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Master Thesis

Evaluation and optimization strategies for a photovoltaic UPS system as a replacement of fuel generators

Case study on the Nigerian electricity market

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Statutory Declaration

I herewith formally declare that I have written the submitted thesis independently. I did not use any outside support except for the quoted literature and other sources mentioned in the paper. I clearly marked and separately listed all the literature and all other sources which I employed when producing this academic work, either literally or in content. This work has not been submitted to another audit authority in the same or a similar form.

Berlin, 15.11.2021

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Abstract

This work aims to evaluate and optimize the technical performance as well as the economic and environmental framework of a photovoltaic uninterruptible power supply system (PV-Inverter-Battery) in two different sizes (800Wp-1000W-50Ah and 800Wp-3000W-100Ah) installed in different locations of Nigeria. The system presented is designed to bridge daily power outages and substitute small fuel generators on a large scale. To carry out the evaluation, real-time technical data and survey data from micro enterprises and households are collected and analyzed. Initial technical issues and data collection issues are identified and solved. Further operational strategies to optimize the system performance are proposed. The local grid availability, solar irradiation resources, and consumption patterns of the targeted users and their effects on the performance of the solar UPS system are analyzed. Real grid availability profiles from different locations in Nigeria, as well as load profiles and electricity consumption information from micro enterprises and households are derived. The consumption data reveal that the users could achieve tier 3 and tier 4 according to the Multi-Tier Framework of electrification. The evaluation of the economic framework proves that the utilization of Result-Based-Finance subsidies and long-term financial tools like Pay-As-You-Go make the solar UPS system an attractive alternative to the popular fuel generators. The average CO_2 mitigation per system resulted in four tons of CO_2 per year, showing that this product is a relevant element for achieving SDG7.

Keywords: electrification, power outages, Nigeria, RBF, PAYGO, SDG7

List of Abbreviations

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1. Introduction

The world's population access to electricity increased from 83% from 2010 to 90% in 2018 and according to the Social Development Goal (SDG) 7 it should reach 100% by 2030 [1]. Despite this accelerated progress in electrification, an estimated 1.5 billion people in 2019 experienced an unreliable electricity connection [2]. Grid outages that extend for hours or even days force people to rely on fossil fuel generators to meet their electricity demands. The extensive use of fossil fuel generators comes with immense economic, environmental, and health impacts [2]. Ensuring access to clean, reliable, and affordable energy is a key factor in developing countries to overcome extreme poverty as well as inequality and to stimulate sustainable human development [3]. Fossil fuel generators have for many years been the only financially viable and easily accessible alternative to unreliable and low quality grid connection [2]. The cost competitiveness of renewable energy compared to traditional electricity generation has steadily improved due to the rising prices of fossil fuels and the falling prices of renewable energy technologies such as PV.

1.1. Status Quo

Nigeria is the largest African economy in nominal GDP [4] and its population reached 206 million people in 2020 [5]. Despite its high economic importance in the region, Nigerian electrification efforts lagged behind population growth. In 2018, Nigeria reached the world's largest access-to-electricity-deficit in the world after India [1], with 43% of its population having no access to electricity [6]. Nigeria's electricity consumption per capita in 2018 was 160kWh [7]. This is clearly behind the world's average electricity consumption per capita of 3260kWh in 2018 [7]. This is a remarkable situation when considering that Nigeria is the largest oil producer and has the largest natural gas reserves on the continent [8]. The Nigerian electricity sector faces challenges in all its areas. The average electricity capacity, losses, and supply from 2015 are shown in figure 1.1. The installed generation capacity is 12.5GW, which is mainly covered by gas power plants (85%) and hydro power plants (14%). On average, due to maintenance and constraints, only 3,9GW are available for generation. After losses in transmission, distribution, and collection, only 3.1GW are distributed to the users [9].

Those who have access to grid electricity experience an unreliable electricity supply. Previous grid data collection in a Nigerian market showed that the grid is not available almost three-quarters of the time and power outages can extend over days [10]. Also, a survey conducted in 2014/2015 claims that 61% of the grid-connected people experience electricity service working ”never or occasionally” [11]. It is estimated that 80% of the grid-connected customers in Nigeria use alternatives such as fossil-fuel generators to meet their electricity demands during electricity outages [12]. The number of small gasoline generators (0-4kVA) that power small businesses and households is estimated to be 22 million [13].

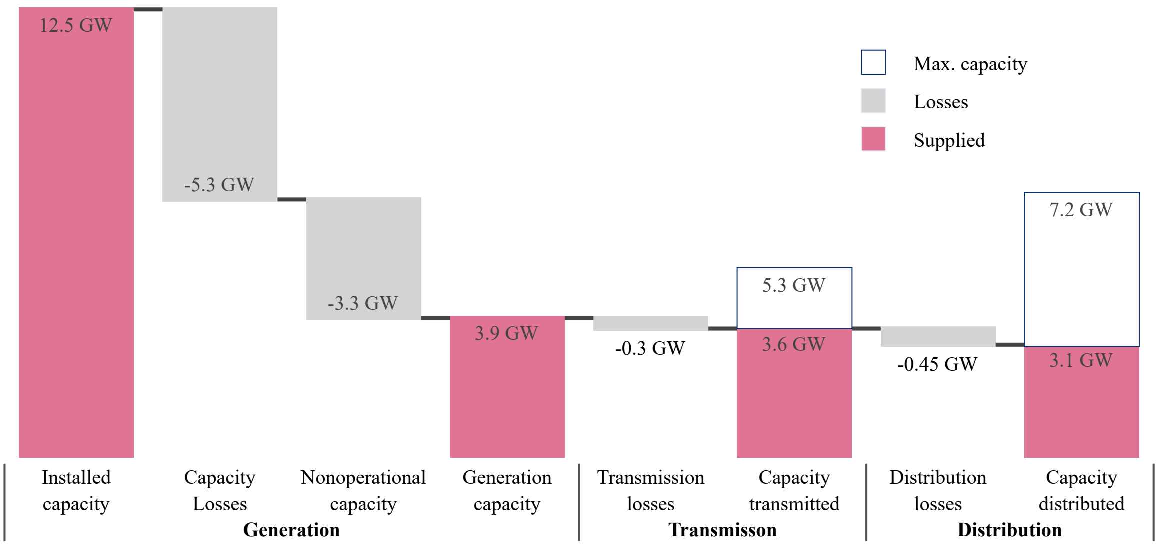

Figure 1.1.: Capacity, losses, and supply of Nigeria’s power sector [9]

Access to electricity plays an important role in socioeconomic development, such as creating employment and reducing poverty [14]. Especially for small firms, unreliable grids affect the productivity of Micro Enterprises (MEs) and their added value [15]. In 2014, a survey showed that 48% of the firms interviewed identify electricity as a major constraint [16]. MEs report that one of the main challenges is an unreliable electrical supply [14]. Ensuring access to reliable energy to MEs in Nigeria is also an opportunity to decrease gender inequality, where 43% of MEs are owned by female entrepreneurs [14].

Different scenarios for future electricity generation still show a predominantly fuel-based self-generation in Nigeria's electricity market [17]. Other studies show that different back-up renewable technologies like Solar Home System (SHS) with storage are still not cost effective compared to fuel-based generation for low-consumption customers [18]. Other research shows that taking into account rising fuel prices, the decrease in investment costs for PV-storage technologies, and the increasing operation cost for fuel generators, PV-storage systems can offer electricity consumers a viable alternative to fuel generators in the near future [2]. A techno-economic study on a PV with fuel generator mini-grid shows the importance of considering the outage duration, outage frequency, and user consumption level for system evaluation [19]. Previous research from A2EI showed that depending on the electricity consumption, a solar generator is able to replace fuel-based generators for "day-only" opening hour MEs. The same work also showed the economic advantages of a solar generator when operational and maintenance costs are considered. Despite the higher investment cost of a solar generator in comparison with a fuel-powered generator, a break-even point is reached after five years of operation. Currently, the initial investment cost for a 1.5kVA PV+Storage System ($2500) is very high compared to a 1.5kVA fuel-based generator ($150) [13]. Reducing the upfront cost with correct component sizing, external incentives, and supplying a long-term financing framework could also help PV+Storage backup systems break through and mass replace fuel-based generators.

1.2. The Project

The presented work is part of the Solar Killed the Generator Star (SKGS) project, in which a solar UPS system (PV-Inverter-Battery) in two different sizes (AAM1000-50Ah and AAM3000-100Ah) was launched in the Nigerian market in late 2020 as an affordable alternative to replace small fuel generators. This project is part of the Access to Energy Institute (A2EI), a non-profit and collaborative research and development institute focusing on the productive use of solar energy.

1.3. Research Objectives

This work aims to evaluate and optimize a solar UPS system's technical, economic, and environmental framework designed to replace fuel generators for MEs and households in locations with low grid quality in Nigeria. After the installation and first months of use of these systems, technical data from the systems and valuable experiences from the users and operators can be collected to evaluate and optimize the performance of the presented product. The following research questions are defined to carry out this evaluation:

1. Which hardware, software, and design issues need to be solved to ensure an optimal system installation, operation, and performance?

2. What are the current conditions of the local grid availability, solar irradiation resources, and consumption patterns of the targeted users and their effects on the performance of the solar UPS system?

3. Are the users experiencing a positive economic effect, and what is the environmental impact of replacing a small fuel generator with a solar UPS system?

The present study is expected to contribute to a better understanding of how solar UPS systems need to be designed to be a reliable and economically attractive alternative to replace polluting fuel generators on a large scale.

1.4. Research Design

Technical data and user information will be gathered from the installed systems to perform the evaluation. In an attempt to close the knowledge gap in the sector, national grid data, solar system performance data, and MEs electricity consumption data will be collected and analyzed. A Python-based data tool will be built to visualize, compare, and share the different results of the studied systems. Furthermore, to extend the understanding of the economic and environmental framework of MEs using backup PV-storage systems to replace fuel-based generators, additional information will be collected through a survey with the users. Several optimizations will be implemented and tested directly on the installed systems. Further optimization proposals will be discussed and proposed for future project stages. The impact on electricity reliability and economic and environmental benefits will be at the center of the analysis of possible optimizations.

2. Background

2.1. National grid electricity

The electricity network in Nigeria supplies power to just 55% of the total population. 84% of the people living in urban areas and 25% in rural areas have access to the national grid [6]. Nigeria's hydro power plants are concentrated in central Nigeria, and the thermal power plants are concentrated in southern Nigeria, where most of the generated power is also distributed [9]. The quality of the grid is defined by the level and stability of its voltage and frequency [20]. The nominal voltage of the national grid in Nigeria is 230V, and the nominal frequency is 50Hz.

2.1.1. Grid availability and reliability

The availability A of the grid defines which percentage of the intended demand time t_{dem} can be supplied by grid t_{sup}.

$$A = \frac{t_{sup}}{t_{dem}} \cdot 100\% \tag{2.1}$$

In addition, the available grid cannot be used entirely; the availability of the usable grid A_{use} is defined in this work by the time of usable input voltage of the inverter/charger $t_{sup,use}$, generally in the range from 180V to 250V.

$$A_{use} = \frac{t_{sup,use}}{t_{dem}} \cdot 100\% \tag{2.2}$$

A blackout is defined in this work by the temporal absence of the national grid. The grid reliability R can be measured by its failure rate or blackout frequency. This means the number of blackouts n_{bl} in a given period of demand time.

$$R = \frac{n_{bl}}{t_{dem}} \tag{2.3}$$

2.1.2. Grid Electricity Cost

The tariff for electricity can vary depending on the region and its use. The average tariff for commercial use is 38.9 Nairas/kWh ($0.11) [21]. Furthermore, electricity customers can be grouped into metered and non metered customers. Metered Customers usually have a prepaid meter, where customers first need to buy credit to get electricity from the grid. Non metered customers at the other side are connected directly to the grid and get a monthly estimated bill based on the total consumed energy in a cluster, divided by the number of customers. The estimated bill system is problematic since customers are forced to pay an estimated electricity tariff for consumed or non consumed electricity in a very unreliable grid. Approximately 60% of the customers in Nigeria are still not metered [22].

2.1.3. Multi-Tier Framework

To evaluate the impact of the presented system on the quality of life of the customers, it is necessary to define access to electricity. The binary measurement of grid connection as available or not available does not look at the quantity and quality of this connection. The World Bank and the International Energy Agency (IEA) developed in 2015 a Multi-tier Framework of electrification (MTF) to evaluate the quality and quantity of electricity access in detail [20]. The MTF approach evaluates access to electricity based on capacity, duration, reliability, voltage quality, affordability, legality, health, and safety [17]. The MTF standards for capacity and duration are shown in Table 2.1.

Table 2.1.: Multi-Tier Framework of electrification[20]

Attributes	Tier1	Tier2	Tier3	Tier4	Tier5
Peak Power	Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 KW
Daily Consumption	Min 12Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
Availability Day	Min 4 h	Min 4 h	Min 8 h	Min 16 h	Min 23 h
Availability Evening	Min 1 h	Min 2 h	Min 3 h	Min 4 h	Min 4 h

In this framework, reliability is defined by the number of electricity outages per week. Tier 4 allows a max of 14 outages per week and Tier 5 max 3 with a total duration of 2h. Quality is defined by the available voltage range of the power supply. For tiers 4 and 5, voltage fluctuations should not prevent the usage of appliances nor damage them. Affordability considers that 365 kWh/year should cost less than 5% of the household income. For tiers 4 and 5, legality differs if the electricity is supplied and paid through legal and authorized ways [20].

By definition MEs in Nigeria have less than ten employees and assets less than 5 Mio. Naira (approx $30.000 in 2013) [14]. Furthermore, low grid reliability affects MEs also in a different way not measured by this framework. Low productivity, low profitability, higher cost of operations, and losing customer goodwill are some of the challenges MEs face regarding low-quality electricity supply [23]. Especially interesting is the experienced direct economic returns for MEs through a more reliable electricity supply compared to households [18]. Even though a MTF for productive applications is available, the evaluation of MEs within this work is done with the MTF for households. Since the analyzed MEs in this work usually use small appliances similar to household appliances, like light ventilators and TV and no heavy motive power or heating.

2.2. Fuel Generator

Small generators (<=4kVA) in Nigeria are standard gasoline generators. Many of them run with two-stroke motors that are usually very loud and pollutant. It is estimated that the actual fleet of generators is 22 Mio [13], but since the government banned importing this type of generator in 2015, the official number is unknown [2].

2.2.1. Fuel Generator Cost

The average investment cost $C_{i,gen}$ of a 1.5kVA generator is estimated to be $150, and its average lifetime is five years [13]. In addition, a survey conducted in a Nigerian market showed that the average maintenance cost of a generator $C_{m,gen}$ is $30 per year [10]. The main factor in determining the operational cost of a generator is fuel consumption. The fuel consumption of a fuel generator depends on the load factor of the generator. Another study from A2EI shows that most of the time, fuel generators are over-dimensioned and, on average, operate below 0.2 load factor [13]. The load factor LF is the ratio of actual used power $P_{Load,AC}$ to the generator's rated power $P_{rated,Gen}$.

$$LF = \frac{P_{Load,AC}}{P_{rated,Gen}} \tag{2.4}$$

The cost of operation is then the product of the fuel consumption $G_{fuel\_consumption}$, energy demand E_{Load_AC}, and the fuel cost per liter C_F.

$$C_o\left(LF\right) = C_F * E_{Load\_AC} * G_{fuel\_consumption}\left(LF\right) \tag{2.5}$$

Due to subsidies from the government, the fuel price in Nigeria is one of the lowest in the world [24][25]. The current price of fuel (gasoline) is 164 Naira/liter ($0.40) [26]. The Nile University in Nigeria tested the fuel consumption under different load factors of ten common generator models in the Nigerian market [27]. The average measured fuel consumption under different load factors is shown in Figure 2.1. An average fuel consumption of 2 liters/kWh results from the reported average load of 0.2.

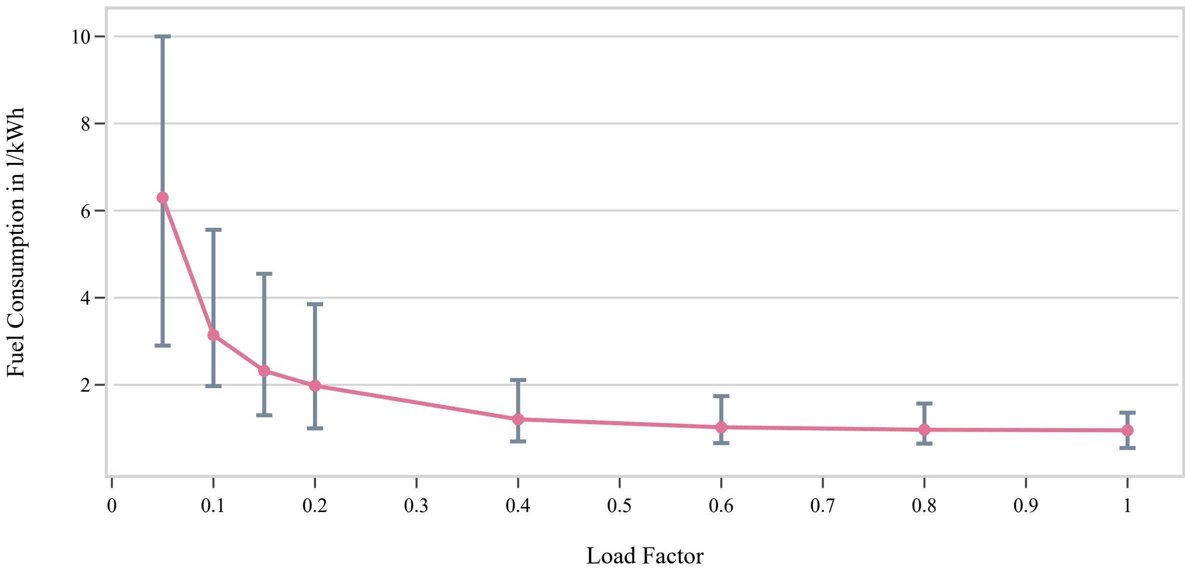

Figure 2.1.: Fuel generator consumption [27]

2.2.2. Environmental Impact of Fuel Generator

The usage of fuel generators is a source of air pollution that impacts the local and regional environment and human health. Of all pollutants, the most significant contributor to climate change is CO_2 [2]. The CO_2 emissions of the fuel generator during operation e_{total_co2} are calculated as follows:

$$e_{total\_CO2}(LF) = E_{Load\_AC} * G_{fuel\_consumption}(LF) * e_{liter\_CO2} \tag{2.6}$$

With: E_{Load_AC} Consumed energy in kWh

$G_{fuel\_consumption}$ Specific fuel consumption in liter_fuel/kWh

The CO_2 per liter fuel (gasoline) e_{liter_CO2} is calculated as follows:

$$e_{liter\_CO2} = E_{Fuel\_PE} \cdot e_{kWh\_fuel} \cdot e_{liter\_fuel} \tag{2.7}$$

$$e_{liter\_co2} = 12.08 \frac{kWh_{PE}}{kg\_fuel} \cdot 279 \frac{gCO2}{kWh_{PE}} \cdot 0.75 \frac{kg}{liter\_fuel} = 2.52 \frac{gCO2}{liter\_fuel} \tag{2.8}$$

With:	E_{Fuel_PE}	Primary energy content of gasoline in kWh$_{PE}/kg_fuel$[28]
	e_{kwh_fuel}	Specific CO2 emission of fuel in gCO$_2/kWh_{PE}$[28]
	d_{liter_fuel}	Density of fuel in kg/liter_fuel

2.3. Solar UPS System Description

This section will present the system design, components, and operation modes used in this work. A complete data sheet of the system can be found in the Appendix A.14. The two different models used in this work and their component sizes are shown in table 2.2.

Table 2.2.: Technical parameters of the solar UPS system models

Model Name	**AAM1000 50Ah**	**AAM3000 100Ah**
PV Panels	800Wp	800Wp
Inverter/Charger	1000W	3000W
Solar Charger	800W	800W
Battery	50Ah(24V)	100Ah(24V)

2.3.1. System Design

The system is designed as an Uninterruptible Power Supply (UPS) system; this means the system ensures electricity availability when needed and protects the loads from voltage fluctuations from the grid. The system is also a design that can be easily integrated into the current electrical installation of the users. As seen in figure 2.2, the system is installed just after the change-over-switch, where users normally can manually change the incoming power source from the national grid to the fuel generator in case of a power outage.

Ideally, the fuel generator can be completely replaced by the AAM system, but in case of very long power outage events combined with bad solar irradiation, users still have the option to connect a fuel generator to power up the loads. Apart from the solar panels, all system components are delivered as an all-in-one system, reducing the installation time and space. In addition, the all-in-one solar system can be imported as a UPS system, which in Nigeria has a lower import duty (5%) compared to the import of single components like batteries (20%) [29].

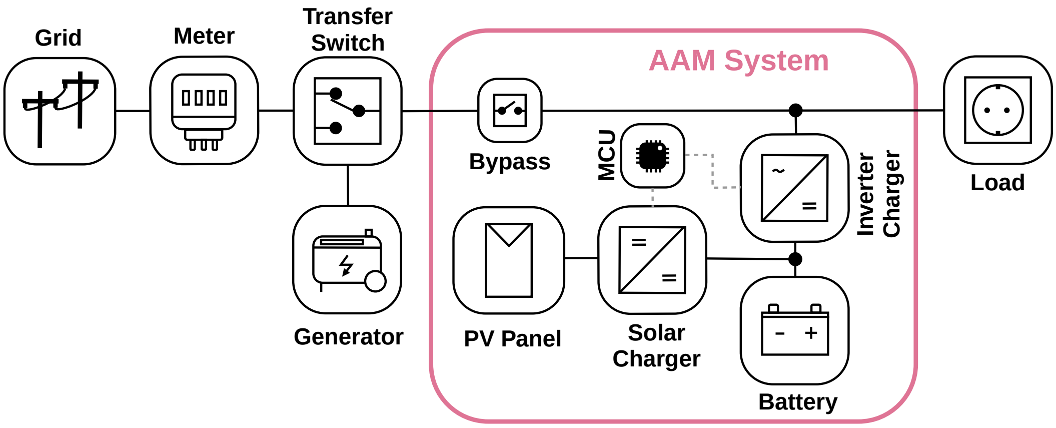

Figure 2.2.: Block diagram of AAM components and typical setup

It is also important to mention that the PV system in this design can only charge the battery and supply power for the load. Any surplus PV energy output is not fed into the grid and therefore, not all potential of the PV system is being used. If the battery is fully charged and no load is required, the PV power is reduced to the minimum to cover the system's self-consumption. As a result, a PV input under 20W is neglected in the load calculation presented later in chapter 3.1.

2.3.2. System Operation

This UPS system is classified as a line-interactive UPS [30]. The load is supplied by the grid or generator directly through the bypass in normal operation mode or grid mode. At the same time, the batteries are getting charged by the rectifier. The backup operation mode or battery mode is activated when a power outage occurs, or the grid voltage fluctuates out of a specific range. In this case, the Alternating Current (AC) loads are supplied by the Direct Current (DC)-bus through the inverter. If solar power is available during battery mode, the solar charge controller feeds into the inverter directly. If the power output of the solar charger is higher than the current load, the solar chargers also charge the batteries. Furthermore, if the power output of the solar charge controller is not available or less than the current load, the backup time of the load in this mode is restricted by the battery capacity. If the battery reaches the cut-off voltage during battery mode, the load is deactivated, and the power supply is interrupted to protect the battery from deep discharge.

2.3.3. System Components

PV Panels

Based on previous calculations [10] and to meet the minimal PV size for governmental grants for Tier 4 (MTF) [31], the system was designed with a minimum 800Wp of PV panels. For the installation of the AAM system, two pieces of 410Wp half-cell Monocrystalline PV panels are installed. The specifications of the panels are shown in table 2.3.

Table 2.3.: PV panel parameters [32]

Parameter	Max Power P_{max}	Voltage at MPP V_{mpp}	Current at MPP I_{mpp}	Module Efficiency η_m
Value	410Wp	40.7V	10.07A	20.2%

Inverter-Charger

A bidirectional inverter/charger can function as an inverter in battery mode and as a charger in grid mode. The inverter is a 3000VA single-phase inverter that transforms DC voltage from the batteries and solar charge controller to AC voltage to supply the AC appliances. Its integrated auto-switch recognizes a power outage and, in less than 15ms switches between AC to DC power input. The main specifications of the inverter are presented in table 2.4.

Table 2.4.: AC inverter parameters [33]

Parameter	Output Power $P_{out,inv}$	Surge Power $P_{out\_sur,inv}$	Output Voltage $V_{out,inv}$	Output frequency $f_{out,inv}$
Value Model 1	3000VA	9000VA	230V +/-3%	50Hz +/-5%
Value Model 2	1000VA	3000VA	230V +/-3%	50Hz +/-5%

Furthermore, the battery charger transforms AC voltage from the grid or fuel generator to DC voltage to charge the batteries. The charging current (DC) I_{chg} is set to 10A due to the maximal charging current of the battery. The main parameters of the charger are presented in table 2.5.

Table 2.5.: AC charger parameters [33]

Parameter	Input Voltage $V_{in,chg}$	Input Frequency $f_{in,chg}$
Value Model 1&2	190-240V	40-70Hz

During the preparation of this work, only the 3000 VA inverter/charger could be delivered by the manufacturer. Therefore, the first pieces of the AAM1000-50Ah were also released with a 3000W inverter. The inverter self-consumption $P_{sc,inv}$ of 34W was measured with the 3000W inverter. Furthermore, the inverter efficiency for both inverter models is calculated by measuring the DC input power $P_{in,inv,DC}$ and the AC output power $P_{out,inv,AC}$:

$$\eta_{inv} = \frac{P_{out,inv,AC}}{P_{in,inv,DC}} \cdot 100\% \tag{2.9}$$

The inverter efficiency of the 3000 W inverter was measured using AC loads from 50W to 1000W in 20 W steps. The results are presented in figure 2.3.

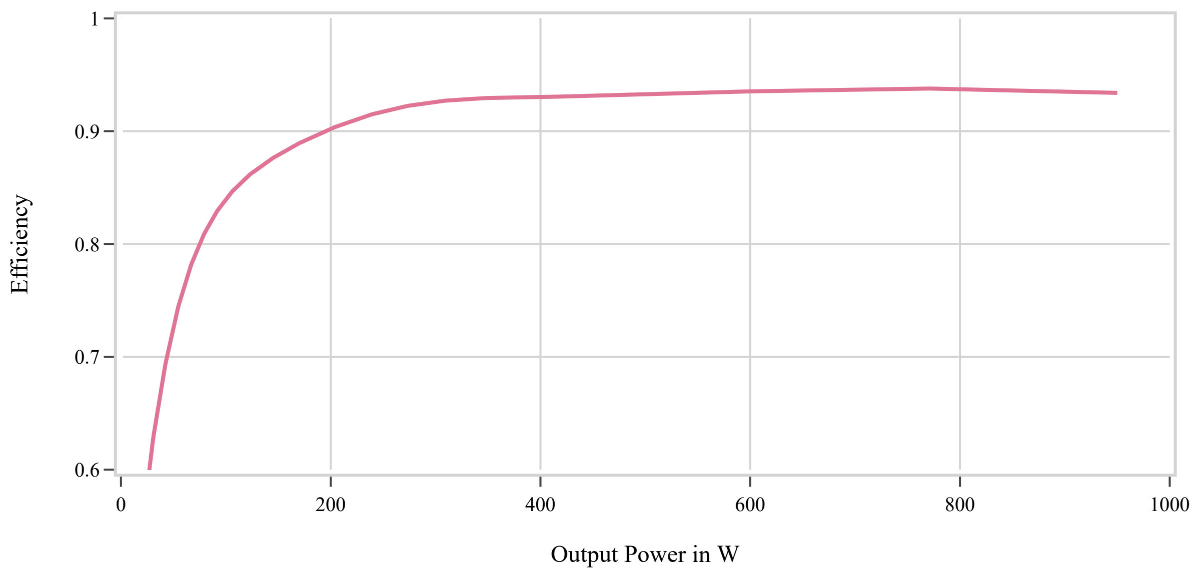

Figure 2.3.: Measured inverter efficiency

Solar Charge Controller

To charge the batteries with the PV Panels, a solar charge controller converts the higher DC voltage of the PV panels to the lower DC charging voltage of the batteries. Its Max Power Point Tracking (MPPT) algorithm constantly tracks out the optimal power output of the PV Panels. The main parameters of the solar charger are presented in table 2.6.

Table 2.6.: Solar charger parameters [34]

Parameter	Nominal System Voltage $V_{Bat,DC}$	Rated charge current I_{mppt}	Max PV input power $V_{max\_pv,mppt}$	Input Voltage Range $V_{in,mppt}$
Value	24V	30A	780W	26V-108V

Battery

The battery installed in this system is a lead-carbon battery type. This type of battery is suitable for solar UPS systems due to their reduced negative plate sulfation at partial states of charge. Furthermore, this battery has a life cycle of more than 3000 cycles at 70% Depth of Discharge (DOD) [35]. Two 12V batteries are connected in series to reach the system voltage of 24V. The main technical parameters of the two battery models are found in table 2.7

Table 2.7.: Battery packs parameters [35][36]

Parameter	Nominal Voltage V_{bat}	Nominal Capacity (C10 25°C) C_{bat}	Maximal Charging Current I_{chg}	Bulk charging Voltage V_b	Float Charging Voltage V_f	End of discharge voltage V_{cutoff}
Value Model 1	24V	50Ah	10A	28.8V	27V	21.6V
Value Model 2	24V	100Ah	20A	28.8V	27V	21.6V

Taking into consideration the constant power discharge data down to 23.4V on the battery data sheet [35][36] and the inverter efficiency presented in figure 2.3, an estimated time of discharge for the two battery modules is calculated. The time of discharge as a function of the AC Load is presented in figure 2.4.

To later calculate the discharge time of a specific AC output load, a mathematical model is determined for each battery by creating a polynomial fit for the 50Ah battery (equation 2.10) and for the 100Ah battery (equation 2.11) as follows:

$$t_{D,50Ah}\left(P_{Load,AC}\right) = 1853 \cdot \left(P_{Load,AC}\right)^{-1.157} \tag{2.10}$$

$$t_{D,100Ah}\left(P_{Load,AC}\right) = 4835 \cdot \left(P_{Load,AC}\right)^{-1.204} \tag{2.11}$$

Furthermore, the battery lifetime is influenced mainly by two parameters; one is the number of cycles depending on the DOD, and the second is the influence of ambient temperature. The data sheet of the batteries [35][36] shows that the battery life cycles

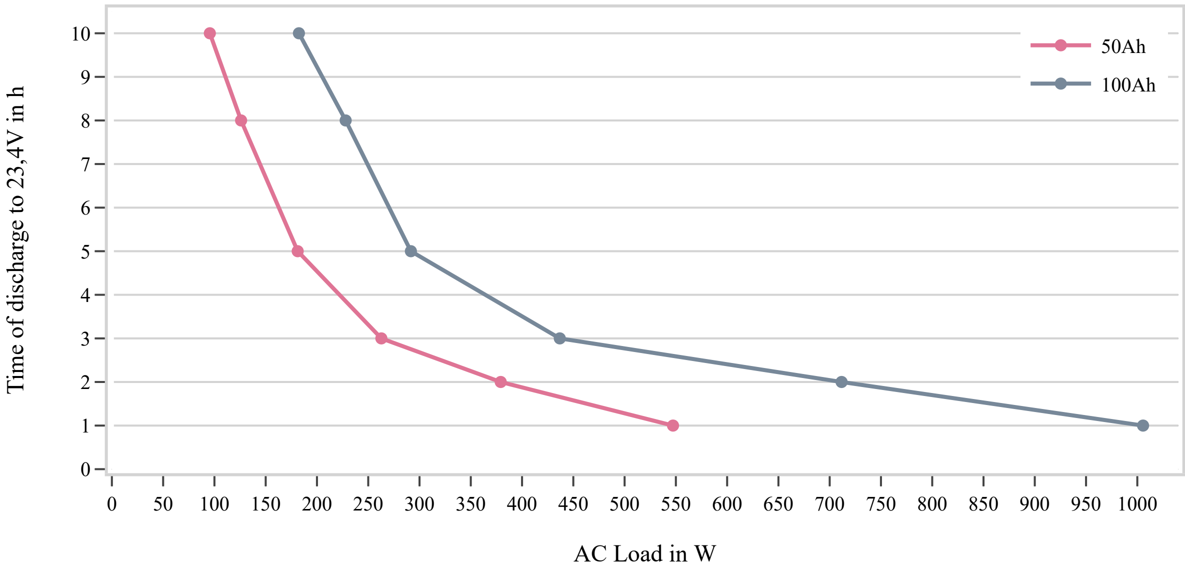

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Figure 2.4.: Battery pack time of discharge under constant load

by 70% DOD are of 3000 cycles. Considering that the cycles of batteries connected to a renewable energy source can be irregular [37]; if it is assumed that the battery goes through one charging and discharging cycle every day, this results in a lifetime of 8.2 years. In addition, considering the average annual maximal temperature of 33.2°C [38], the design life is only below ten years according to the data sheets.

MCU

As seen in figure 2.2, the Monitoring and Control Unit (MCU) is connected to the inverter, the solar charger, and the AC input. This device plays a central role in the system. The MCU has the function to give the system a Pay-As-You-Go (PAYGO) functionality. This means that the operator can enable or disable the inverter remotely if the client had paid or not paid for the given service. How this function plays a role in the financial framework will be explained in section 2.3.4. The MCU also collects technical data from the inverter, the solar charger, and the grid connection. This data can be later analyzed for troubleshooting and system optimization. Specific data points will be discussed in chapter 3.

2.3.4. Cost of a solar UPS system

RBF

A known method to stimulate the introduction of "low carbon technologies" into a new market and reduce the total product's cost is through subsidies. Subsidies add financial resources to an emerging market to align private interests with social interests. Result-Based-Finance (RBF) is a way to administer public subsidies and support public policy goals to reach sustainable development. Unlike traditional subsidies frameworks where a grant is given to a project without proof of supply, an RBF makes payments if a delivered result can be verified [39]. In Nigeria, a solar system with a PV power equal to or higher than 800Wp is eligible for a $320 grant [31]. This subsidy creates an attractive price for technologies aligned with sustainable development goals.

PAYGO

Even if in the long run the solar generator can be more affordable than the traditional fuel generators [10], the upfront costs for this kind of solar-UPS system are still higher than the upfront costs if a fuel generator. However, through its ability to be activated and deactivated remotely by the operator, a very different approach to traditional electrification options can be chosen for this type of system. With the PAYGO model, customers does not need to pay the investment costs all at once. Instead, customers pay an attractive down payment and monthly fees over a period of several months. The final price of the system with this model covers the leasing and risk cost of the operator. This PAYGO or "rent-to-own" business model can provide electricity customers access to electricity at a fraction of the normal upfront cost [40].

Table 2.8 present the current prices of the AAM models offered by one of the operators in the Nigerian market under the PAYGO payment agreement. The price for this kind and size of system in Nigeria is usually higher. This was achieved firstly through the RBF subsidy mentioned above and through the product's large-scale manufacturing, import, and logistics. Due to the current COVID-led global supply chain disruption, it is unsure if these prices will still be achievable in the near future. The solar generator's operation cost $C_{o,pv}$ can be neglected since there is no extra operational expenditure while using a solar system. Maintenance costs $C_{m,pv}$ of $50 a year are assumed for inspection, cleaning of the inverter, and cleaning of the PV panels.

Table 2.8.: PAYGO payments terms for the AAM system

Model	Initial payment	Monthly payment	Total cost
AAM1000W-50Ah	$70	$31 (30 Months)	$1000
AAM3000W-100Ah	$100	$53 (30 Months)	$1690

2.3.5. Solar Resources

Nigeria is a country rich in solar irradiation resources. Nevertheless, different climatic zones can be found through Nigeria, where different solar irradiation and ambient temperatures affect the the solar system's energy production and respectively, the cost of produced energy [41]. In order to analyze how different locations affect the sizing of the system, three representative locations in Nigeria in different zones were chosen, the monthly average solar irradiation at optimal slope inclination and 0° azimuth from the years 2005 to 2016 was taken and their average yearly irradiation is shown in table 2.9.

Table 2.9.: Nigerian average monthly solar irradiation in kWh [42]

Location	Abuja	Lagos	Cross River State
Optimal Angle	16°	11°	10°
January	221.3	193,2	196,4
February	197.7	172,6	168,2
March	203.8	178,8	162,7
April	178.9	168,7	150,2
May	165.1	149,0	143,4
June	142.5	116,2	115,9
July	136.3	119,9	102,1
August	127.5	132,0	106,5
September	153.8	130,8	118,5
October	187.3	150,1	143,1
November	211.3	163,8	153,5
December	220.9	182,3	184,8
Total	2146.3	1857,4	1745,2

Based on the ideal irradiation values $H_{G,inc}$ presented in table 2.9, the ideal PV energy yield can be calculated as follows:

$$E_{ideal} = \frac{P_{PV} \cdot H_{G,inc}}{1000 \frac{W}{m^2}} \tag{2.12}$$

The Performance Ratio (PR) is used to reveal the relation between the measured PV yield E_{real} with the ideal energy yield E_{ideal} [28]:

$$PR = \frac{E_{real}}{E_{ideal}} \tag{2.13}$$

Another value that shows the performance of a solar system is the specific yield Y_F [28], also known as full load hours. This is calculated by dividing the measured PV yield by the PV system's maximum power P_{max}:

$$Y_F = \frac{E_{real}}{P_{max}} \tag{2.14}$$

2.4. Load Profiles

An important factor to the right-sizing of the system is the electricity demand. Further than just the amount of energy consumed, the time of consumption must be considered. The time of demand for electricity of the users can be categorized into three groups; all day, day only, and opening hours. All day consumers need electricity supply also during night hours, this can be small grocery shops with cooling applications. Day-only consumers are, for example, market shops opening mainly during the day. Opening hours do not have a fixed time frame. Shops like barber shops can open from 6:00 until 23:00. An example of each of these different timings can be seen in figure 2.5.

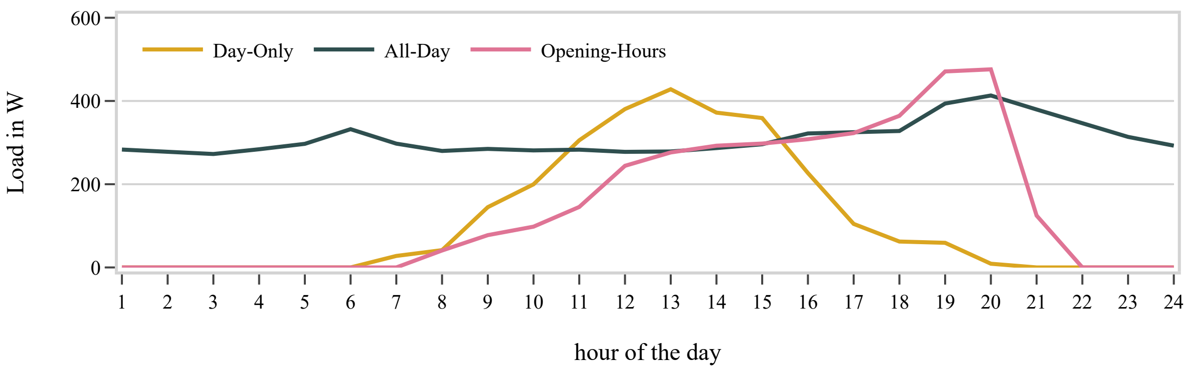


Figure 2.5.: Measured daily loads, illustrating three different load profiles

2.5. Cost of Energy

To get a comparable number displaying the cost of energy from different scenarios, the Levelized Cost of Energy (LCOE) for each solution needs to be calculated. First, the

Net Preset Value (NPV) of the system is calculated including the initial investment cost C_i and all cash flows CF during the project lifetime in present value. Cash flow can be operation and maintenance costs $C_{O\&M}$, fuel cost C_f, replacement cost C_r, and grid electricity cost C_G. The NPV is calculated as follows [43]:

$$NPV_{tot} = \sum C_i + \sum \frac{CF}{(1+i)^t} \tag{2.15}$$

Furthermore, the NPV can be turned into an annuity by the Cost Recovery Factor (CRF) [18], considering the annual real discount rate i, and the project lifetime T. The CRF is calculated as follows [43]:

$$CRF(i, T_{proj}) = \frac{i \cdot (1+i)^T}{(1+i)^T - 1} \tag{2.16}$$

The annual real discount rate i is calculated with the nominal discount rate i' and the expected inflation rate f [43].

$$i = \frac{i' - f}{1 + f} \tag{2.17}$$

Finally, the LCOE can be calculated considering the annual electricity supply by the system E_{sup} [43].

$$LCOE = \frac{CRF(i, T_{proj}) \cdot NPV_{tot}}{E_{sup}} \tag{2.18}$$

3. Data Collection

In this chapter, an overview of the collected data and subsequent derivations will be presented. This includes technical data from the different system components, as well as information collected from the users and operators through a survey and a registration tool. Furthermore, the identified technical issues and data collection errors will be introduced.

By the end of July 2021, 200 AAM systems were already installed in nine different locations across Nigeria. In the initial time frame of this work, several technical issues and data collection issues were encountered. The causes of these hardware and software issues were recognized through preliminary data analysis as part of this work. Solutions were developed in collaboration with the A2EI team and the author implemented these in various of the installed systems in Nigeria. Within the limited time frame of this work, a number of 23 systems have been identified delivering acceptable data for deeper analysis for August and September 2021. The basic information of each of the analyzed systems can be found in appendix table A.1.

3.1. Technical Data

The central component for the data collection, storage, and transmission is the MCU (see: 2.3.3). It contains a Real Time Clock (RTC), which sets and keeps the local time even during a power outage. Data from the inverter/charger and the solar charger is measured and collected in a 5 minutes interval. The MCU has an internal AC Voltage measurement through an Analog Digital Converter (ADC). Data measured by the ADC is logged internally every second and every 5 min the average value is recorded in the data log. The 5 min logs from all devices are saved internally, merged, and sent once a day via GSM to a server. The communication between the MCU and the components is displayed in figure 3.1.

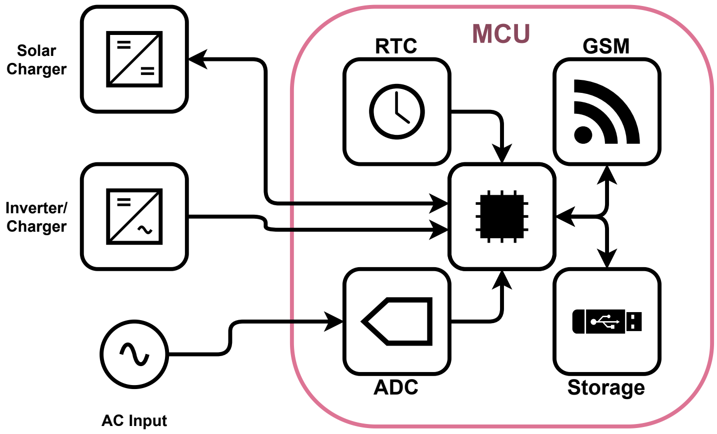


Figure 3.1.: Schematic of data collection with the MCU

The monitored and collected parameters measured from the inverter/charger, the solar charge controller, and the AC input are shown in table 3.1. Due to instability in the inverter-MCU communication, the inverter and MCU data points must be cleaned from outliers to ensure correct data analysis. The steps taken for data cleansing are presented in Appendix A.15. The raw and derived data files are available from [44].

Table 3.1.: Data collection parametric

Component	**Parameter Name**	**Symbol**	**Comment**
MCU	UTC+1	t	Time stamp in dd.mm.yyyy hh:mm.ss
	input_voltage_mcu	$V_{in,ADC}$	Grid input voltage in V
Inverter	input_voltage_inv	$V_{in,inv}$	Grid input voltage in V
	output_voltage_inv	$V_{out,inv}$	AAM output voltage in V
	output_current_inv	$I_{out,inv}$	AAM output current in A
	battery_voltage_inv	$V_{bat,inv}$	Battery voltage in V
	temperature_inv	T_{inv}	Inverter internal temperature in °C
Solar charge controller	pv_input_voltage	V_{pv}	PV input voltage in V
	pv_input_current	I_{pv}	PV input current in A
	mppt_output_voltage	V_{mppt}	MPPT output voltage in V
	mppt_output_current	I_{mppt}	MPPT output current in A
	temperature_mppt	$V_{bat,mppt}$	Inverter internal temperature in °C
	temperature_bat	ϑ_{mppt}	Outer battery temperature in °C

Derived Data

Before starting with the evaluation, the following values need to be derived from the collected data. First, the effective power output from the inverter $P_{out,inv}$ is calculated with equation 3.1. This calculation of the power output presents some limitations; since the DC voltage and current measurements are used, the real and apparent power parts of the AC power are not considered. To simplify the calculation, a constant power factor $cos(\varphi)$=1 is assumed. Even if in reality, the power factor changes through the use of inductive or capacitive loads in an AC grid. Furthermore, the energy consumed $E_{out,inv}$ can be calculated with equation 3.2:

$$P_{out,inv}(t) = I_{out,inv}(t) \cdot V_{bat,inv}(t) \tag{3.1}$$

$$E_{out,inv}(t) = P_{out,inv}(t) * \Delta t \tag{3.2}$$

Similarly, the power input and energy delivered from the PV panels for charging batteries can be calculated as follows:

$$P_{PV}(t) = I_{out,mppt}(t) \cdot V_{bat,mppt}(t) \tag{3.3}$$

$$\tag{3.4}$$

$$E_{PV}(t) = P_{out,inv}(t) * \Delta t \tag{3.5}$$

$$\tag{3.6}$$

A binary value for grid availability and grid usability is needed to later quantify the number and duration of blackouts. To dismiss a data gap through a device failure, the grid voltage is measured by two different components. Mainly the inverter data can be used to determine the availability and usability. In case there is no grid voltage data available from the inverter, MCU data is then used. Availability of the national grid $AVL_{grid,all}$ is calculated as follows:

$$AVL_{grid,all}(t) = \begin{cases} 1 & \text{if } V_{in,inv}(t) \neq 0 \ \vee \ V_{in,adc}(t) \neq 0 \\ 0 & \text{if } V_{in,inv}(t) = 0 \ \wedge \ V_{in,adc}(t) = 0 \end{cases} \tag{3.7}$$

As stated before, not all the available grid can be used because of its poor voltage quality. If inverter data is available, a binary value for grid usability is generated using equation 3.8. Here, it is unnecessary to apply the range of use, since the inverter output voltage $V_{out,inv}$ is only unequal 0V and unequal 230V when the grid quality can be used by the inverter.

$$AVL_{grid,use}(t) = \begin{cases} 1 & \text{if } V_{in,inv}(t) \neq 0 \ \wedge \ V_{out,inv}(t) \neq 230 \\ 0 & \text{if } V_{in,inv}(t) = 0 \ \vee \ V_{out,inv}(t) = 230 \end{cases} \tag{3.8}$$

Furthermore, to determine more accurately the economic and environmental savings of the system, it is necessary to determine which source is supplying the load. The flow chart in figure 3.2 is used to determine the source of the load supply for each data point. If the usable grid is available, the load is covered by the grid. If the usable grid is not available, the load is covered directly by the PV input or the battery.

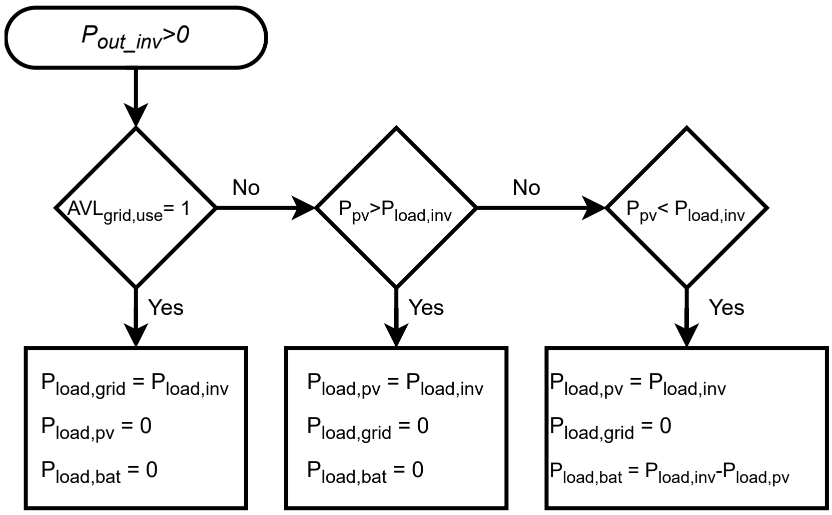


Figure 3.2.: Decision flowchart for determining the power source

Measurement Uncertainties

Since the AAM system is installed after the change-over-switch (see figure: 2.2), it is possible that the collected grid data also includes the usage of a fuel generator. Furthermore, users may manipulate the grid data by manually disconnecting the grid input during the day to supply the load purely on PV and battery. In addition, when the inverter is turned off manually, and the available grid is out of the specified range, the inverter can not deliver the grid data.

Moreover, some users who own small generators ($\approx$ 1000VA) and cannot charge the batteries and supply the load simultaneously reported connecting the AAM system before the change-over-switch. This solves the possible error mentioned above, but whenever the transfer switch is set to "generator-use", the load data is not measured by the inverter. This means that the measured load data possibly did not represent the complete load profile of the user.

Another source of uncertainty is the temporal resolution of data logging. The measured data from the inverter and MPPT presented in this work is just a snapshot of the actual system conditions. For example, a load used for one minute might not be measured at all, and if it is measured, this short load represents the load for the complete five minutes. Moreover, the output current from the inverter is measured as a percentage of the rated nominal output in 1% resolution. For the 3000W inverter, this translates into a resolution of 30W for the derived load power.

3.2. Users Data

Surveys with users were carried out in three different locations despite the spatial distances between the localities and the difficulty accessing these. In total, 18 users were interviewed; Thirteen of these participants are located in Mararaba, a city near Abuja, one participant in Abuja, and three others in different localities of Lagos. Twenty-one of the users interviewed are MEs and two households. As anticipated, all the participants had a connection to the national grid but the low quality and reliability of the national grid force electricity customers to use fuel generators. The surveyed data points are presented in table 3.2. Since the survey was limited to a small number of customers located in urban locations, the results may differ when considering users in rural areas in Nigeria. Nevertheless, this survey intends to find out if the expected results are being reached in these locations. A summary of the survey results can be found in the Appendix A.8 and A.9. Furthermore, 9 of the 18 users surveyed are in the list of analyzed technical data.

Additional information of the customers was previously gathered during the installation process through a registration tool developed by A2EI [45]. Out of the registration tool, the shop type, the GPS location, and pictures of the system and solar panel installation are taken. Due to data confidentiality, private data from the users can not be published. Moreover, useful insights were also collected through unstructured interviews with operators and installers who accompanied the user surveys. The Information from the operators who not only know the local technical challenges but also have valuable experience

Table 3.2.: User survey questions

Surveyed Data	Possible Values
Shop type	Barber saloon, Herbal shop, Grocery shop, Phone charging shop, Household
Business opening hours	hh:mm - hh:mm
Energy supply before AAM	Grid / Generator / Inverter+Battery
Type of installation	Ongrid / Offgrid
Grid meter type	Prepaid meter - Estimated bill
Kept generator	Yes / No
Use generator	Yes / No
Fuel consumption (Before - After)	xNGN - xNGN
National grid expenses (Before - After)	xNGN - xNGN
Satisfaction level	1-5
Experience economic savings?	Yes / No

with local logistics and customer service, is highly valuable. The main focus of these unstructured interviews was to collect issues experienced so far with the installed systems and suggestions to improve the system installation process and performance. Relevant findings gathered during the interviews are presented in chapter 5. An exchange rate of 410 Nigerian Naira (NGN) = 1 United States Dollar (USD) is used in this work.

4. Data Evaluation

In this chapter, the steps of data evaluation of the different parts of the AAM system will be presented. An interactive dashboard to analyze the data of each of the selected systems was built for this analysis. An online version of this dashboard was published [here] [44] with the aim to provide stakeholders access to the selected data and presented results. The dashboard is built using an open-source Python library called Streamlit [46]. Data analysis is done with Pandas [47] and data visualization with Plotly [48]. Furthermore, the data collected from the users through a survey is also evaluated.

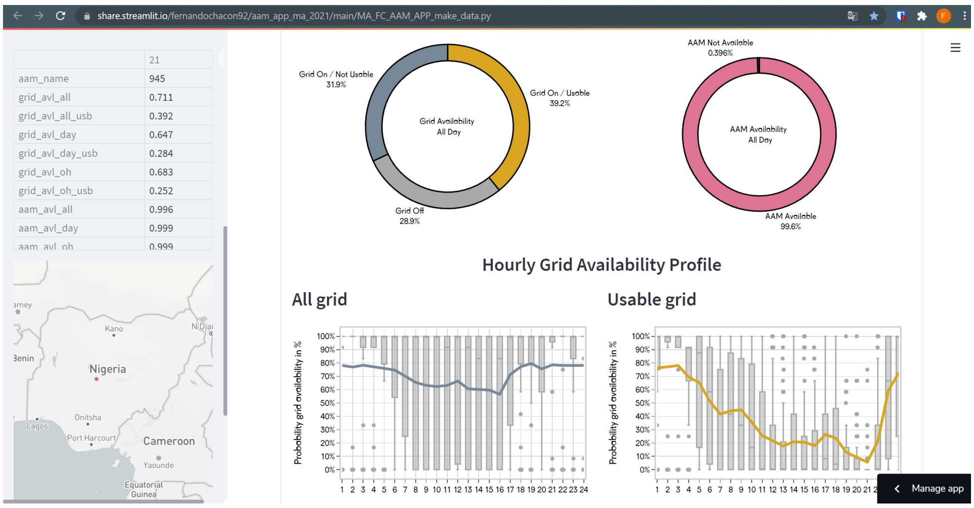


Figure 4.1.: Screenshot of the published dashboard for data visualization

On the top left of the dashboard, the AAM system-to-analyze can be selected. An overview of the system information, a summary of the analysis results, the location, and installation pictures are visualized on the sidebar. In the main panel, a diagram is available to visualize and compare all collected data points. Furthermore, the different analysis categories used in this work can be seen by clicking on the respective expander boxes; grid, PV, load, batteries, and CO_2 savings are presented. Moreover, a few diagrams of all systems are presented as well as the derived daily profiles. The grid availability profiles and load profiles can be downloaded in this section of the dashboard.

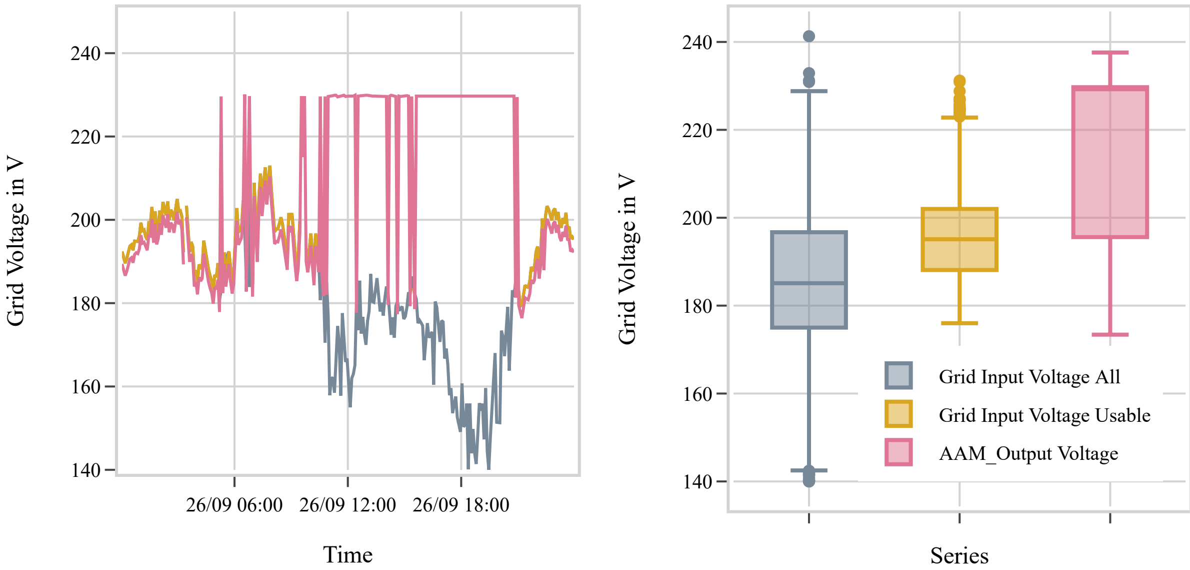
4.1. Initial Issues

First, through the battery voltage data, it was noticed that the bulk charging voltage of the inverter was 1V higher than expected. The reason for this issue was a missing temperature sensor in the inverter, causing an overvoltage charging of the batteries due to failed temperature compensation. Temperature compensation in a battery charger is used to adjust the charging voltage depending on the ambient temperature dynamically. Normally, the charging voltage is reduced with increasing temperature to avoid overcharging the batteries. To solve this, a resistor with same value as the temperature sensor at 25°C was installed. The temperature compensation is then taken over only by the MPPT charging process. A further flaw noticed through the battery voltage data was that MCU self-consumption power could potentially deep discharge the battery if the power input was removed for several days. This issue was solved by changing the source of power of the MCU to the DC output of the MPPT, which cuts off the power when the battery reaches 22.4V. It was also identified that the inverter data for many systems was either unavailable or not stable. The source of this issue was a faulty adapter used for the data query between the inverter and MCU. This could only be solved by manually replacing this adapter in already installed systems. Finally, several firmware issues affecting the GSM data usage, the timestamps of the measured data, could only be solved by manually reinstalling the MCU's software package.

4.2. National Grid

Since the reported unstable electricity service is the main reason users need to rely on fuel generators, it is necessary to analyze the national grid's reliability and quality in-depth to understand the size of the problem being addressed. Moreover, like a battery-inverter backup system, the AAM system can also use the national grid as an energy input. Therefore, understanding the behavior of the national grid is essential for the correct sizing of the system.

Diagram 4.2a shows the daily grid voltage input, the usable grid voltage input, and the AAM voltage output for system ID 945. In this case, it is clear that the voltage input is unstable and far below the nominal value of 230 V, leading to just a portion of the supplied voltage being available to supply the load and charge the battery. It was reported from the installers that the low grid voltage is not only because of the low quality of the grid but also originates in the quality of the electrical installations. The two main



(a) 24-hour voltage plot

(b) Voltage data distribution (Aug-Sep)

Figure 4.2.: Grid input and AAM output voltage from system 945

functions of the AAM can be seen here. Firstly, when the input voltage drops below the desired threshold and secondly, when there is a power outage, the AAM system supplies the necessary voltage. The voltage output provided by the AAM, when not bypassing the available and usable grid, is a very stable 230V voltage supply. The distribution over the two measured months of the available and usable grid input voltage as well as the AAM output voltage data points can be visualized in Diagram 4.2b. The boxes show the median, the first and third quantiles (25th and 75th quantiles), the whiskers show the maximum and minimum, and the points show outliers. Furthermore, the average grid voltage input is recorded for each system in table A.4. Only for two systems, an average grid voltage higher than 220V was recorded.

As mentioned before in chapter 3, a binary grid availability and usability values are created out of the grid voltage data. With this, the grid availability and usability over the measured time period can be calculated for each system (see appendix tables A.2 and A.3). Likewise, the availability of the AAM system is also calculated.

Figure 4.3 shows the grid and AAM availability of the systems analyzed. The grid availability is, as expected, very low for most of the grid-connected systems but yet not constant. As seen in appendix table A.1, 12 systems are connected continuously to the grid, two systems were recognized that are actively turning on and off the grid input (528

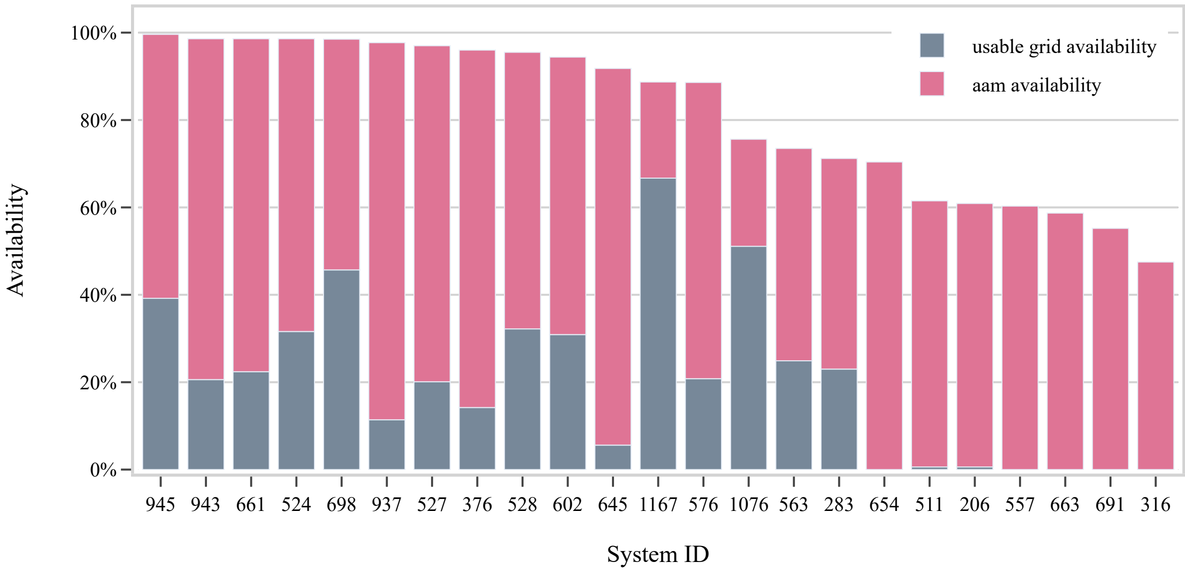


Figure 4.3.: Usable grid and AAM availability (Aug-Sep)

and 661), and four others were recognized that are using generators sometimes to power their loads (645, 511, 206). System 937 is recognized to be just a fraction of the analyzed time connected to the grid (937). Furthermore, five systems are completely off-grid (691, 316, 557, 663, 654). As expected, the AAM availability over 24 hours per day is lower for off-grid systems compared to on-grid systems. This is due partly because off-grid systems are shut off overnight, either because users turn them off manually (557, 691) or because the battery reaches the cut-off voltage and the AAM goes off. The grid availability during the daytime increases for the off-grid systems. Moreover, no direct trend can be seen between the usable grid availability and AAM availability for on-grid systems. It can also be observed that some of the on-grid systems experienced a significant increase in the overall power availability with the installation of the AAM and some others just a relatively small increase.

More insights can be drawn by analyzing an hourly profile of the grid availability. For this, the probability of grid availability over a typical day is calculated by taking the hourly average availability and then grouping the values by the hour of the day and taking its average. In addition, the same is done with the usability values. An example of the empirical grid usability on a typical day is shown in figure 4.4. The distribution of the data points is shown on the hourly box plots in the diagram's background.

Furthermore, the daily hours of the available grid are calculated for every system. In

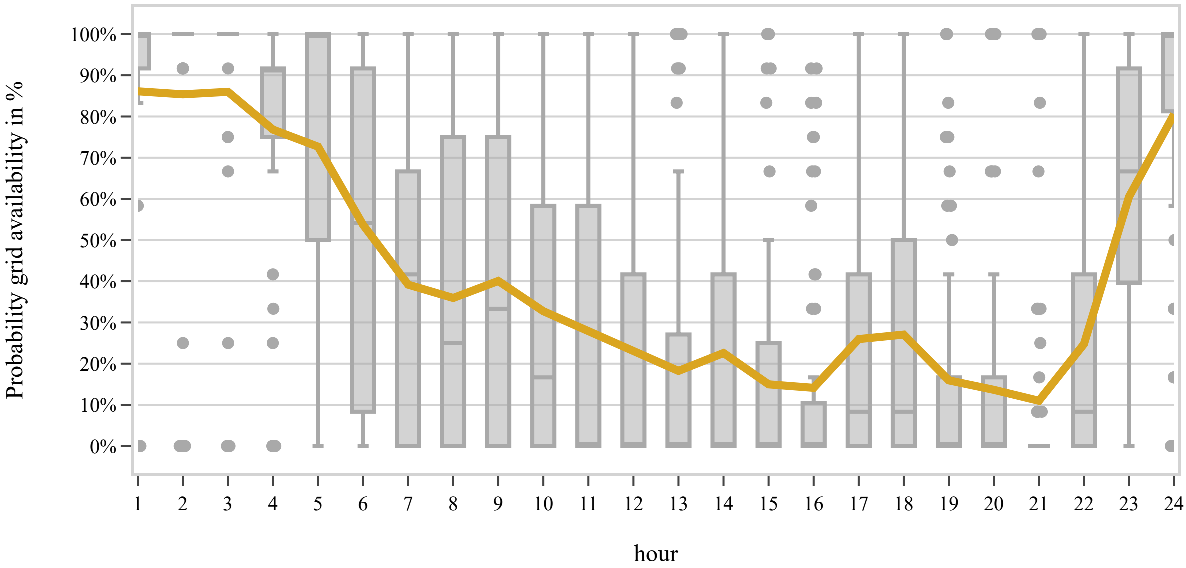
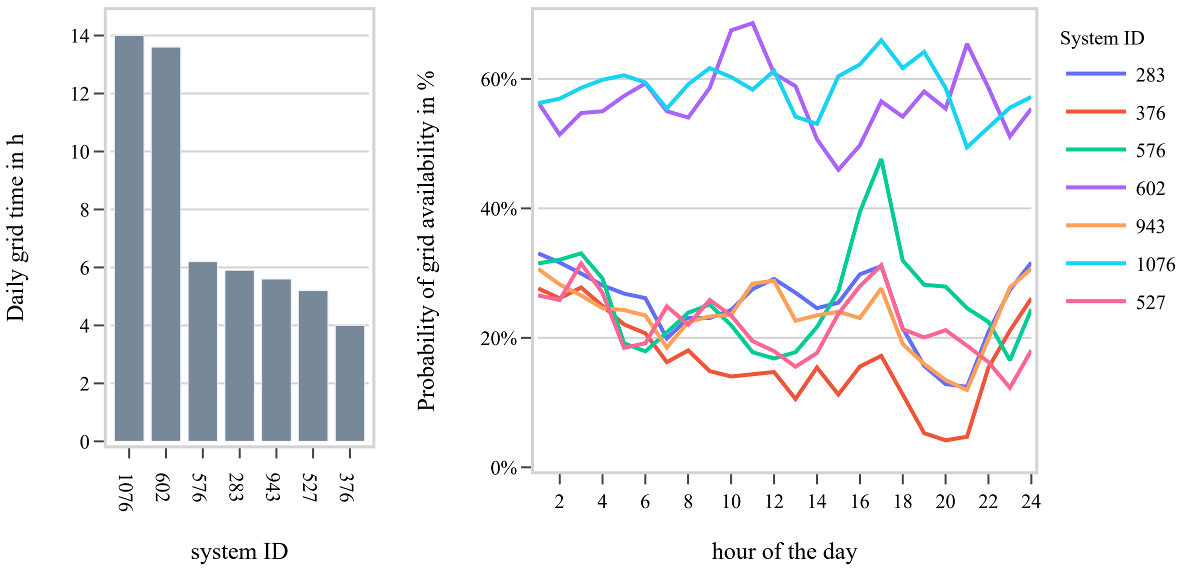


Figure 4.4.: Daily profile of usable grid availability

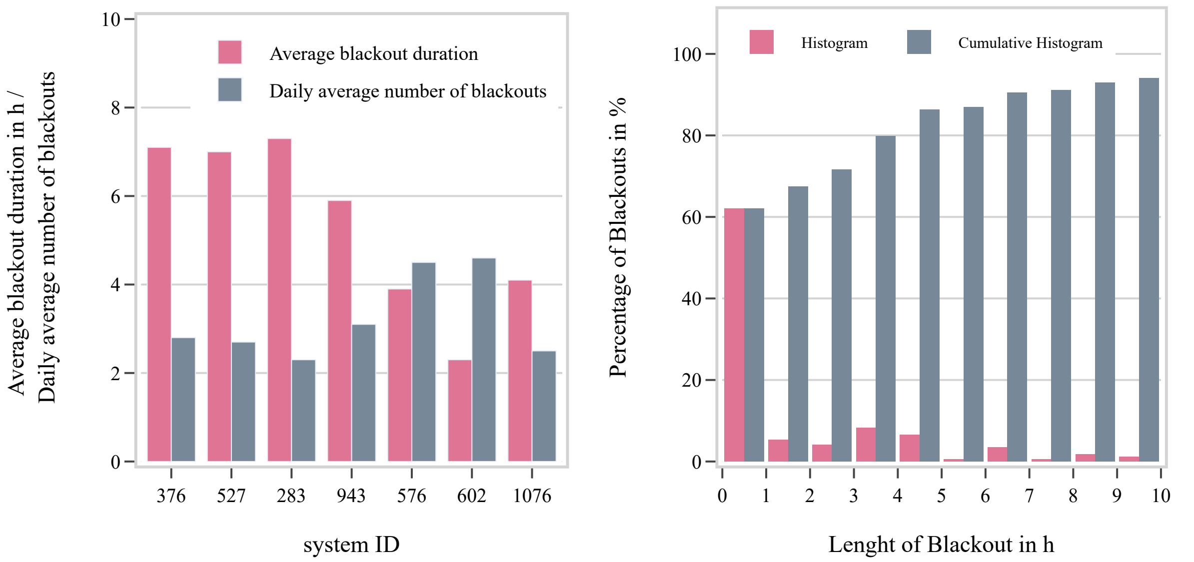
figure 4.5a, the average daily grid time and the hourly grid availability profile for the grid-connected systems in Mararaba is shown. Clearly, all systems show different values but two main categories can be identified. Systems 1076 and 602 get more than twelve hours of grid per day and have a relatively higher availability during the day compared to the other five systems that report between four and six hours of daily grid time. This difference in grid time and daily availability profile corresponds to the different tariff classes the national grid operators offer (see appendix figure A.1). Depending on their tariff-class, grid customers are guaranteed to obtain a minimum amount of hours of grid supply per day. This can vary between 4 hours and 20 hours per day.

Two further parameters that help describe the quality of the national grid are blackout duration and blackout frequency. In the considered grid data, each time a grid outage is identified, the number of events and the duration of each event are counted. The resulting average blackout duration and daily blackout frequency for grid-connected systems in Mararaba are presented in figure 4.6a. As expected, the systems with a lower tariff experience longer average blackout duration but not necessarily higher blackout frequency. Taking a closer look at the blackout duration data, it was recognized that the distribution of blackout length is not symmetrically distributed by length. Instead, it results in a skewed right distribution. An example of the distribution of blackout duration by length is shown for system 945 in Figure 4.6b. Here, it can be seen that 60% of the outages experienced by this user during the two analyzed months are under one-hour duration.



(a) Average available grid time (b) Daily profile of grid availability

Figure 4.5.: Grid access in Mararaba, Nigeria



(a) Blackout duration and frequency (b) Blackout duration histogram of system 945

Figure 4.6.: Blackout duration and frequency in Mararaba, Nigeria

4.3. PV Analysis

Out of the MPPT output voltage and output current, the derived PV Power and daily PV yield can be calculated (see equations 3.4 and 3.5). The most interesting observation emerging from the PV data is its relation to grid availability. The daily PV yield and grid availability during the daytime for all systems analyzed are shown in Figure 4.7. It can be observed that the off-grid systems have the highest average and summed up PV yield of all analyzed systems. This is due to the almost complete usage of PV power during the day compared with grid-connected systems that have grid priority during grid time. Contrarily, the system with the lowest daily PV Yield has the highest availability during the day.

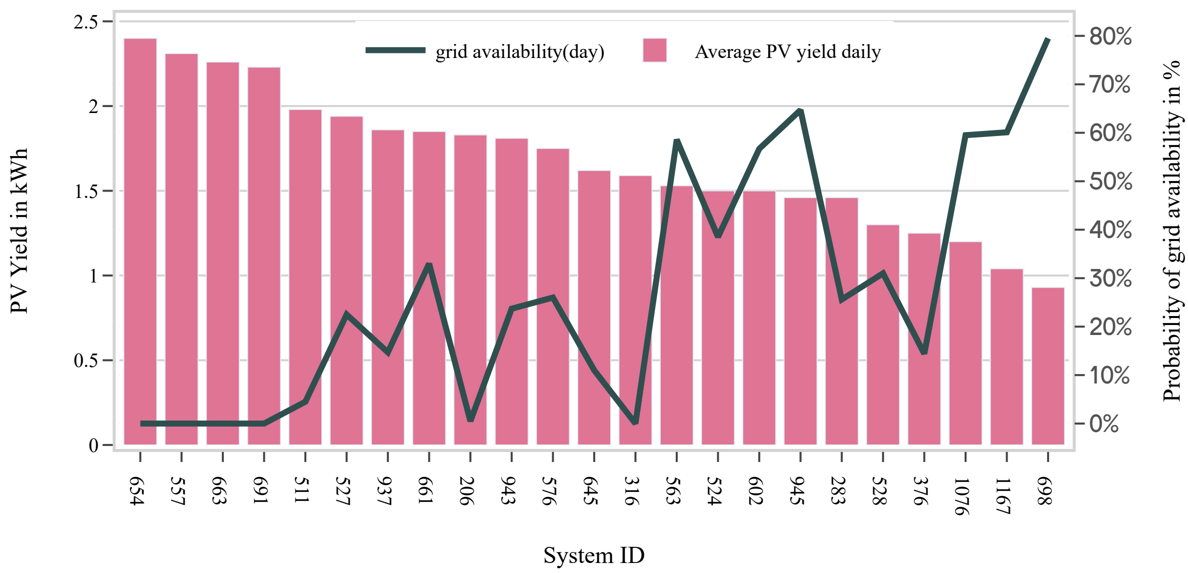
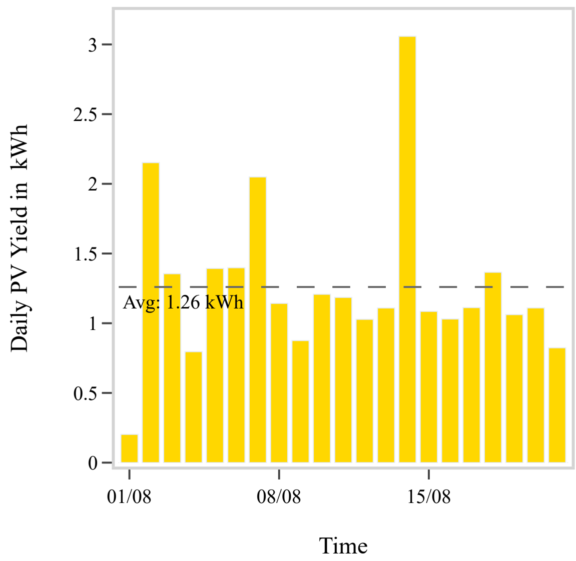


Figure 4.7.: Daily PV yield and probability that the grid is available during daytime

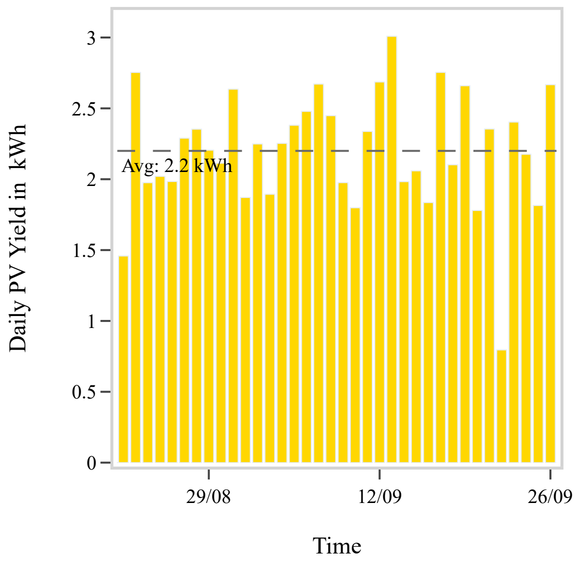
The difference in PV yield between on-grid and off-grid operation can be seen clearly for system 937 on figure 4.8. On one side (see figure 4.8a), from 01.08.2021 until 22.08.2021, the system was grid-connected with an average daily PV yield of 1.26 kWh. On the other side (see figure 4.8b), the user switched completely to off-grid operation mode reaching an average daily PV Yield of 2.2kWh. The average daily PV yield increased 74% from the on-grid to off-grid time.

Moreover, the monthly PR and full load hours are tracked for all systems (see appendix table A.5). As expected, due to the lower radiation in Cross River State, the PR of systems 528, 524, and 698 is higher than other systems with similar total PV yield.

Furthermore, a daily PV power profile can be calculated by taking the hourly average PV power and then grouping the values by the hour of the day and taking its average. This profile can be used to analyze the hourly performance of the PV systems, azimuth orientation, and possible shading of the PV panels. For example, the PV power daily profiles for systems 654 and 283 are shown in figure 4.9. System 654 is an off-grid system



(a) PV yield with grid connection



(b) PV yield without grid connection

Figure 4.8.: Average daily PV yield of system 937

and probably the PV panels are slightly facing west due to max PV power after noon (12:30 pm). Differently, System 283 reaches on average its maximum PV power at 9:00 am. Due to the grid availability during the night, the batteries of this system are already partially charged in the morning and the load required is lower than the PV power, leading to low PV Power output for the rest of the day.

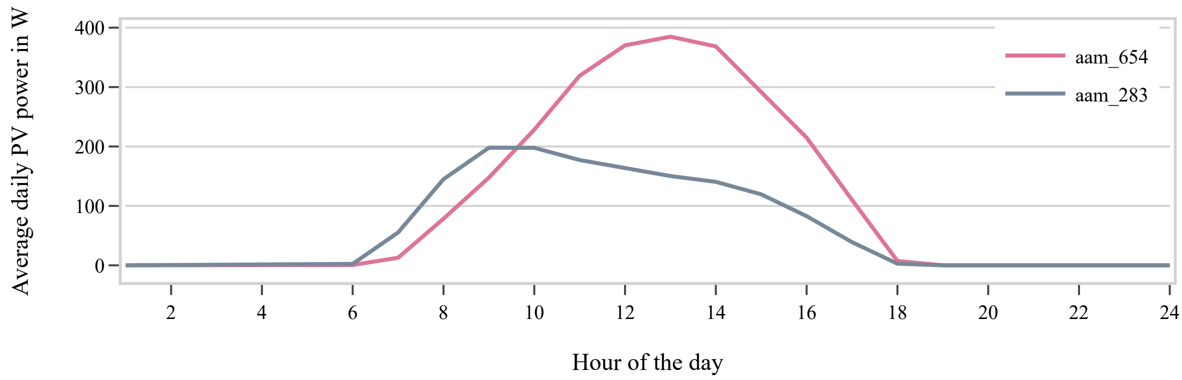


Figure 4.9.: Daily PV power profile of systems 283 and 654

4.4. Consumption Profile

The load and consumption data are derived from the inverter output current and output voltage. The average daily consumption and average load are shown in figure 4.10. The measured average daily consumption varies drastically between users regardless of the battery size. Operators reported, for example, that System 524 combines up to four 50Ah battery packs and uses one load of 1100W just during the day, reporting the highest average load of all analyzed systems. In addition, System 937 with a 100Ah battery is a household that reported the use of a refrigerator, and due to intermittent load, it can be possible that the actual load is not being measured correctly with the current measuring method of 5 min intervals. In addition, it can be seen that the two systems reached an average daily consumption of tier 4 (3.4kWh) and most of the systems reached tier 3 (1kWh) daily consumption.

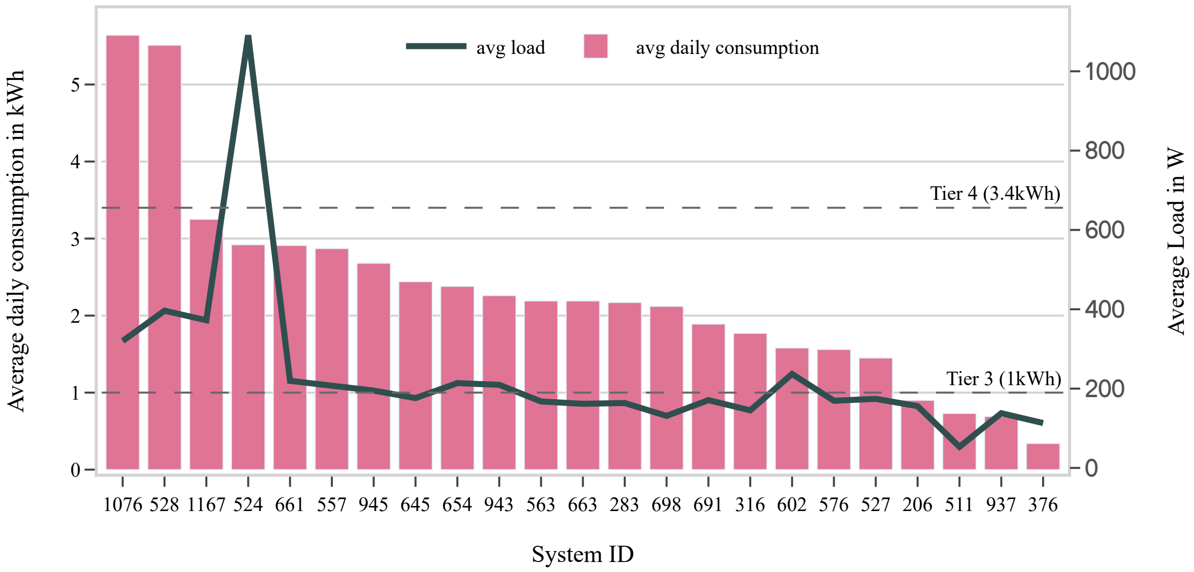


Figure 4.10.: Average daily consumption and average load

Similarly, as with the PV power profile, a daily load profile can be calculated by taking the hourly average load and then grouping the values by the hour of the day and taking its average. This profile reveals the distribution of consumption during the day. In figure 4.11, the average load profiles for ME's and households are shown. A clear difference can be seen between the two load profiles; the highest load of households is around noon and of MEs in the evening. As expected, most of the MEs do not require electricity out of the business opening hours. Contrarily, the household load profile indicates a need for electricity during the night. A typical load during the night of a household is a ventilator.

Another interesting observation emerges if the average grid availability and the average load profile of all analyzed grid-connected systems are compared. This can be seen in

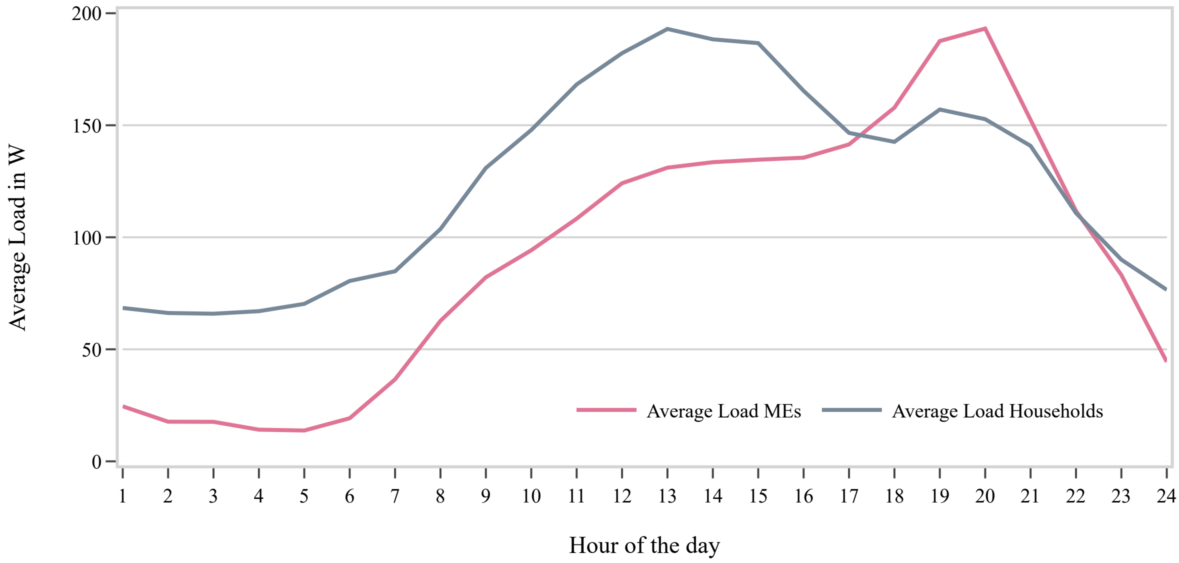


Figure 4.11.: Average load profiles of MEs and households

figure 4.12. The two peaks on the average load profile correlate with the two drops of the grid availability profile. These results show that the electricity grid is most probably unavailable during the highest demand time, showing the necessity and importance for users to own a backup system under this particular grid condition.

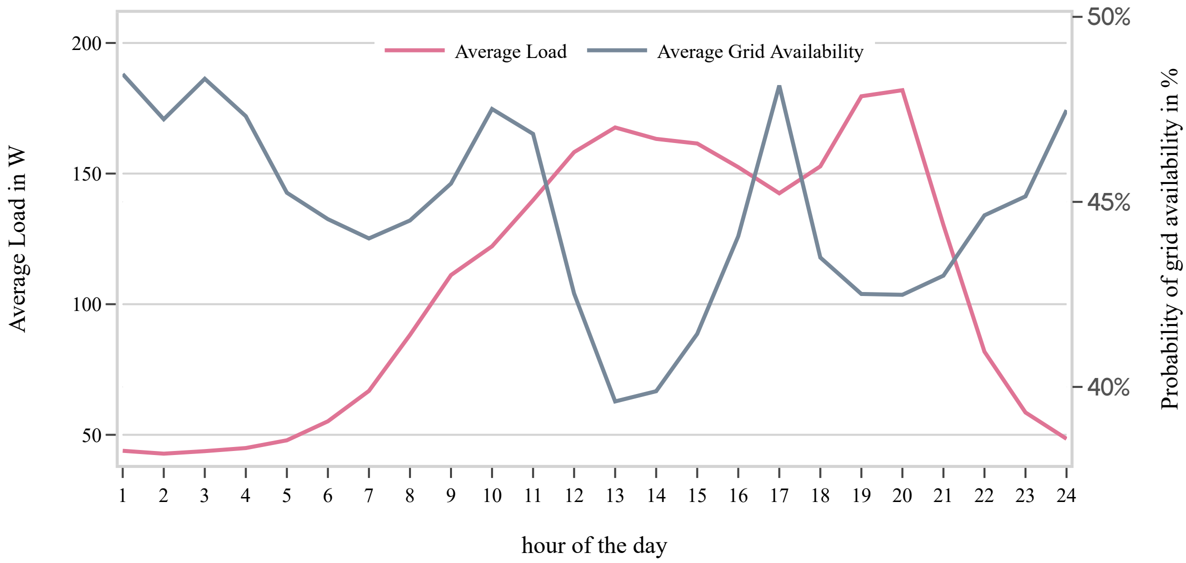
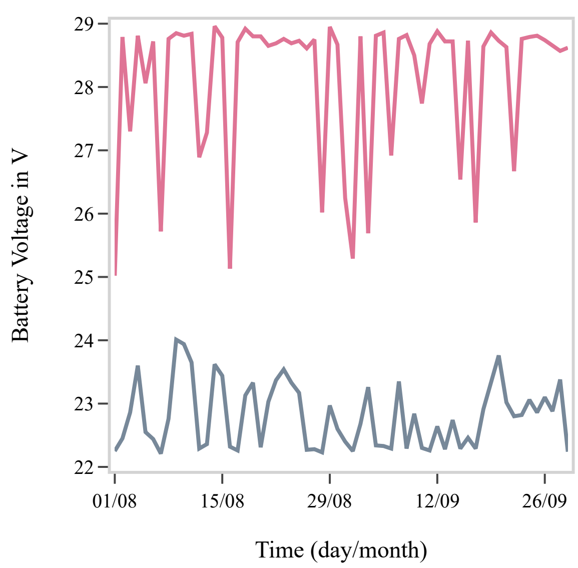


Figure 4.12.: Daily load profile and daily grid availability

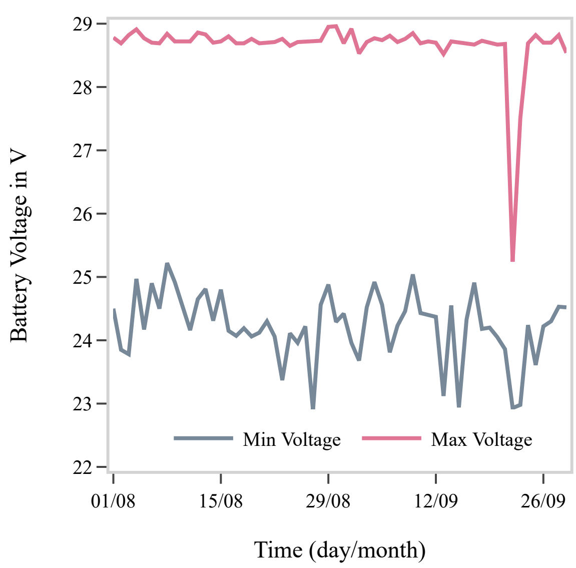
4.5. Battery Usage

A specific SOC can not be derived from the battery voltage data. Nevertheless, out of the daily maximal and minimal voltage data, it can be evaluated if the battery's total capacity is used correctly or not. For example, the daily maximal and minimal battery voltage of systems 557 and 1167 are shown in figure 4.13. On the right side, the user of system 557 changed the cut-off voltage of the inverter from 23.4V to 22.0V. Although System 557 has a 50 Ah battery, setting the cut-off voltage of the battery to 22 V gives the user extra capacity reaching consumption levels as 100Ah battery users. This can give the impression of a positive setting change. Nevertheless, discharging the batteries under the suggested voltage of 23.4V can significantly impact on the lifetime of the battery. On the other side, system 1167 reported mostly using his system until the low battery alarm goes on at 24,4V, this means that this user does not use the 70% DOD suggested capacity for this battery. Even though this behavior could result in a positive impact on the lifetime of the battery, the user experiences a shorter backup time.

Comparing the total load provided by the battery of both systems (see table A.6), it is evident the impact these setting changes can have. System 557 reports a load from the battery of 82kWh and system 1167 of 63.5kWh, even though the battery of system 1167 has double the nominal capacity than system 557.



(a) System 557



(b) System 1167

Figure 4.13.: Daily maximal and minimal battery voltage

Similarly, as with the PV power profile, a daily voltage profile can be calculated by taking the hourly average battery voltage and then grouping the values by the hour of the day and taking its average. In figure 4.14, the average battery voltage profiles for an off-grid and an on-grid system are displayed. As expected, both profiles reach the same average battery voltage, whereas the on-grid system reaches its highest voltage earlier in the day compared to the off-grid profile because on average the battery voltage at the beginning of the day is higher. The off-grid systems show on average lower battery voltage during the night hours compared to the on-grid system.

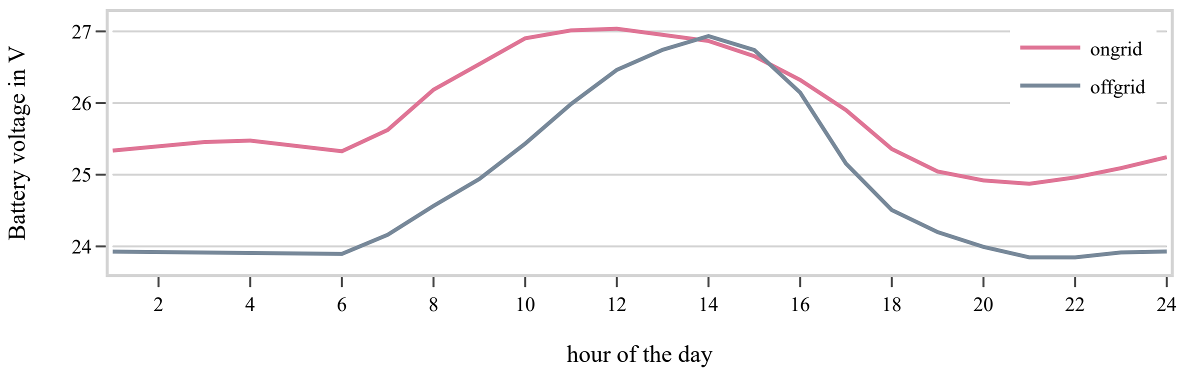


Figure 4.14.: Average of daily battery profiles of on-grid and off-grid systems

4.6. Environmental and Economic Impact

In this work, two different ways of calculating the CO2 emission and fuel cost savings are presented. First, simply by assuming the total PV Yield is proportional to the energy that the generator would have produced. Second, by breaking up the load into different sources and considering the amount of energy of direct PV and battery usage as the energy that the generator would have produced. The total CO_2 is then calculated with equation 2.6 and the cost of fuel is calculated with equation 2.5 with an initial assumption (see chapter 2.2) for the generator fuel consumption of 2 liters/kWh and a fuel price of 0.40 USD/liter.

Figure 4.18 shows the results of both methods for all systems analyzed. For some systems, both values are similar. For others, the PV method results in higher values than the load method, this can be the case for systems where the load can not be measured accurately or in case the idle time of the system is relatively long compared to the actual usage of the power output. In addition, the load method can result in a higher value if during the day the batteries get charged mostly by the grid than by PV. The limitation of the PV method is that it does not account for the economic and environmental benefits of charging the batteries with grid electricity.

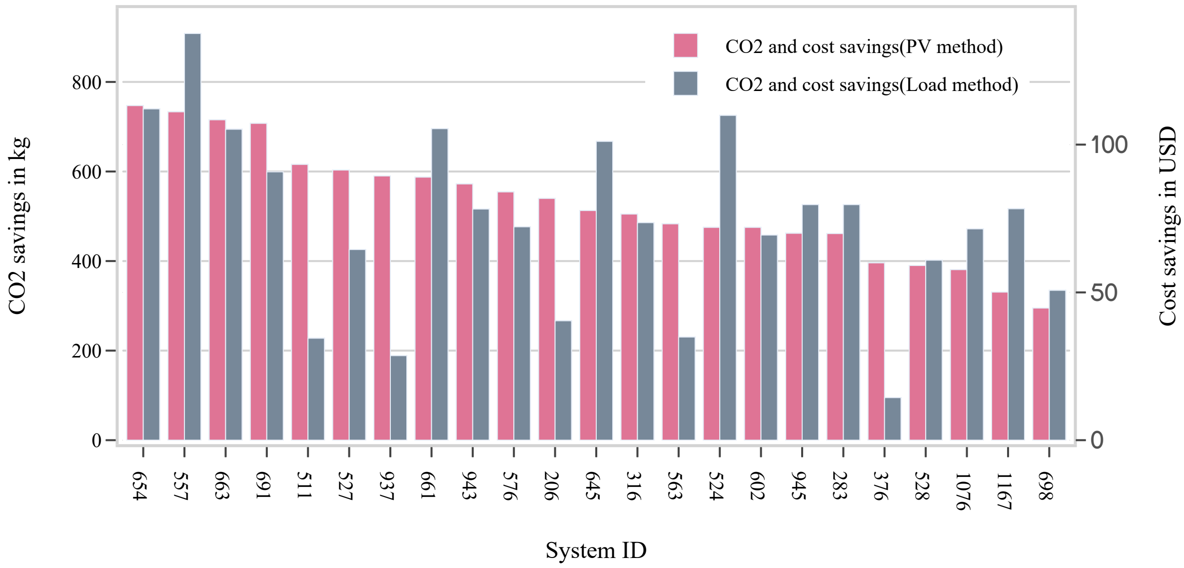
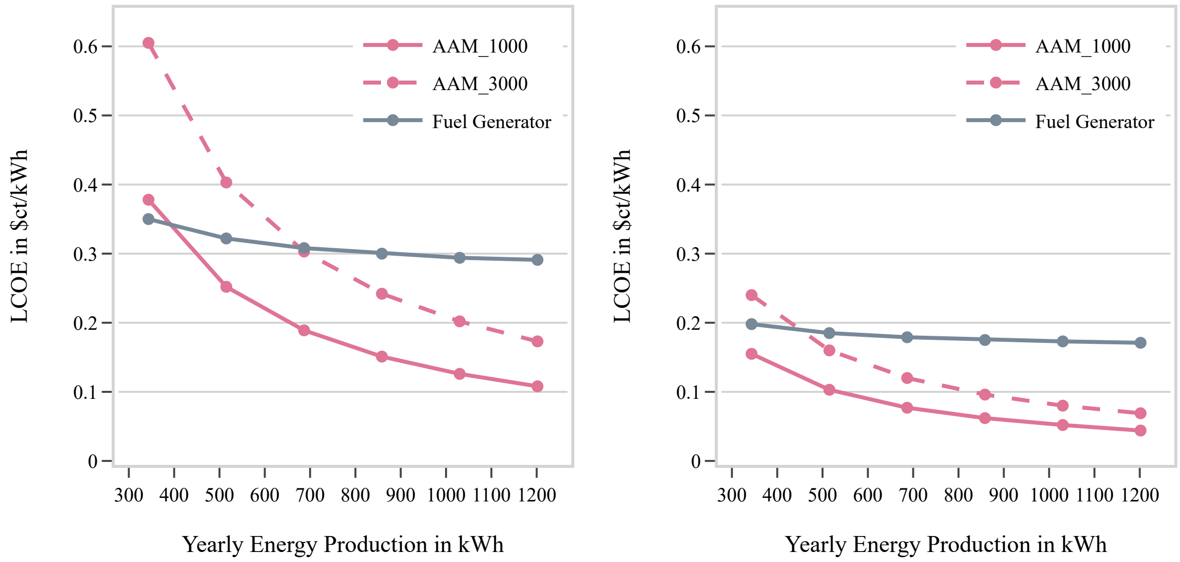


Figure 4.15.: CO2 and cost savings

Since the PV method shows more consistency than the load method, a simplified version of the resulting LCOE for both system sizes can be calculated based on a yearly PV yield. The resulting LCOE only considers the backup expenses of the user and not the overall electricity expenses. The expenses for the AAM take into account the initial down payment, the 30 monthly payments, and a maintenance cost (see chapter 2.3.4). The LCOE is then calculated for the AAM system according to different yearly PV yields. Similarly, the expenses for the fuel generator take into account the investment cost of the generator, the fuel cost, and the maintenance cost. To be able to compare the LCOE's of the AAM with the fuel generator, the LCOE of the fuel generator is then calculated assuming the same yearly energy production as the PV yield.

Firstly, figure 4.16a shows the LCOE for the AAM and for the fuel generator for the first three years of operation. Three years is the time frame where the AAM system balance payments occur. This comparison shows that the yearly PV yield of the AAM1000-50Ah and AAM3000-100Ah systems should be at least 400kWh and 700kWh respectively to be able to compete economically with the fuel generator.

The same calculation is done expanding the time frame to the first five years of operation (see figure 4.16b). Since five years is the average lifetime of a diesel generator and the average lifetime of a standard lead-acid battery. It is also expected that the lead-carbon batteries used in these systems achieve a longer lifetime than regular lead-acid batteries. This comparison shows that even with low yearly PV yields, both AAM systems prove a significant improvement in the cost of energy production compared to a fuel generator. This result can be explained by the higher fuel expenses of the fuel generator compared to the AAM expenses for years four and five that are reduced to only maintenance costs. A detailed table of the yearly cash flows is presented in appendix tables A.10, A.11, A.12, and A.13.



(a) LCOE in a three-year time frame

(b) LCOE in a five-year time frame

Figure 4.16.: Levelized cost of energy comparison

4.7. User Survey

The main focus of this survey is to analyze the situation before and after the installation of the AAM system. An overview of the information gathered during the user interviews is presented in appendix tables A.8 and A.9. As expected, 17 out of 18 participants reported using the national grid in combination with a fuel generator as a backup, one participant reported just using a fuel generator, and one participant reported using a combination of the national grid, a fuel generator, and a battery+inverter backup. From the 17 users connected to the national grid, just five reported owning a prepaid meter. The remaining participants pay their electricity bill through an estimated bill. The opening hour of the MEs is on average 07:00 am, and the closing hour is on average 10:30 pm. Furthermore, 17 out of the 18 participants kept their fuel generator in their store, which is understandable since the user already made the upfront investment. Nevertheless, just 6 of the 17 participants that kept the fuel generator are still using it, in case the battery of the AAM system is discharged, and the national grid is not available.

The average load factor of 9 participants is calculated with equation 2.4. The average load is taken from the inverter data and the nominal capacity of the fuel generator is taken from the survey data. For the participants from which load data was measured, the average load factor is shown in figure 4.17. The horizontal line shows that the average load factor of these fuel generators would be 0.12. As seen in figure 2.1, this can result in almost 50% higher fuel consumption than initially assumed with the load factor of 0.2. Even if the quantity of analyzed systems is not representative for all fuel generators, these results reveal that the CO2 emission savings and fuel cost savings through the usage of an AAM system could be in reality, higher than initially assumed.

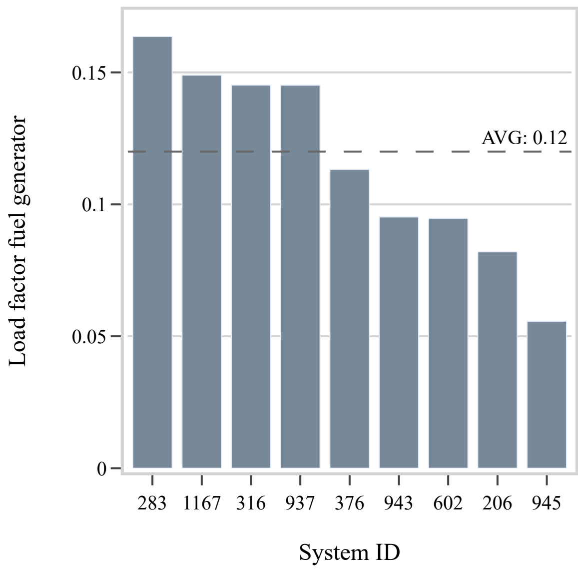


Figure 4.17.: Load factor of fuel generator

Considering only the expenses on fuel and on the national grid, the cost reduction after the AAM installation relative to the expenses before the AAM installation is calculated for each participant and presented in Figure 4.18. Participants reported an average 85% reduction from the initially reported overall electricity cost. The primary factor is recognized to be the fuel cost savings, which dropped on average 91% for all participants. Contrarily, the grid cost savings dropped just 14%. This relatively low reduction of the grid cost occurs because most of the participants use the estimated bill method and still need to pay the same amount for the grid electricity as before. However, some participants that own a prepaid meter could experience a reduction in their electricity bill.

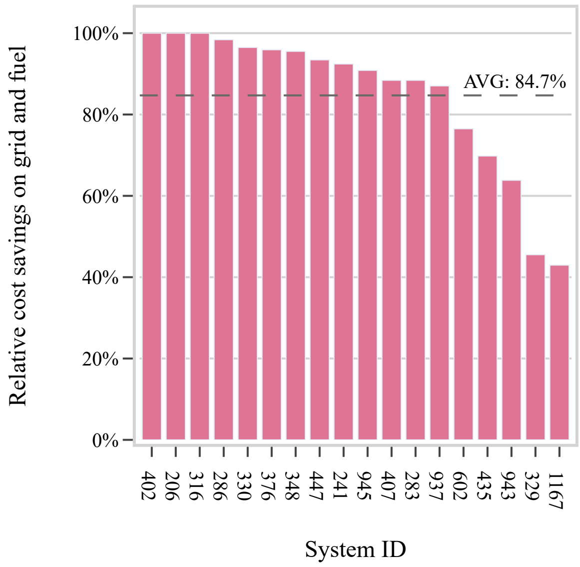


Figure 4.18.: Relative grid and fuel cost savings on

Furthermore, the bars in diagram 4.19 display the absolute daily expenses on fuel and grid reported by each participant. In addition, the horizontal lines indicate the daily fees expressed by the operators to pay the AAM systems ($1.95 for the AAM1000 and $1.21 for the AMM3000-100Ah). Comparing the previous daily expenses on electricity with the daily fees for the AAM system, almost all participants experience economic benefits with the use of the AAM system. Especially system 206 experiences high savings since this user dropped the grid and fuel generator usage. Likewise, system 945 also experiences high savings, partly due to the savings on the grid cost experienced through the prepaid meter. Contrarily, for systems 937 and 943, higher expenses after the AAM installation are observed. Interestingly, 17 out of the 18 participants reported experiencing a positive economic impact by using the AAM system, even systems 937 and 943.

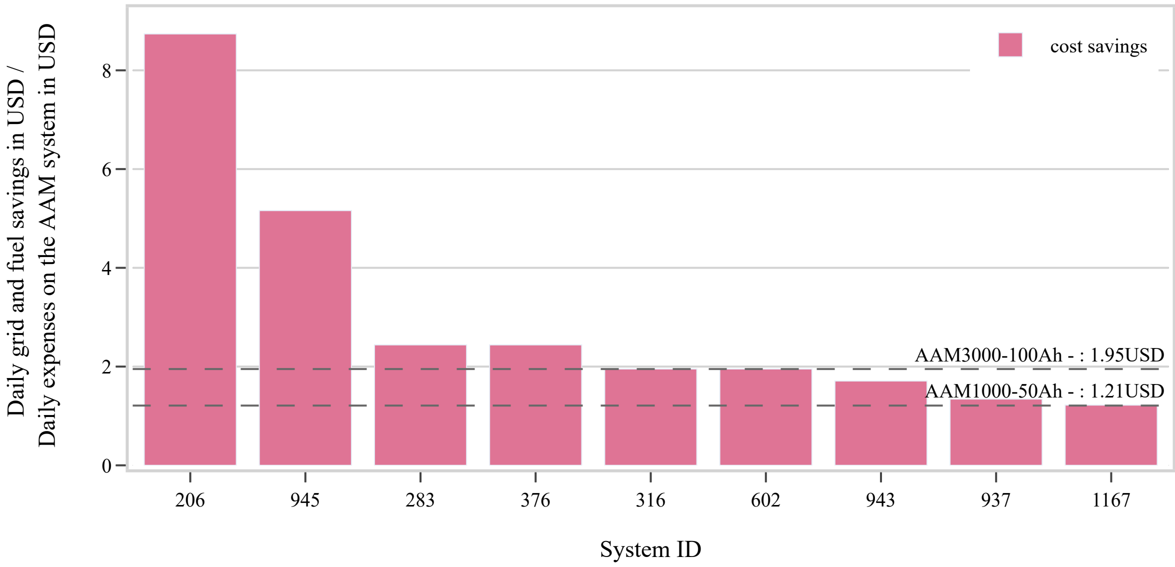


Figure 4.19.: Daily savings and expenses through the use of the AAM system

Finally, the participants reported an overall satisfaction level of 4.4 out of 5. As mentioned before, further analysis showed that system 1167 reported the lowest satisfaction level (2/5) because the participant uses the low-voltage alarm at 24,4V as an indicator that the battery is almost empty, experiencing a short back-up time.

5. Discussion

The most important observations of the data evaluation in the previous chapter and their importance for optimizing the AAM system will be discussed in this chapter. Furthermore, an interpretation of the observed system performance and recommendations for future project stages and future research in this field will be provided.

After analyzing the collected data, it is evident that several factors influence the system's performance. The measured grid data is an essential basis for creating grid reliability profiles for simulating this kind of backup system. Including the following criteria in the production of these profiles is recommended. The grid data analyzed in this work showed that the quality and reliability of the national grid is different for each grid-connected system. Even in the same localities, different grid reliability values were measured. Nevertheless, different tariff classes could be recognized from the grid data in Mararaba. From this observation, knowing the tariff-class of the grid-connected user can give an approximation of the average daily grid availability profile and daily reliability and therefore be an important factor for the choice of component sizes. In addition, it is necessary to consider that the grid voltage's quality can differ at different hours of the day is also to be considered, since this system can use only a specific voltage range.

The grid data also showed that the distribution of blackout event duration is not symmetrical. This means that to include the blackout duration into the creation of grid profiles for simulations, taking the median and the interquartile range can create more accurate profiles than taking the measured mean and its standard deviation. Moreover, it is necessary to analyze further the effects of excluding longer blackouts from the grid profiles since trying to compensate longer blackouts with a backup system can lead to oversizing of the components.

Furthermore, installers reported that grid availability varies depending on the season due to the effects of the rainy season on the electricity production of hydropower plants. For this reason, it could be necessary to analyze grid data over a complete year to be able to include seasonality effects into the grid profile. Likewise, it can be observed in the solar irradiation table that during the dry season, the solar yield is higher compared to the rainy season. How these two seasonal effects influence each other can also be further analyzed with a full year data set.

Even though the analyzed systems are located mainly in urban areas with grid connection, it is necessary to state that the operators reported that the highest necessity for this kind of solar backup system is in rural areas, where very low or no grid is available. This can be explained by the higher expenses for electricity that off-grid users experience, covering their load with a fuel generator. The operators also reported that the AC charging function should also be kept for off-grid systems, since charging the batteries with a fuel generator during a period of low solar radiation is considered a useful feature of the system.

The uncertainties regarding the source of grid data due to the system set-up like the uncertainty, if the measured grid data is actually produced by a fuel generator or if the grid connection is being manually manipulated by the users, presents a conflict for using the measured grid data for extensive national grid analysis.

Since some operators reported that generators with very high voltage output were damaging the installed AAM systems, the set-up recommendation changed to setting the AAM system before the change-over-switch and not after. Even though the system's safety is ensured with this new recommendation, the benefit of using the fuel generator under a higher load factor and consequently increasing their efficiency, is eliminated. An alternative practiced by one of the operators is the usage of a surge-protector on the input side of the AAM system. This kind of device are already standard in regions where the grid quality is low. A further disadvantage of this new set-up is that if the generator is being used to supply the load, this load data in not collected.

Furthermore, one of the main customer complaints reported by the operators was the low battery alarm of the system, which its factory set-up is 24,4V, 1V greater than over the cut-off voltage(23,4V). Most of the users deactivated this alarm, thus users like 1167 reported the usefulness of this alarm for MEs. User 1167 reported turning on the generator when the low voltage alarm turns on to have a constant light supply in his pharmacy, since complete darkness leads to theft vulnerability. Nevertheless, at this voltage the battery is not discharged yet, yet is the alarm steady and loud. Settings for the newly produced systems were changed, the alarm is short, and the gap between the alarm voltage and cut-off voltage is smaller.

A particular emphasis on the resilience of components and a fail-safe installation process is essential for the long-term sustainability of this system in this location. It was observed that the installed systems were just after some weeks of operation extremely dusty. The operators also reported that some systems are installed in remote areas difficult to reach in case of system maintenance.

The analysis of the PV data mainly showed the difference in PV yield between the on-grid and off-grid systems. The lower PV yield of grid-connected systems can be explained by the relatively high average battery voltage at the beginning of the day and the grid priority setting of the system. The PV daily profiles also showed that the PV capacity is generally oversized with the currently used grid priority set-up for on-grid systems. A new PV operation mode that prioritizes PV or grid depending on the time of the day and available PV power could increase the PV yield for grid-connected systems and decrease the payback period of the AAM system since grid cost savings could also be achieved. Changing the setting to PV priority should be done so that the overall AAM availability is not reduced, since the highest priority is a constant power supply. Some users did recognize the benefit of using the PV power during the day instead of the grid electricity and manually deactivated the grid connection during the day.

Moreover, it was observed in the installations that the PV panels are generally not installed with an ideal azimuth and inclination angle, since the PV panels observed were mounted parallel to the available roof surface and these are generally not optimally inclined nor aligned. This inaccuracy can have a negative effect on the overall performance of the PV system and be one of the causes for a low PR value. For users where the PV panels can not be installed with the optimal orientation, the PV nominal power could be increased by installing additional PV panels. Nevertheless, the economic viability of this approach should be further analyzed.

The resulting average load for almost all systems confirmed the finding of previous studies that fuel generators are normally operated with very low load factors. The reported inaccuracies of the current method of load measurement can be partly solved, without increasing the transferred data volume, by simply logging the average of the load in the five-minute interval rather than logging the momentary load. The load data showed that the smaller inverter size (1000VA) is able to supply 22 out of the 23 analyzed systems.

An interesting observation worth highlighting is that some users that manually switched off their systems during the night had a positive impact on the overall performance of their systems. The main reason for this is the relatively high self-consumption of the system (34W) during idle or low consumption. It is possible to reduce the self-consumption during idle by 50% activating the "eco-modus" of the inverter. Nevertheless, a minimum of 50W resistive load is required for the inverter to go on. One possible solution for low consumption loads can be to introduce a DC output for efficient DC loads like lights and ventilators. Nevertheless, operators reported that the DC appliance market is not yet developed to be a comparable alternative to the well-established AC appliance market. Another solution could be to add an external switch for the user to switch off the system when it is not needed, or to give the user the possibility to configure and activate an automatic shut-off switch for the time when the system is not in use, for example during the night.

An important realization emerging from the battery data analysis was that some users changed the cut-off voltage of the inverter from 23.4V to 22.2V. For example, it was observed on system 654 that just by changing the cut-off voltage and by gradually reducing the load in late evening hours resulted in nearly double the backup time when compared with the recommended setting. Moreover, the battery lifetime is expected to be shorter if the 70% DOD is surpassed. If operators want to give a guarantee over the battery lifetime, this setting needs to be immutable. The necessity of higher battery capacity and PV power was shown by users purchasing and combining several systems. Further add-on PV and battery modules could be offered for users with higher energy demand. Another setting that was not considered is the charging current of the battery charger. Currently, both battery sizes are being charged by the grid with maximal current of 10A (DC), since this is the maximal charging current for the 50Ah batteries. Nevertheless, the 100Ah batteries can be charged with a maximal current of 20A. Moreover, the reported issue that a small generator cannot charge the AAM and simultaneously supply the load can be solved by limiting the charging current to the desired maximal current of the generator.

The results of the CO_2 savings with the PV yield and load method need to be interpreted with caution. On the one side, measuring the CO_2 savings by only assuming the system PV yield does not consider the inverter and battery efficiency and neglects the self-consumption of the system. On the other side, using the load would be more precise to calculate the CO_2 savings. Nevertheless, the current method of measuring the load has the limitation that in a 5-minute interval, short or intermittent loads might not be correctly measured. Another limitation of the CO_2 savings result is that the source of battery charging can not be determined. Since the grid charging of the battery implies a CO_2 emission from the grid electricity production.

A simplified way of calculating the LCOE was proposed using the monthly cash flow and the PV yield. This result can be representative for off-grid systems but not entirely for on-grid systems. Since the economic benefit of charging the battery from the grid, resulting in less fuel generator usage, is not considered. This affects the overall economic context of the system, just as the stated before with the CO_2 savings calculation.

The operators reported that the PAYGO function is essential for the distribution of this kind of system, since this financial tool will enable the users to purchase the system and at the same time it gives the operators financial security towards their financiers. Currently, this function allows operators to shut on and off the system remotely. This function could be optimized by adding automatic payment reminders and balance status for the customer and adding automatic blocking of the system in case of payment delay for the operators.

The survey data reveals the benefit for some participants of owning a prepaid meter for the national grid for the overall economic performance of the system. Since prepaid meter users pay only for what they actually use, the incentive to increase the PV yield and therefore decrease the grid usage is high. Contrarily, the users using the estimated bill method still need to pay the same amount of grid electricity as before, the reduction of grid usage is not so attractive. Further analysis is required to determine how the different tariff classes and their cost for metered and non-metered customers affect the economic framework of this system.

Finally, if the average grid availability profile, the PV power profile, and the load profile are overlayed, the benefit of the PV system is shown by covering the midday grid availability gap. Moreover, the necessity of the batteries is also clear that if well sized, they could cover the evening grid availability gap.

6. Conclusion

This research aimed to evaluate the technical, economic, and environmental framework of solar UPS systems designed to substitute backup fuel generators during power outages in different locations with low grid quality in Nigeria. Real-time technical data and survey data from different on-grid and off-grid MEs and households were collected and analyzed. An online data tool was published to visualize the results of the data evaluation.

Firstly, through data evaluation and close cooperation with users and operators, initial issues affecting the overcharging and deep discharging of the batteries were identified and successfully repaired. Moreover, several data collection issues like a more precise load measurement and other software issues were found and proposed for future system updates. Further operation strategies to optimize the system performance were presented and discussed; for the complementary use of fuel generators in this system set-up, adding a surge protector or installing the AAM system before the transfer switch is necessary to protect the AAM from high peak voltage from fuel generators. The manual change of the cut-off voltage should be prevented to ensure a long battery lifetime, and also changing the low battery alarm to a short alarm will allow users to benefit from this feature and use the entire battery capacity. The necessity of either manually or automatically switching off the system to reduce standby self-consumption was identified.

Moreover, the grid data analysis results revealed that grid availability and reliability could differ drastically among grid users depending on the grid tariff of the location; knowing the tariff the users have, can give an estimate of the actual grid availability. This study highlighted the importance of differentiating between the available grid and the usable grid and considering an hourly grid availability profile to study the effect of the national grid in this kind of system. Even though these systems were initially planned to be installed in areas where the national grid is at least partially available, off-grid users were also identified, highlighting the necessity of this type of system in off-grid locations. Nevertheless, with the current set-up, the PV yield of systems with no grid availability can be more than double compared to systems with high grid availability, showing the importance of a new PV priority operation mode. Further research is needed to determine the effects of not using the available grid to increase the PV yield without affecting the security of the electricity supply. The potential of the PV capacity of 800W is not fully used with the current grid priority set-up for users with high grid availability.

The load data presented here underlines the fact that the availability of the national grid supply is low during the hours of the day, where electricity supply is mainly needed. Moreover, the results of the load data emphasize the difference between the load profile of MEs, which in average open daily from 07:00 am to 10:30 pm, with the highest load in the evening hours and households which have the highest load during the day and a low but steady consumption during the night. Moreover, it was determined that a 1000W inverter would be sufficient for most of the analyzed users. It was shown that the 100Ah battery system has the potential to reach tier 4 daily consumption (3.4kWh), and the 50Ah system achieves tier 3 daily consumption (1kWh). It would be recommended to facilitate the installation of add-on PV power and battery capacity to flexibly adjust them based on the given conditions of the targeted users. Future studies can use the grid availability profile, the MEs and household load profiles, and the PV profiles presented in this work as a basis for simulations to achieve optimal system sizing.

The economic framework analysis showed the relevance of implementing long-term financial tools to make this technology economically attractive from the beginning of the project's lifetime. If the PV performance reaches per year 400kWh for the AAM1000-50Ah and 700kWh for the AAM3000-100Ah, the energy cost will be lower than the fuel generator in the first three years of operation. Even though only a portion of the CO2 mitigation could be analyzed, it was still shown that 4 tons of CO2 per system could be mitigated yearly with the current average PV performance. Further data collection strategies need to be implemented to quantify the CO2 mitigation through battery charging with the national grid.

In conclusion, it can be stated that the solar UPS system presented in this work provides a reliable and economically attractive alternative that could partially or entirely substitute small fuel generators for small businesses and households in regions with unreliable grids. This kind of bottom-up electrification through renewable and decentralized energy systems will be an essential milestone for developing countries with poor grid connections to step out of energy poverty, improve life quality, and increase the productivity of small businesses.

A. Appendices

NERC ELECTRICITY TARIFF REVIEW

SEPTEMBER - DECEMBER, 2020

TABLE 1

TARIFF BAND	HOURS OF SUPPLY	TARIFF CLASS	TARIFF (per kWh)
Life-line (R1)			N4.00
BAND A	20 hours & above	A - Non MD	N49.75
	20 hours & above	A - MD 1	N67.70
	20 hours & above	A - MD 2	N67.70
	20 hours & above	A - MD 3	N53.05
BAND B	16 hours & above	B - Non MD	N47.72
	16 hours & above	B - MD 1	N64.65
	16 hours & above	B - MD 2	N64.65
BAND C	12 hrs. and above (but less than 16 hrs.)	C - Non MD	N45.69
	12 hrs. and above (but less than 16 hrs.)	C - MD 1	N63.63
	12 hrs. and above (but less than 16 hrs.)	C - MD 2	N63.63
BAND D	8 hrs. and above (but less than 12 hrs.)	{NON-MD } {MD-1} {MD-2}	FROZEN
BAND E	4 hrs. and above (but less than 8 hrs.)	{NON-MD } {MD-1} {MD-2}	FROZEN

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@abujaelectricity

Figure A.1.: Hours of electricity supply and corresponding tariff in Abuja, Nigeria [49]

Table A.1.: Analyzed AAM systems information

AAM Name	Location	Location Solar Radiation	Latitude	Longitude	User Type	Connection Type	Battery Size
206	Maraba	Abuja	9.011953	7.649325	ME	generator	50
283	Maraba	Abuja	9.0344284	7.6058305	ME	grid	50
316	Maraba	Abuja	9.0406849	7.6017644	ME	offgrid	50
376	Maraba	Abuja	9.0393203	7.6014256	ME	grid	50
511	Lafia	Abuja	8.49856473	8.50697994	ME	generator	50
524	Uyo	Cross_River	5.025664	7.905952	Household	grid	100
527	Maraba	Abuja	8.475312	8.585365	ME	grid	50
528	Calabar	Cross_River	4.980546	8.337248	ME	active_grid	100
557						offgrid	50
563	Kabusa	Abuja	8.967258	7.4546	Household	grid	100
576	Maraba	Abuja	9.025711	7.607765	ME	grid	50
602	Maraba	Abuja	7.5996183	7.5996183	ME	grid	50
645	Makurdi	Abuja	7.72342	8.541556	Household	generator	100
654	Lafia	Abuja	8.494548	8.505777	Household	offgrid	50
661						active_grid	100
663	Lafia	Abuja	8.511549	8.507851	ME	offgrid	50
691	Gboko	Abuja	7.336764	9.005173	ME	offgrid	50
698	Calabar	Cross_River	5.0005392	8.3419492	Household	grid	50
937	Maraba	Abuja	9.0424209	7.6075224	Household	grid_offgrid	100
943	Maraba	Abuja	9.0293834	7.6010868	ME	grid	100
945	Abuja	Abuja	9.136733	7.366741	Household	grid	100
1076	Maraba	Abuja	9.012958	7.604537	Household	grid	100
1167	Lagos	Lagos	6.6370417	3.3803933	ME	grid	100

Table A.2.: Grid availability data

AAM Name	**Grid Availability**	**Usable Grid Availability**	**Grid Availability Day only**	**Usable Grid Availability Day only**	**Grid Availability OH**	**Usable Grid Availability OH**
206	1%	1%	1%	1%	1%	1%
283	25%	23%	26%	24%	23%	22%
316	0%	0%	0%	0%	0%	0%
376	17%	14%	14%	11%	13%	10%
511	5%	1%	5%	0%	6%	0%
524	40%	32%	39%	29%	41%	32%
527	22%	20%	23%	20%	21%	20%
528	43%	32%	31%	19%	49%	39%
557	0%	0%	0%	0%	0%	0%
563	52%	25%	59%	27%	58%	22%
576	26%	21%	26%	19%	26%	20%
602	57%	31%	57%	27%	57%	26%
645	9%	6%	11%	5%	10%	5%
654	0%	0%	0%	0%	0%	0%
661	25%	22%	33%	30%	31%	27%
663	0%	0%	0%	0%	0%	0%
691	0%	0%	0%	0%	0%	0%
698	81%	46%	80%	38%	78%	41%
937	13%	11%	15%	13%	13%	11%
943	23%	21%	24%	19%	22%	18%
945	71%	39%	65%	28%	68%	25%
1076	59%	51%	60%	52%	59%	49%
1167	70%	67%	60%	58%	62%	60%

Table A.3.: AAM availability data

AAM Name	**AAM Availability**	**AAM Availability Day only**	**AAM Availability OH**
206	61%	94%	88%
283	71%	94%	89%
316	48%	69%	69%
376	96%	96%	97%
511	62%	86%	87%
524	99%	99%	99%
527	97%	98%	98%
528	96%	97%	96%
557	60%	86%	84%
563	74%	85%	81%
576	89%	97%	97%
602	94%	97%	97%
645	92%	91%	92%
654	70%	92%	91%
661	99%	99%	99%
663	59%	88%	85%
691	55%	91%	80%
698	99%	99%	99%
937	98%	98%	98%
943	99%	99%	99%
945	100%	100%	100%
1076	76%	83%	80%
1167	89%	91%	90%

Table A.4.: Grid voltage and blackout data

AAM Name	**Avg Grid Voltage [V]**	**Avg Grid Hours**	**Avg Grid Hours Day only**	**Avg Grid Hours OH**	**Avg Blackout Duration**	**Avg Blackout Frequency (day)**	**Avg Blackout Frequency (month)**
206	219	0.2	0.1	0.2	98.6	0.2	5.5
283	215.8	5.9	3	3.8	7.3	2.3	70
316		0	0	0		0	0
376	198.5	4	1.7	2.1	7.1	2.8	83
511	159.5	1.1	0.5	0.9	22.5	0.7	22
524	216.8	9.6	4.6	6.8	4.3	3.3	100
527	212.4	5.2	2.7	3.5	7	2.7	80
528	221.5	9.6	3.4	7.5	6.9	1.8	54
557		0	0	0		0	0
563	201.8	12.6	7	9.6	4	2.6	77.5
576	200.0	6.2	3.1	4.2	3.9	4.5	136
602	185.9	13.6	6.8	9.4	2.3	4.6	137.5
645	188.7	2	1.2	1.5	17.7	1.1	34
654		0	0	0		0	0
661	208.2	5.7	3.9	4.9	6.6	2.7	80
663		0	0	0		0	0
691		0	0	0		0	0
698	221.1	19.1	9.4	12.7	1.3	3.4	101
937	195.5	3.1	1.7	2.2	17.4	1.2	36
943	204.3	5.6	2.8	3.6	5.9	3.1	92.5
945	186.2	17	7.8	11.3	2.5	2.9	85.5
1076	198.1	14	7.1	9.7	4.1	2.5	74.5
1167	224.1	16.9	7.2	10.3	3.1	2.3	68.5

Table A.5.: PV data

AAM Name	Total PV Yield [kWh]	Avg daily PV Yield [kWh]	PR (August)	PR (September)	Full Load Hours (August)	Full Load Hours (September)
206	102.24	1.83	0.44	0.45	56.24	68.45
283	87.32	1.46	0.39	0.37	50.09	56.41
316	95.59	1.59	0.44	0.39	55.96	60.61
376	75.06	1.25	0.34	0.32	43.02	48.52
511	116.66	1.98	0.55	0.47	70.5	71.76
524	90.04	1.5	0.53	0.45	56.81	52.99
527	114.26	1.94	0.47	0.51	60.3	79.04
528	73.88	1.3	0.48	0.33	51.45	38.65
557	138.9	2.31	0.64	0.57	81.95	87.44
563	91.51	1.53	0.48	0.33	61.53	50.07
576	105.06	1.75	0.49	0.43	62.15	65.98
602	90.01	1.5	0.34	0.43	43.69	66.08
645	97.14	1.62	0.46	0.39	59.1	59.37
654	141.5	2.4	0.69	0.55	87.85	84.71
661	111.28	1.85	0.47	0.49	60.37	75.34
663	135.46	2.26	0.66	0.52	84.51	80.68
691	133.99	2.23	0.65	0.53	82.54	80.87
698	55.87	0.93	0.25	0.35	27.15	40.98
937	111.72	1.86	0.46	0.5	58.93	77.31
943	108.41	1.81	0.46	0.48	58.21	73.99
945	87.55	1.46	0.37	0.39	46.92	59.85
1076	72.08	1.2	0.29	0.33	37.53	50.37
1167	62.61	1.04	0.31	0.24	39.51	36.84

Table A.6.: Load data

AAM Name	Avg Load [W]	Total Consumption [kWh]	Total Consumption (PV) [kWh]	Total Consumption (Grid) [kWh]	Total Consumption (Battery) [kWh]	Avg daily Consumption [kWh]
206	155.8	50.55	34.25	0.01	16.28	0.9
283	163.6	130.03	50.27	30.42	49.35	2.17
316	145.2	92	48.84	0	43.15	1.77
376	113.2	18.89	6.67	0.93	11.29	0.34
511	53.3	43.34	25.22	0.21	17.91	0.73
524	1090.9	160.37	31.21	23	106.16	2.92
527	174.1	86.87	34.46	6.27	46.14	1.45
528	396.3	330.45	22.48	254.37	53.61	5.51
557	207.2	172.01	90.04	0	81.97	2.87
563	167.5	127.29	18.27	83.62	25.4	2.19
576	169.4	93.64	41.27	3.45	48.92	1.56
602	236.8	91.52	40.08	4.74	46.69	1.58
645	176.1	146.64	60.81	20.29	65.55	2.44
654	213.8	140.15	83.2	0	56.95	2.38
661	219.6	174.43	56.52	42.71	75.2	2.91
663	161.7	131.56	75.36	0	56.2	2.19
691	170.9	113.44	70.48	0	42.96	1.89
698	131.2	127.24	20.14	63.83	43.27	2.12
937	137.9	41.51	19.55	5.73	16.22	0.69
943	209.5	135.51	43.38	37.7	54.43	2.26
945	195	160.88	36.31	61.24	63.34	2.68
1076	320	338.21	24.82	248.88	64.52	5.64
1167	372.4	195.24	34.47	97.31	63.46	3.25

Table A.7.: CO2 and cost savings

AAM Name	**CO2 Savings (PV method) [kgCO2]**	**Cost Savings (PV method) [USD]**	**CO2 Savings (Load method) [kgCO2]**	**Cost Savings (Load method) [USD]**
206	266.8	40.4	539.8	81.8
283	526	79.7	461.1	69.9
316	485.7	73.6	504.7	76.5
376	94.8	14.4	396.3	60
511	227.7	34.5	615.9	93.3
524	725.3	109.9	475.4	72
527	425.6	64.5	603.3	91.4
528	401.8	60.9	390.1	59.1
557	908.2	137.6	733.4	111.1
563	230.6	34.9	483.2	73.2
576	476.2	72.2	554.7	84
602	458.2	69.4	475.2	72
645	667.2	101.1	512.9	77.7
654	740	112.1	747.1	113.2
661	695.5	105.4	587.6	89
663	694.6	105.2	715.2	108.4
691	599	90.8	707.5	107.2
698	334.8	50.7	295	44.7
937	188.9	28.6	589.9	89.4
943	516.4	78.2	572.4	86.7
945	526.1	79.7	462.3	70
1076	471.7	71.5	380.6	57.7
1167	517.1	78.3	330.6	50.1

Table A.8.: Survey data part 1

AAM Name	**Location**	**Connection Type**	**User Type**	**Opening Time**	**Closing Time**	**Electricity Supply Before**	**Meter Type**
206	Ikeja-Lagos	Ongrid	Barber Shop	07:00	22:00	Grid+Gen	Prepaid meter
241	Oborushoki-Lagos	Offgrid	Barber Shop	07:00	23:00	Grid+Gen	Estimated Fee
283	Mararaba	Ongrid	Barber Shop	07:00	22:00	Grid+Gen	Estimated Fee
286	Mararaba	Ongrid	Barber Shop	06:00	21:00	Grid+Gen	Prepaid meter
316	Mararaba	Offgrid	Herbal medicine store	08:00	23:00	Gen	
329	Mararaba	Ongrid	Phone charging	07:00	22:00	Grid+Gen	Estimated Fee
330	Mararaba	Ongrid	Barber Shop	07:00	22:00	Grid+Gen	Prepaid meter
348	Mararaba	Ongrid	Pharmacy	07:00	23:00	Grid+Gen	Estimated Fee
376	Mararaba	Ongrid	Barber Shop	08:30	23:59	Grid+Gen	Estimated Fee
402	Bariga Shomolo-Lagos	Offgrid	Barber Shop	08:00	22:00	Grid+Gen	Estimated Fee
407	Mararaba	Ongrid	Barber Shop	07:00	22:00	Grid+Gen	Estimated Fee
435	Mararaba	Ongrid	Phone charging	06:30	22:30	Grid+Gen	Estimated Fee
447	Mararaba	Ongrid	Barber Shop	06:00	23:00	Grid+Gen	Estimated Fee
602	Mararaba	Ongrid	Barber Shop	07:30	22:00	Grid+Gen	Estimated Fee
937	Mararaba	Ongrid	Small herb shop + house			Grid+Gen	Estimated Fee
943	Mararaba	Ongrid	Barber Shop	06:00	23:00	Grid+Gen	Estimated Fee
945	Kubwa-Abuja	Ongrid	Household			Grid+Gen	Prepaid meter
1167	Lagos	Ongrid	Pharmacy	07:00	22:30	Grid+Gen +Inv+Bat	Prepaid meter

Table A.9.: Survey data part 2

AAM Name	Kept FG	Still Use FG	FG Capacity in kVA	Daily Fuel Cost Before in NGN	Daily Fuel Cost Afer in NGN	Monthly Grid Cost Before in NGN	Monthly Grid Cost After in NGN	Satis-faction Level 1-5	Experience Economic Savings
206	Yes	Yes	1900	3500	0	2500	0	4	Yes
241	Yes	No	850	800	0	2000	2000	4	Yes
283	Yes	No	1000	1000	0	4000	4000	5	Yes
286	Yes	No	950	1000	0	500	500	5	Yes
316	Yes	No	1000	800	0	0	0	5	Yes
329	Yes	Yes	2000	1000	500	3000	3000	5	Yes
330	Yes	No	2500	900	0	1000	1000	4	Yes
348	Yes	No	950	350	0	500	500	5	Yes
376	Yes	No	1000	1000	0	1300	1300	4	Yes
402	Yes	No	850	5000	0	15000	0	5	Yes
407	No	No	1900	1000	0	4000	4000	5	Yes
435	Yes	Yes	1000	1400	400	1000	1000	5	Yes
447	Yes	Yes	1000	700	0	1500	1500	4	Yes
602	Yes	No	2500	800	0	7500	7500	5	Yes
937	Yes	No	950	550	0	2500	2500	5	Yes
943	Yes	Yes	2200	900	200	6000	6000	3	Yes
945	Yes	No	3500	2000	0	10000	6500	5	Yes
1167	Yes	Yes	2500	1000	500	5000	5000	2	

Table A.10.: LCOE of AAM systems in 3 Years

Input Parameter	Value	Unit
Discount Rate	0.08	
Inflation Rate	0.09	
Annual Discount rate	0.06	
Project Time T	3.00	years
CRF(T)	0.37	
PV max	800	Wp
Hg inc (year)	2146	kWh/m^2
E ideal (year	1716.8	kWh

AAM1000-50Ah					
Year	**Cash Flow**	**C Maintainance**	**C Total**	**Discount Factor**	**Yearly NPV**
0	$ 70.00			1.00	$70.00
1	$372.00	$50.00	$422.00	1.06	$ 398.56
2	$372.00	$50.00	$422.00	1.12	$ 376.41
3	$186.00	$50.00	$236.00	1.19	$ 198.81
Total	**$ 1,000.00**	**$ 150.00**	**$1,080.00**		**$ 1,043.78**

AAM3000-100Ah					
Year	**Cash Flow**	**C Maintainance**	**C Total**	**Discount Factor**	**Yearly NPV**
0	$ 100.00			1.00	$ 100.00
1	$636.00	$50.00	$ 686.00	1.06	$647.89
2	$636.00	$50.00	$ 686.00	1.12	$611.90
3	$318.00	$50.00	$ 368.00	1.19	$310.01
Total	**$ 1,690.00**	**$ 150.00**	**$ 1,740.00**		**$ 1,669.79**

PR	Yearly PV Yield	Total PV Yield	AAM1000-50Ah LCOE	AAM3000-100Ah LCOE
0.2	343.36	1030.08	$0.378	$0.605
0.3	515.04	1545.12	$0.252	$0.403
0.4	686.72	2060.16	$0.189	$0.303
0.5	858.40	2575.20	$0.151	$0.242
0.6	1030.08	3090.24	$0.126	$0.202
0.7	1201.76	3605.28	$0.108	$0.173

AAM1000-50Ah Annuity	AAM3000-100Ah Annuity
$389.639	$623.327

Table A.11.: LCOE of AAM systems in 5 Years

Input Parameter	Value	Unit
Discount Rate	0.08	
Inflation Rate	0.09	
Annual Discount rate	0.06	
Project Time T	5.00	years
CRF(T)	0.37	
PV max	800	Wp
Hg inc (year)	2146	kWh/m^2
E ideal (year	1716.8	kWh

AAM1000-50Ah					
Year	**Cash Flow**	**C Maintainance**	**C Total**	**Discount Factor**	**Yearly NPV**
0	$ 70.00			1	$ 70.00
1	$ 372.00	$ 50.00	$ 422.00	1.06	$ 398.56
2	$ 372.00	$ 50.00	$ 422.00	1.12	$ 376.41
3	$ 186.00	$ 50.00	$ 236.00	1.19	$ 198.81
4		$ 50.00	$ 50.00	1.26	$ 39.78
5		$ 50.00	$ 50.00	1.33	$ 37.57
Total	**$ 1,000.00**	**$ 250.00**	**$ 1,180.00**		**$ 1,121.13**

AAM3000-100Ah					
Year	**Cash Flow**	**C Maintainance**	**C Total**	**Discount Factor**	**Yearly NPV**
0	$ 100.00			1.00	$ 100.00
1	$ 636.00	$ 50.00	$ 686.00	1.06	$ 647.89
2	$ 636.00	$ 50.00	$ 686.00	1.12	$ 611.90
3	$ 318.00	$ 50.00	$ 368.00	1.19	$ 310.01
4		$ 50.00	$ 50.00	1.36	$ 36.75
5		$ 50.00	$ 50.00	1.33	$ 37.57
Total	**$ 1,690.00**	**$ 250.00**	**$ 1,840.00**		**$ 1,744.12**

PR	**Yearly PV Yield**	**Total PV Yield**	**AAM1000-50Ah**	**AAM3000-100Ah**
			LCOE	**LCOE**
0.2	343.36	1716.80	$0.155	$0.240
0.3	515.04	2575.20	$0.103	$0.160
0.4	686.72	3433.60	$0.077	$0.120
0.5	858.40	4292.00	$0.062	$0.096
0.6	1030.08	5150.40	$0.052	$0.080
0.7	1201.76	6008.80	$0.044	$0.069

AAM1000-50Ah Annuity	**AAM3000-100Ah Annuity**
$265.302	$412.723

Table A.12.: LCOE of fuel generator in 3 Years

Input Parameter	Value	Unit
discount rate	**0.08**	
inflation rate	0.09	
annual discount rate	0.06	
laufzeit T	3.00	years
CRF(T)	0.37	
PV max	800	Wp
Hg inc(jahr)	2146	kWh/m^2
E ideal	1716.8	kWh
Fuel Cost	0.4	USD/l
Fuel Consumption	2	l/kwh

Year	Yearly PV Yield	C inv	C Main	C Fuel	C Total	Discount Factor	Yearly NPV
0		$ 150.00			$ 150.00	1	$ 150.00
1	343.4		$ 30.00	$ 274.69	$ 304.69	1.06	$ 287.76
	515.0			$ 412.03	$ 442.03		$ 417.47
	686.7			$ 549.38	$ 579.38		$ 547.19
	858.4			$ 686.72	$ 716.72		$ 676.90
	1030.1			$ 824.06	$ 854.06		$ 806.62
	1201.8			$ 961.41	$ 991.41		$ 936.33
2	343.4		$ 30.00	$ 274.69	$ 304.69	1.12	$ 271.77
	515.0			$ 412.03	$ 442.03		$ 394.28
	686.7			$ 549.38	$ 579.38		$ 516.79
	858.4			$ 686.72	$ 716.72		$ 639.30
	1030.1			$ 824.06	$ 854.06		$ 761.80
	1201.8			$ 961.41	$ 991.41		$ 884.31
3	343.4		$ 30.00	$ 274.69	$ 304.69	1.19	$ 256.68
	515.0			$ 412.03	$ 442.03		$ 372.38
	686.7			$ 549.38	$ 579.38		$ 488.08
	858.4			$ 686.72	$ 716.72		$ 603.78
	1030.1			$ 824.06	$ 854.06		$ 719.48
	1201.8			$ 961.41	$ 991.41		$ 835.18

PR	Yearly PV Yield	Total PV Yield	NPV total	Annuity	LCOE
0.2	343.36	1030.08	$ 966.21	$360.7	$0.350
0.3	515.04	1545.12	$ 1,334.13	$498.0	$0.322
0.4	686.72	2060.16	$ 1,702.06	$635.4	$0.308
0.5	858.40	2575.20	$ 2,069.98	$772.7	$0.300
0.6	1030.08	3090.24	$ 2,437.90	$910.1	$0.294
0.7	1201.76	3605.28	$ 2,805.82	$1,047.4	$0.291

Table A.13.: LCOE of uel generator in 5 Years

(same input parameters as table A.12)

Year	Yearly PV Yield	C Inv	C Main	C Fuel	C Total	Discount Factor	Yearly NPV
0		$ 150.00			$ 150.00	1	$ 150.00
1	343.36		$ 30.00	$ 274.69	$ 304.69	1.06	$ 287.76
	515.04			$ 412.03	$ 442.03		$ 417.47
	686.72			$ 549.38	$ 579.38		$ 547.19
	858.40			$ 686.72	$ 716.72		$ 676.90
	1030.08			$ 824.06	$ 854.06		$ 806.62
	1201.76			$ 961.41	$ 991.41		$ 936.33
2	343.36		$ 30.00	$ 274.69	$ 304.69	1.12	$ 271.77
	515.04			$ 412.03	$ 442.03		$ 394.28
	686.72			$ 549.38	$ 579.38		$ 516.79
	858.40			$ 686.72	$ 716.72		$ 639.30
	1030.08			$ 824.06	$ 854.06		$ 761.80
	1201.76			$ 961.41	$ 991.41		$ 884.31
3	343.36		$ 30.00	$ 274.69	$ 304.69	1.19	$ 256.68
	515.04			$ 412.03	$ 442.03		$ 372.38
	686.72			$ 549.38	$ 579.38		$ 488.08
	858.40			$ 686.72	$ 716.72		$ 603.78
	1030.08			$ 824.06	$ 854.06		$ 719.48
	1201.76			$ 961.41	$ 991.41		$ 835.18
4	343.36		$ 30.00	$ 274.69	$ 304.69	1.26	$ 242.42
	515.04			$ 412.03	$ 442.03		$ 351.69
	686.72			$ 549.38	$ 579.38		$ 460.96
	858.40			$ 686.72	$ 716.72		$ 570.24
	1030.08			$ 824.06	$ 854.06		$ 679.51
	1201.76			$ 961.41	$ 991.41		$ 788.78
5	343.36		$ 30.00	$ 274.69	$ 304.69	1.33	$ 228.95
	515.04			$ 412.03	$ 442.03		$ 332.15
	686.72			$ 549.38	$ 579.38		$ 435.35
	858.40			$ 686.72	$ 716.72		$ 538.56
	1030.08			$ 824.06	$ 854.06		$ 641.76
	1201.76			$ 961.41	$ 991.41		$ 744.96

PR	Yearly PV Yield	Total PV Yield	NPV total	Annuity	LCOE
0.2	343.36	1716.80	$ 1,437.57	$340.184	$0.198
0.3	515.04	2575.20	$ 2,017.97	$477.528	$0.185
0.4	686.72	3433.60	$ 2,598.37	$614.872	$0.179
0.5	858.40	4292.00	$ 3,178.77	$752.216	$0.175
0.6	1030.08	5150.40	$ 3,759.17	$889.560	$0.173
0.7	1201.76	6008.80	$ 4,339.57	$1,026.904	$0.171

Table A.14.: Components data-sheets

Component	Name(Hyperlink)	Publisher
AAM3000	AAM3000 user manual	A2EI [33]
CRT Inverter	CRT Data Sheet	Cosuper [50]
50Ah Battery	DCS12-50	Sacred Sun [35]
100Ah Battery	DCS12-100	Sacred Sun [36]
800W Solar Panel	DuomaxM	Trina Solar [32]
Solar Charge Controller	EPEVER-tracer-BN	EP Solar [34]

Table A.15.: Data cleaning description

Data Parameter	Restriction
input_voltage_inv	$\mathrm{V}_{in,inv}(t) = NaN \Leftrightarrow V_{in,inv}(t) \geq 320 \ \vee \ V_{in,inv}(t) \leq 140$
output_voltage_inv	$\mathrm{V}_{out,inv}(t) = NaN \Leftrightarrow V_{out,inv}(t) \geq 300 \ \vee \ V_{out,inv}(t) \leq 150$
battery_voltage_inv	$\mathrm{V}_{bat,inv}(t) = NaN \Leftrightarrow V_{out,inv}(t) \geq 30 \ \vee \ V_{out,inv}(t) \leq 20$
output_current_inv	$\mathrm{I}_{out,inv}(t) = NaN \Leftrightarrow I_{out,inv}(t) \geq 100$
temperature_inv	$\mathrm{T}_{inv}(t) = NaN \Leftrightarrow V_{out,inv}(t) \geq 50 \ \vee \ V_{out,inv}(t) \leq 10$

Bibliography

[1] IEA, IRENA, UNSD, World Bank, WHO, "Tracking SDG 7: The Energy Progress Report," 2020. [Online]. https://trackingsdg7.esmap.org/data/files/download-documents/tracking_sdg_7_2020-full_report_-_web_0.pdf. [Accessed: 19.08.2021].

[2] N. Lam, E. Wallach, C.-W. Hsu, A. Jacobson, P. Alstone, P. Purohit, and Z. Klimont, "The dirty footprint of the broken grid: The impacts of fossil fuel back-up generators in developing countries," 2019.

[3] S. Karekezi, S. McDade, B. Boardman, and J. Kimani, "Energy, poverty, and development," *Global Energy Assessment–Toward a Sustainable Future [Johansson, TB, N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria*, pp. 151–190, 2012.

[4] IEA, "Africa energy outlook 2019," *International Energy Agency, Paris*, vol. 1, 2019. [Online]. https://www.iea.org/reports/africa-energy-outlook-2019. [Accessed: 19.08.2021].

[5] Worldometers, "Nigeria population live," 2020. [Online].https://www.worldometers.info/world-population/nigeria-population/#:~:text=Nigeria. [Accessed: 01.07.2021].

[6] World Bank, " Access to electricity (% of population) (EG.ELC.ACCS.ZS) World Development Indicators," 2018. [Online]. https://databank.worldbank.org/reports.aspx?source=2&country=NGA#. [Accessed: 01.07.2021].

[7] IEA, "Electricity consumption per capita, energy consumption," 2018. [Online]. https://www.iea.org/countries/nigeria. [Accessed: 01.07.2021].

[8] BP, "Statistical Review of World Energy June 2020," vol. 69th, 2020. [Online]. https://www.bp.com/content/dam/bp/business-sites/

en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf. [Accessed: 01.07.2021].

[9] Nesistats, "Nigeria Power Baseline Report," 2016. [Online]. http://mypower.ng/wp-content/uploads/2018/01/Baseline-Report.pdf. [Accessed: 01.07.2021].

[10] F. Schmidt, "Can solar energy displace small fuel generators?, An applied case study using the example of a marketplace in Nigeria," 2019.

[11] A. Oyuke, P. H. Penar, and B. Howard, "Off-grid or'off-on': Lack of access, unreliable electricity supply still plague majority of Africans," 2016.

[12] IEA, "World Energy Outlook Special Report: Energy Access Outlook, From Poverty to Prosperity," *Paris, France*, 2017. [Online]. https://www.gogla.org/sites/default/files/resource_docs/weo2017specialreport_energyaccessoutlook.pdf. [Accessed: 01.07.2021].

[13] A2EI, Dalberg, "Putting an End to Nigeria's Generator-Crisis," 2019.

[14] National Bureau of Statistics, SMEDAN, "Collaborative survey: selected findings," 2013. [Online]. https://www.smedan.gov.ng/images/PDF/2013-MSME-Survey-Summary-Report.pdf. [Accessed: 01.07.2021].

[15] S. Poczter, "You Can't Count on Me: The Impact of Electricity Unreliability on Productivity," vol. 46, pp. 579–602, Cambridge University Press, 2017.

[16] World Bank, "Percent of firms identifying electricity as a major constraint (IC.FRM.INFRA.IN12) Enterprise Surveys," 2014. [Online]. https://databank.worldbank.org/source/enterprise-surveys/preview/on. [Accessed: 01.07.2021].

[17] M. Yetano Roche, H. Verolme, C. Agbaegbu, T. Binnington, M. Fischedick, and E. O. Oladipo, "Achieving Sustainable Development Goals in Nigeria's power sector: assessment of transition pathways," vol. 20, pp. 846–865, Taylor & Francis, 2020.

[18] M. Hoffmann, S. Pelz, Ò. Monés-Pederzini, M. Andreottola, and P. Blechinger, "Overcoming the bottleneck of unreliable grids: increasing reliability of household supply with decentralized backup systems," *Journal of Sustainability Research*, vol. 2, no. 1, 2020.

[19] C. Bastholm and F. Fiedler, "Techno-economic study of the impact of blackouts on the viability of connecting an off-grid PV-diesel hybrid system in Tanzania to the national power grid," vol. 171, pp. 647–658, Elsevier, 2018.

[20] M. Bhatia and N. Angelou, "Beyond Connections," World Bank, Washington, DC, 2015.

[21] "Cost of NEPA (Grid Electricity) in Nigeria," Mar 2021. [Online]. `https://resagratia.com/dashboards/cost-of-grid-electricity-in-nigeria/`. [Accessed: 21.09.2021].

[22] A. Soyemi, I. Samuel, A. O. Ayobami, and A. Akinmeji, "The Challenges of Estimated Billing on Electricity Consumers in Nigeria: A Review," in *IOP Conference Series: Earth and Environmental Science*, vol. 730, IOP Publishing, 2021.

[23] O. D. Olatunji, "Electricity insecurity and the performance of small scale businesses in Akoko Area of Ondo State, Nigeria," *International Journal of Business and Social Science*, vol. 10, no. 7, pp. 158–167, 2019.

[24] World Bank, *Diesel Power Generation: Inventories and Black Carbon Emissions in Nigeria.* 2014.

[25] "Nigeria Gasoline Prices, 20-Sep-2021." [Online]. `https://www.globalpetrolprices.com/Nigeria/gasoline_prices/`. [Accessed: 21.09.2021].

[26] S. Varrella, "Nigeria: Average gasoline prices 2021," Sep 2021. [Online]. `https://www.statista.com/statistics/1166124/average-petrol-prices-in-nigeria/`. [Accessed: 21.09.2021].

[27] A2EI, Nile University, "A2EI Generator Consumption Test Results Nile University 2021," 2021. [Internal Report A2EI].

[28] V. Quaschning, *Regenerative Energiesysteme: Technologie–Berechnung–Klimaschutz.* Carl Hanser Verlag GmbH Co KG, 2019.

[29] ACE, "Africa Clean Energy. Importation guide for solar PV products and technologies in Nigeria. 2019.." [Online]. `https://www.ace-taf.org/wp-content/uploads/2020/01/ACE-NIGERIAN-IMPORTATION-GUIDE-2019122001.pdf`. [Accessed: 10.11.2021].

[30] M. Aamir, K. A. Kalwar, and S. Mekhilef, "Uninterruptible power supply (ups) system," *Renewable and sustainable energy reviews*, vol. 58, pp. 1395–1410, 2016.

[31] I. Nwandu-Dozie, "Nigerian Electrification Project- Stand-alone Solar Home System (SHS) Component) ," 2019. [Online]. `http://rea.gov.ng/wp-content/uploads/2019/04/SHS-component-Presentation_Online.pdf`. [Accessed: 21.09.2021].

[32] Trina Solar, *The Duomax Half-cell dual glass 144 Layout module*, 4 2020.

[33] A2EI, *Owners Manual AAM 3000*, 2021.

[34] EPEVER EPSOLAR Technologies, *Tracer- BN Series MPPT Solar Charge Controller*, 2020.

[35] Sacred Sun Power Sources Co., Ltd., *DCS Series DCS12-50 12V100Ah*, 2020.

[36] Sacred Sun Power Sources Co., Ltd., *DCS Series DCS12-100 12V50Ah*, 2020.

[37] T. M. Layadi, G. Champenois, M. Mostefai, and D. Abbes, "Lifetime estimation tool of lead-acid batteries for hybrid power sources design," vol. 54, pp. 36–48, Elsevier, 2015.

[38] World Bank, "Climate change knowledge portal, country Nigeria," 2021. [Online]. `https://climateknowledgeportal.worldbank.org/country/nigeria/climate-data-historical`. [Accessed: 21.09.2021].

[39] Vivid Economics, "Results-Based Financing in the Energy Sector: An Analytical Guide," World Bank, Washington, DC, 2013. [Online]. `https://openknowledge.worldbank.org/handle/10986/17481`. [Accessed: 21.09.2021].

[40] F. Sioshansi, "Consumer, prosumer, prosumager: How service innovations will disrupt the utility business model," pp. 311 – 239, Academic Press, 2019.

[41] N. H. Umar, B. Bora, C. Banerjee, P. Gupta, and N. Anjum, "Performance and economic viability of the PV system in different climatic zones of Nigeria," *Sustainable Energy Technologies and Assessments*, vol. 43, p. 100987, 2021.

[42] T. Huld, R. Müller, and A. Gambardella, "A new solar radiation database for estimating PV performance in Europe and Africa," *Solar Energy*, vol. 86, no. 6, pp. 1803–1815, 2012.

[43] "HOMER Pro 3.14." [Online]. `https://www.homerenergy.com/products/pro/docs/latest/glossary.html`. [Accessed: 21.09.2021].

[44] Fernando Chacon, "AAM Data Tool." [Online]. https://share.streamlit.io/fernandochacon92/aam_app_ma_2021/main/MA_FC_AAM_APP_make_data.py. [Accessed: 15.11.2021].

[45] A2EI, "A2EI Impact Survey Bot ," 2021. [Online]. https://a2ei.org/resources/uploads/2021/06/A2EI_Impact_Survey_Bot.pdf. [Accessed: 05.10.2021].

[46] "Streamlit Python Library." [Online]. http://docs.streamlit.io/getting_started.html. [Accessed: 21.09.2021].

[47] "Pandas Python Library." [Online]. https://pandas.pydata.org/. [Accessed: 21.09.2021].

[48] "Plotly Python Library." [Online].https://plotly.com/. [Accessed: 21.09.2021].

[49] AEDC Electricity, "The NERC Approved Service Reflective Tariff for AEDC, effective from 1st September 2020.." [Online]. https://twitter.com/aedcelectricity/status/1301428245351497728/photo/1. [Accessed: 21.09.2021].

[50] Cosuper (SUZHOU) Energy technology CO.,LTD, *CRT Series Inverter/Charger*, 2020.