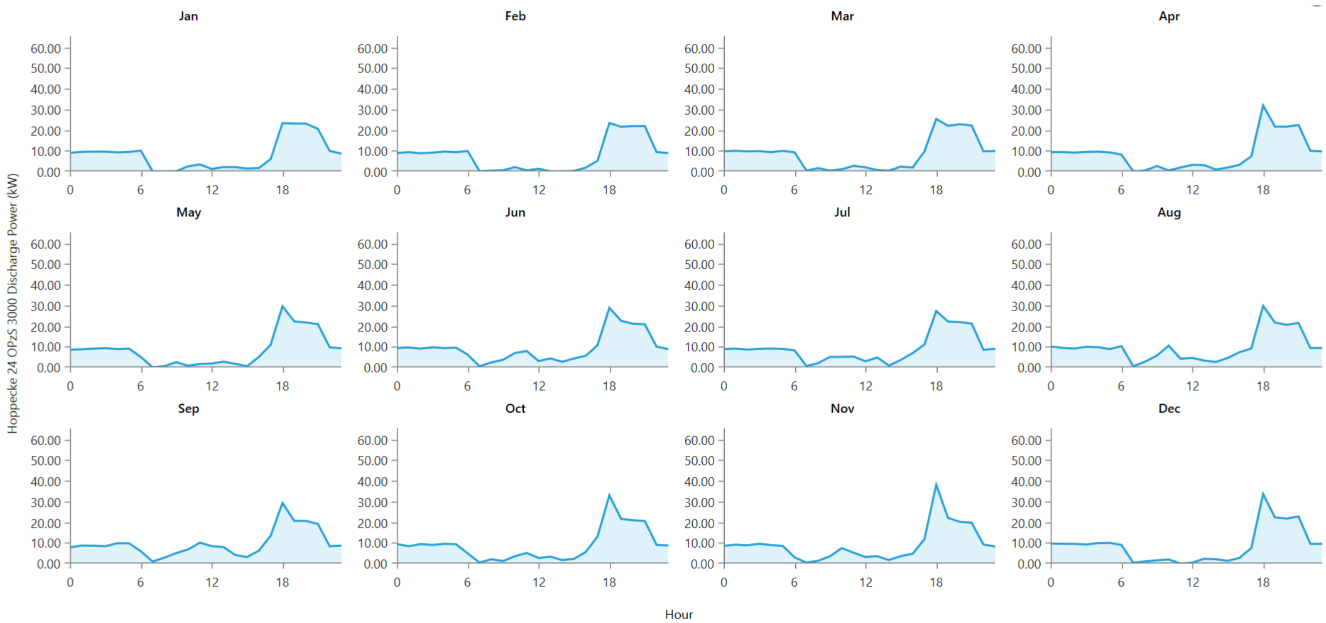


Figure 8: Average daily battery discharge profile for Baseline System (BL) architecture.

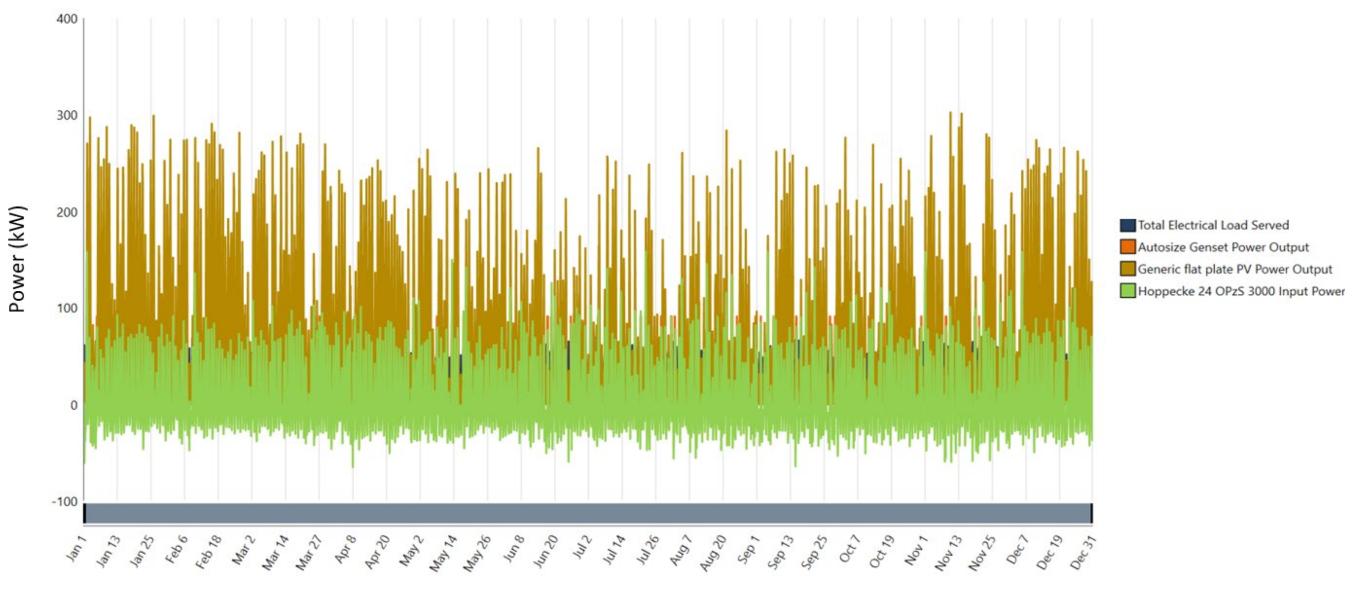


Figure 9: The time-series operation of the Baseline (BL) System.

The average daily battery discharge profile of the BL system architecture is shown in Figure 8. The findings indicate that the battery is functional during periods of insufficient energy generation by the PV system, specifically from 12 am to 6 am and 5 pm to midnight. During these time intervals, the battery system offsets the deficiency in energy generation by providing power to meet the required amount. This further signifies the importance of the battery system in ensuring uninterrupted power delivery during insufficient solar energy production periods.

The time-series operation showing the comprehensive functioning of the entire system is shown in Figure 9. The graph shows the load being fulfilled by solar PV, with gold representing this. The green color represents the input power from the PV used to charge the battery. The orange indicates the instances when the generator is used to satisfy the load demand. The graph vividly depicts the fluctuating behavior of the system, as the battery undergoes charging during periods of abundant solar energy production and discharging during periods of limited solar energy generation.

This iterative system enables a smooth and uninterrupted switch between various power sources, guaranteeing a steady and continuous provision of electricity during the day and at night. The battery system serves as a contingency power supply, providing uninterrupted electricity during low solar energy generation and automatically activating when the PV's electricity is insufficient to meet load requirements.

Reference

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4. Growatt 100 kw 200 kw 300 kw 500 kw Hybrid Solar Inverter on off Grid for Project Application-Buy 200 kw off Grid Hybrid Solar Inverter, Hybrid Solar Inverter on off 20 kw,100 kw 200 kw 300 kw 500 kw Hybrid Solar Inverter Product on Alibaba.com. Available online: https://www.alibaba.com/product-detail/Growatt-100Kw-200Kw-300Kw-500Kw-Hybrid_1600763410507.html?spm=a2700.galleryofferlist.0.0.f8aced02pJDHei (accessed on 1 June 2023).
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