DEMAND FLEXIBILITY IN INTERCONNECTED MINIGRIDS IN NIGERIA: OPERATIONAL AND ECONOMIC IMPLICATIONS FOR DEVELOPERS, AND CUSTOMERS

Oluwanifemi Ojo

Academic supervisor: Professor Gianfranco Chicco

Industrial supervisors: Alberto Rodríguez Gómez
Fola Aminu
Ridwan Zubair

Abstract

This thesis investigates the potential for performance enhancement of interconnected minigrids in Nigeria through demand-side flexibility, quantifying the operational and economic implications for project developers, and customers. Using empirical consumption data from over 800 customers, the study categorizes users by consumption level to identify high-demand households with realistic potential for load shifting. Energy use for each appliance was estimated based on common household appliances and their typical usage durations. This analysis identified which appliance loads could be shifted to different times of day. A Time-of-Use pricing model was implemented to encourage the redistribution of shiftable loads to off-peak hours, aligning consumption with periods of higher solar photovoltaic (PV) availability.

A key challenge addressed is evaluating the extent to which residential customers can participate in structured load-shifting programs and the associated system-level benefits. The results demonstrate that demand flexibility can lead to reductions in customer energy costs and lower reliance on fossil-fuel back-up generation during peak hours for developers. Also, solar PV usage improves through better demand alignment, and energy curtailment is minimised. These findings highlight the potential of demand-side management as a scalable strategy to enhance the efficiency, sustainability, and economic viability of interconnected minigrids and more broadly distributed energy resources.

Nomenclature

BESS	Battery Energy Storage System
CPP	Critical Peak Pricing
DER	Distributed Energy Resources
DisCo	Distribution Company
DR	Demand Response
DSO	Distribution System Operator
GEAPP	Global Energy Alliance for People and Planet
GenCo	Generation Company
IBR	Inclined Block Rate
IMG	Interconnected Minigrid
IPP	Independent Power Producer
KEDCO	Kano Electricity Distribution Company
MTF	Multi-Tier Framework
NBET	Nigerian Bulk Electricity Trading
NERC	Nigerian Electricity Regulatory Commission
NEP	Nigerian Electrification Project
PPA	Power Purchase Agreement
PV	Photovoltaic
REA	Rural Electrification Agency
RMI	Rocky Mountain Institute
RSPV	Residential Solar Photovoltaic
RTP	Real Time Pricing
ToU	Time-of-Use
VRE	Variable Renewable Energy

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About RMI

Rocky Mountain Institute (RMI) is an independent nonprofit founded in 1982, headquartered in Basalt, Colorado, USA. RMI engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost-effectively shift from ***fossil fuels*** to efficient and renewable energy sources.

The thesis was in collaboration with RMI's Africa Energy Program which works in Sub-Saharan Africa to increase access to productive use of sustainable electricity. Specifically, the organisation's utility-enabled Distributed Energy Resources (DER) hub aims to provide resources to help electricity distribution companies (DisCos, Utilities) and developers to scale these solutions through innovative business models.

These business models leverage clean energy resources, typically solar photovoltaic with batteries as embedded generation, integrating with already existing distribution network infrastructure to deliver reliable power supply to customers at a lower cost.

1 Introduction

Nigeria, located in West Africa, is home to over 200 million people and is endowed with abundant natural resources, including oil, gas and some of the highest solar irradiation level on the continent [1]. Despite this wealth of energy resources, the country continues to face significant energy access challenges. About 75% of the population lack access to electricity or experience unreliable supply [2]. Electricity supply from the national grid in many Sub-Saharan African countries remains unreliable. In Nigerian for instance, the national grid meets only about 20% of the country's total energy demand.

As the sector evolves, attention has shifted to isolated minigrids, particularly for rural communities because minigrids are seen as one of the least-cost options for accelerating electricity access. Isolated minigrids are stand-alone electricity generation and distribution systems designed to serve communities, especially those in rural areas that lack access to connections from the grid. The system typically consists of a mix of solar photovoltaic (PV) panels, battery energy storage system (BESS), and back-up diesel generators [3].

To bridge the energy access gap, the Rural Electrification Agency (REA), an agency set up as part of the Nigeria's broader power sector reforms to promote access to electricity has, in partnership with private energy developers, significantly expanded Nigeria's off-grid energy sector. This expansion has been through the deployment of solar mini-grids, standalone solar home systems, and hybrid solutions across underserved rural and peri-urban areas. According to the recent progress update, about 176 minigrids have been installed with over 94MW of solar PV capacity under the Nigerian Electrification Project (NEP) sponsored by the World Bank [4].

Despite the progress made, isolated minigrid continues to grapple with the challenge of scalability due to its high upfront capital cost and under-utilization of installed supply capacity resulting from low energy demand amongst rural customers. This low-capacity usage often translates into insufficient revenue generation which makes it difficult to recover the cost of investment, to maintain infrastructure and cover the day-to-day operational expenses required for reliable electricity supply [3]. In addition, millions of Nigerians still lack access to reliable electricity supply, hence the need to consider other innovative business models that can be adopted to strengthen the financial viability of Distributed Energy Resources (DERs).

The Interconnected Minigrid (IMG) business model has been a strategy under consideration and the first of its kind was adopted in the country. IMG contributes to the improvement of electricity access as it leverages existing grid infrastructure instead of developing an entirely new distribution network as the case is for isolated minigrids. This interconnection system uses clean energy resources, which is typically solar PV with batteries, integrated with already existing distribution network infrastructure to deliver reliable power supply [3].

The IMG model helps address some of the longstanding challenges faced by Distribution Companies (DisCos) by repairing or replacing aging infrastructure and providing meters to connected customers – areas that would otherwise have been overlooked due to financial constraints.

Currently, there are four operational interconnected minigrids pilot project across different regions (Zawaciki, Toto, Wuse and Robinyan) in Nigeria supported by GEAPP and RMI [3].

Figure 1: Four interconnected minigrid pilot project's location in Nigeria

RMI Graphic. Source: RMI analysis of IMG pilot data, OpenStreetMap

1.1 Benefits of the Interconnected Minigrid (IMG)

Early results from the IMG projects operational since 2023 have been very positive. Areas served by IMGs have experienced significant improvements in energy supply and reliability, with daily energy supply increasing from 3 hours to 18 hours due to energy from the local PV generation plant and improved grid supply[3]. There has been a 62% increase in metered connections across all four projects, a notable increase in both connections and metering rates. These regions are also reporting about fifteen times higher energy consumption (as indicated by higher ACPU) when compared to their isolated minigrid counterparts, which results in higher monthly revenues for minigrid developers. This is due to more commercial customers and higher-income residential customers being served by the IMGs [3].

1.2 Challenge with Interconnected Minigrids (IMG)

Despite all the benefits provided by IMGs, one of the sites, Zawaciki, is still very expensive to operate. This is due to unreliable grid electricity supply, the absence of battery storage to manage the mismatch between solar generation and demand leading to heavy reliance on diesel generators. RMI's analysis found that the cost of delivering power using diesel generators at night and in the early morning when solar panels are not producing electricity is on the high side, particularly with the fluctuation of the price of diesel. The analysis shows that Zawaciki spent approximately 2.5 times of its total revenue solely on diesel in 2024. When considering additional operational costs, which include grid energy purchases, salaries, and other expenses, the total monthly operational cost could exceed four times the revenue which poses significant challenges to the sustainability of the project.

For Interconnected Minigrids to scale, they need to be more cost-effective. This means reducing the use of diesel generators to the barest minimum, as they account for a major portion of the total operating costs. Among several other solutions, the application of Time of Use (ToU) tariff provides an opportunity to lower costs. While ToU could be a strategic tool for driving down operational costs, the extent of savings is determined by the region-specific services needs and the willingness of customers to shift energy demand to solar-production period during the day and most importantly, the type of appliances they have.

2 Objectives

The primary objective of this thesis is to assess potential demand-side flexibility enabled by Time of Use (ToU) tariffs, to improve the operational and economic performance of Interconnected Minigrids in Nigeria. This study seeks to evaluate whether load shifting can be used to reduce the curtailment of solar energy and reliance on diesel generators.

To achieve this, the thesis aims to:

- Model appliance level load profile considering baseline and demand shifting scenarios
- Determine the impact of ToU tariffs on load shifting
- Estimate system-level savings in diesel usage
- Assess customer-level cost savings

3 Literature Review

3.1 Demand response (DR)

Demand response allows electricity users to contribute to the operation of a grid system, either by reducing demand during peak hours or shifting use of electricity to lower consumption period. This is an adopted strategy to control the load profile of consumers. It plays a critical role in improving power system efficiency, especially with the increasing share of variable renewable energy [5]. Through demand-side management, utility or minigrid operators can address rapidly increasing demand while also reducing overall operational costs. DR programs are divided into categories: incentive-based and price-based. When considering the incentive-based DR, customers are given incentives to adjust their consumption based on what the utility company requires [5]. On the other hand, for price-based DR, utilities or developers assign different electricity prices to different periods of the day to influence consumption patterns.

3.2 Time-of-Use (ToU) Tariffs

Time-of-Use (ToU) tariff is a key component in the design of business models or market schemes, and a strategic demand response tool used to align electricity consumption patterns with grid capacity and price dynamics particularly for DER. With this tariff scheme, customers are able to change their consumption of electricity based on a mutual agreement, either manually or automatically to reduce their overall energy cost [6]. This gives room for demand side flexibility, while enabling the increased penetration of renewable energy.

This price-based demand response programme (ToU) can be *static*, that is, tariffs determined in advance or *dynamic* such that the tariffs are determined on "real time" based on the state of the system. Dynamic tariff structure considers real-time pricing, variable peak pricing and critical peak pricing [6]. In advanced electricity businesses or markets, ToU models are made possible through advanced metering infrastructure, adoption of smart appliances and automation control, active customer engagement and the provision of real-time market signals.

However, in countries like Nigeria where the electricity business remains largely regulated with frequent infrastructure challenges, the adoption and implementation of ToU tariff requires a contextually tailored approach.

3.3 Landscape of Nigeria's electricity sector

The Nigerian electricity business is not yet fully liberalized. Generation and transmission are still dominated by a few major entities. The Nigerian Bulk Electricity Trading (NBET) Plc serves as the financial intermediary, linking electricity generators and distribution companies (DisCos). NBET buys power in bulk from generation companies (GenCos) and Independent Power Producers (IPPs) and sells it to distribution companies via vesting contracts [7]. The Nigeria electricity market structure as shown in Figure 2.

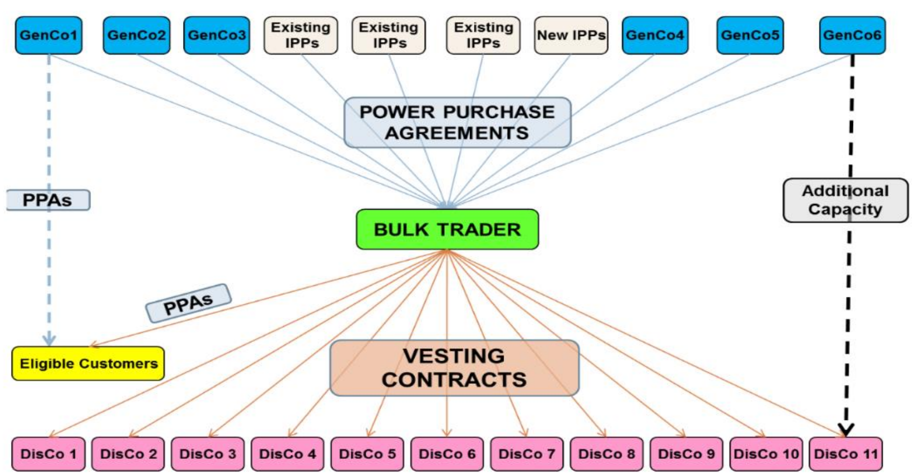

Figure 2: Nigeria's electricity business structure source: NBET

Nigerian electricity prices are not set dynamically through open-market bidding (demand and supply) unlike in liberalised markets such as parts of the U.S and Europe. Rather, electricity prices are determined by regulated tariffs approved by the Nigerian Electricity Regulatory Commission (NERC). It is also important to note that day-ahead or real-time markets do not yet exist, and transactions are majorly based on bilateral contracts and long-term Power Purchase Agreement (PPAs), not open market bidding. This situation is foreseen to limit the flexibility of introducing real-time price signals, which is a core feature of the ToU schemes in a competitive electricity market.

However, for the off-grid situation, regulators permit distributed models like minigrid, isolated minigrid, IMGs, to operate under a tariff structure that is cost-reflective. The developers or operators can charge approved tariff tailored to their specific business models, which allows for ToU opportunities. The regulation allows for a tripartite agreement signed by representatives of the connected community, the minigrid developer and the DisCo concerned, to be approved by the commission [8].

3.4 Overview of global Time-of-Use tariff programs and leading case studies

According to IRENA, ToU tariff are applied in atleast 17 European countries which including Sweden, Germany, Finland, France, Germany and others, while other regions include the USA and India [6]. The most common ToU structure in Europe is the static which differentiates the price of day-time consumption from night-time consumption. On the other hand, countries like Estonia, Romania, Spain, Sweden, already adopts the dynamic real-time pricing, including the United Kingdom, where between 25% and 50% of households are charged based on hourly price changes [6].

3.4.1 Time of Use case study – Finland

In Finland, consumers can choose their desired tariff structure in a liberalised market and one of these is the dynamic pricing[6]. Consumers who choose this dynamic price tariff structure pay hourly for electricity based on the Nord Pool spot price[6]. They also pay retailer’s premiums, and a fixed monthly fee as agreed in the contract. With this, customers can check electricity prices for each hour a day ahead from the retailer’s website to decide when to use it increase or reduce consumption. The price that would be paid by the consumer is dependent on the periods of consumption during the day. In Finland, customers are usually able to access their hourly consumption through their local distribution system operator's (DSO) application, made available a day following delivery. There has been a rapid increase in the adoption of dynamic electricity price contract in Finland moving from just 8% of households in 2020 to about 31% by the end of 2023 [9]. These can be attributed to [6]:

- Widespread rollout of smart meters which allows accurate monitoring of electricity use and supports hourly billing.
- Increased public awareness and policy support from the Finnish government and the energy authority.
- Advanced digital platforms and mobile apps have made it easier for consumers to monitor and adjust their consumption based on real time price signal.

3.4.2 Time of Use case study - Brazil

To strengthen the feasibility of the implementation of Time-of-Use tariff in Nigeria, it is important to consider global best practices and tailored solution that could be inspired by an emerging market like Brazil. The regulatory authority ANEEL implemented the White Tariff structure to encourage retail consumers connected to the low-voltage distribution grid to shift their use of electricity to off-peak periods [10]. This tariff structure divides hours into three categories: peak hours when demand is highest, intermediate hours surrounding the peak (hours just before and after the peak), and off-peak hours during the remaining weekday periods as well as weekends and holidays [10].

3.5 Reflective hours for Nigeria

Learning from the "white tariff" system in Brazil, a static ToU tariff can be introduced where peak, intermediate peak and off-peak periods are predetermined and communicated to consumers. This simplifies the process in a country like Nigeria as it avoids the need for real-time metering infrastructure that is currently a major challenge within the country. This tariff scheme (Static ToU tariffs – Day/night price differentiation), is also common in Europe [6].

4 Methodology

4.1 Overview

Many studies have been carried out to assess the potential for flexible demand and load shifting. According to [11], assessing demand flexibility estimation method can be grouped using two approaches:

1. Appliance-level approach: This is a disaggregated approach that considers individual electrical services to determine their shiftability.
2. Aggregate-level approach: The method models overall demand response across users as a function of changes in the price of electricity.

While both methods provide useful insights, this study focuses on the appliance-level approach. The aggregate, price elasticity-based method was not adopted in this work due to lack of reliable real-time elasticity data of the region under consideration. The appliance-level approach allows for a detailed assessment of the technical potential for load shifting by considering shiftable appliances, determining when specific appliances are typically used and whether their operation can be rescheduled without customer's discomfort.

Given the focus on appliance-level flexibility, this study implements a bottom-up, appliance-level modeling approach to assess the potential for demand flexibility among residential customers in interconnected minigrids in Nigeria. The methodology involves simulating realistic appliance use patterns across different categories of customers based on the average daily energy consumption, appliance ownership and use characteristics. The methodology comprises four major components:

1. Site selection and data analysis.
2. Appliance ownership modeling by customer tier.
3. Simulation of appliance-level load shifting under Time-of-Use (ToU) pricing.
4. Analysis of operational and economic outcomes, including cost savings and diesel generator displacement.

4.2 Site selection and data analysis

The selected site for this study is the Zawaciki interconnected Minigrid in Kumbotso LGA, Kano, which serves over 800 connections and includes residential, SME, and light industrial customers [3]. Being the largest IMG in Nigeria, the Zawaciki IMG was developed by Bagaja Renewables in partnership with Kano Electricity Distribution Company is powered by 1 MWp solar photovoltaic system and supported by grid supply, with a diesel generator serving as a backup. While it provides relatively high energy, the site currently does not have a battery storage system and relies heavily on diesel generator and grid supply. This made Zawaciki a suitable case study for assessing the impact of Time-of-Use tariffs on load shifting and the resulting cost savings. Although this site provided useful insights as one of the first operational interconnected minigrid in Nigeria, data limitation still exists.

A review of the dataset included customer-level electricity consumption, aggregated load profile on a typical day, energy mix, grid and diesel generator supply, and hourly energy balance across the system. These parameters informed the baseline energy demand profile used in the simulation and to identify opportunities for assessing appliance-level demand. The load profile is aggregated at the system level which means it does not show individual household level consumption.

Figure 3 shows the hourly energy mix in Zawaciki on August 1st, 2024. The bars represent the energy supplied by the solar PV, the grid or the diesel generator. The solid blue line shows the total electricity demand across the 24-hour period, and the red dashed line indicates the PV generation for the location, based on solar irradiance data from PVGIS.

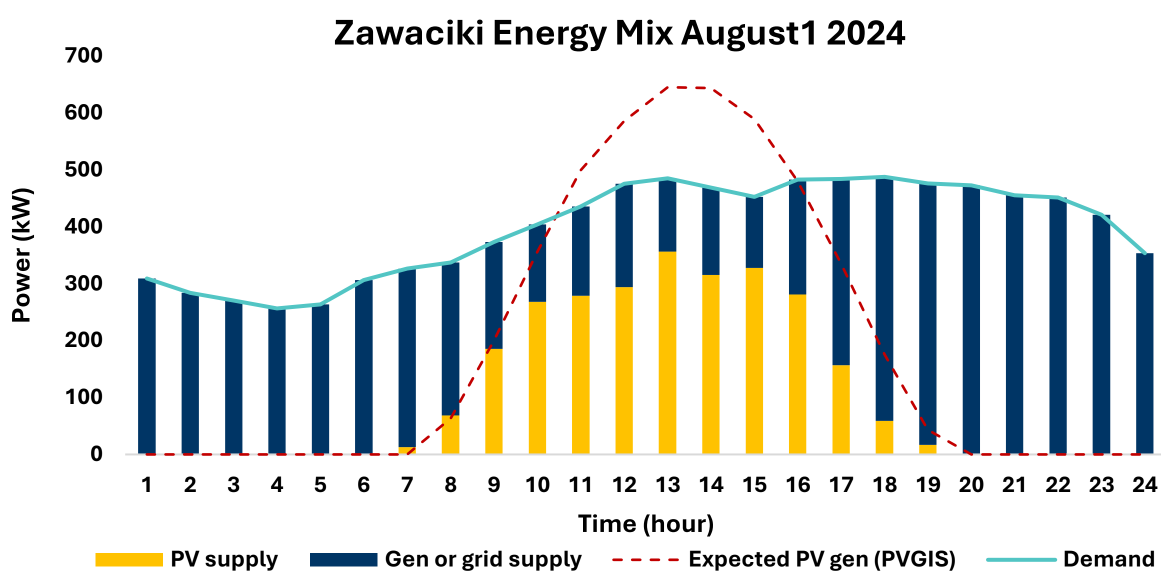

Figure 3 Zawaciki load profile and energy mix of a day in August.

However, there is a noticeable gap between the expected PV generation (dashed red line) and the actual PV supply (light blue bars) during solar hours, particularly between 11:00 a.m. and 3:00 p.m. This is because there is not sufficient demand during these hours, leading to PV curtailment.

As seen above, when the PV generation supplied was compared with the ideal generation obtained from the location's irradiance data, it was observed that about 43% of the total energy generated by the PV is curtailed. This fraction represents 1997 kWh curtailed energy in the day.

4.3 Customer dataset and tier classification

The analysis is based on electricity consumption data from over 800 customers, as provided by RMI. These customers span residential, commercial, industrial, and educational institutions with residential users making up approximately 98% of the total as seen in Figure 2. Given this significant number of residential customers, the load shifting and Time of Use (ToU) analysis focused primarily on the residential category. Among these households, daily electricity consumption ranged from less than 1 kWh to as high as 20 kWh per day, showing multiple ranges of electricity use patterns.

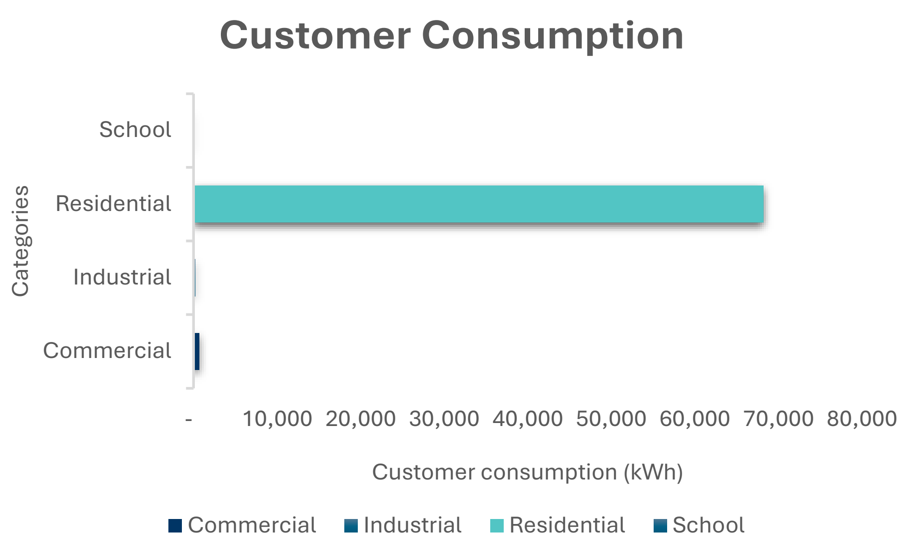

Figure 4: Customer category for Zawaciki

4.4 Customer classification by tier

To model a realistic electricity consumption pattern and evaluate load shifting potential, residential customers were grouped into tiers based on the average daily consumption. This approach follows the World Bank's Multi-Tier Framework (MTF) for Measuring Energy Access, which categorises households by their total energy consumption between Tier 0 and Tier 5. Following this, the residential customers were classified as seen on Table 1 [12].

Table 1: Multi-tier division of Zawaciki customers

Tier	Category	Consumption (kWh/day)	Number of Customers #	Average Consumption per User (kWh/day)
Tier 0	Small	0 – 0.012	1	0.01
Tier 1		0.013 - 0.199	33	0.1
Tier 2		0.200 – 0.999	198	1
Tier 3	Medium	1.0 – 3.424	407	2
Tier 4	Medium-to-high	3.425 - 8.218	186	5
Tier 5	Large	Greater than or equal 8.219	36	12

In this study, three tiers were considered namely, Tier 3, Tier 4, and Tier 5. These categories represent higher energy consumption and hence, the use of electrical appliances with shiftable potential. Out of the 861 households' consumption data, approximately 629 falls within Tier 3 to Tier 5, and are identified as candidates for flexible load shifting and the Time-of-Use tariff system.

4.5 Appliance ownership by tier

Considering that there was no direct data from households showing which appliances they owned, appliance ownership was estimated based on the average daily energy consumption of each tier, and the types of appliances likely to be used in each tier. For example, customers using low amounts of energy per day were assigned basic appliances like light bulbs, phone chargers, or small fans. Those using more energy were assumed to have additional appliances such as blenders, irons, refrigerators, or water pumps.

To assess the load shifting potential, this study considers findings from published research into appliance ownership among residential customers in Nigeria [13]. The investigation used questionnaires to gather basic household information, including ownership of electrical appliances and duration of usage. In the survey of 144 households, 24 households were selected randomly from each of the six states (12 from urban and 12 from rural areas). A total of 28 appliances were identified and divided into four electrical services namely: lighting, cooking, entertainment, laundry, and cooling which is typical of household appliances in Nigeria.

A category that was not included in this existing categorisation is the water pumping machine which is widely used in Nigerian households where water supply is not provided centrally. The typical use of this appliance is to pump water from boreholes, wells or storage tanks and it has relatively high power commonly ranging from 700 W to 1500 W but in limited operation hours. This appliance presents an opportunity for load shifting. Table 2 shows the appliances obtained from the findings and their respective power ratings.

Table 2: Typical household appliance in Nigeria categories and power ratings

S/N	Category	Appliance	Rating (W)
1	Lighting	Incandescent lamps	60
2		Fluorescent lamps	10
3		Compact fluorescent	15
4	Cooking	Rice cooker	946
5		Water dispenser	700
6		Food blender	450
7		Refrigerator	100
8		Freezer	180
9		Toaster	750
10		Coffee machine	983
11		Microwave oven	900
12		Boiling ring	1000
13		Electric kettle	1850
14		Hot plate	1215
15		Electric cooker/oven	1215
16	Entertainment	Mobile phones (charging)	3
17		TV	100
18		PC (desktop)	60
19		Radio	70
20		CD/DVD player	20
21		PC (laptop, charging)	60
22	Laundry	Washing machine	2100
23		Iron	1200
24		Hair dryer	1069
25		Vacuum cleaner	1600
26		Water heater	1916
27	Cooling	Fan	80
28		Air conditioner	1492
29	Water Supply	Water Pump	1119

Power data for these appliances was sourced from an article published by Dataline citing Ikeja Electric [14], and data gathered in the research paper under consideration for this analysis [13].

4.6 Appliance shiftability

A key part of assessing demand flexibility using a bottom-up approach is identifying which appliances can realistically be shifted in time without affecting the comfortability of connected customers. Based on review of relevant literature [15][16][11], household appliances like air-conditional, water pump, washing machine, electric iron, water heater, blender, freezer were found to have high potential for load shifting. These appliances were selected based on their high-power demand per use and the possibility of shifting their operation without significantly affecting the users' daily lifestyles. Freezers contribute to the baseline load in most households in West Africa because of their continuous operation and critical food preservation. Owing to this, they offer limited potential for load shifting [5].

Table 3: Appliance uses by tiers

Appliance	Tier 3	Tier 4	Tier 5
Fluorescent bulbs	✓	✓	✓
Fan	✓	✓	✓
TV	✓	✓	✓
Mobile phone	✓	✓	✓
Laptop	✓	✓	✓
Radio + DVD player	✓	✓	
Refrigerator	✓	✓	✓
Iron	✓	✓	✓
Microwave		✓	✓
Water pump		✓	✓
Blender		✓	✓
Washing machine		✓	✓
AC			✓
Toaster		✓	✓
Water dispenser			✓
Electric cooker			✓
Electric kettle			✓
Water heater			✓

4.7 Bottom-Up load simulation

The aggregate load profile provided by RMI helped to identify the challenge of energy curtailment (see figure 3). However, it lacked the necessary granularity needed to simulate the effects of demand flexibility. To evaluate the potential for load shifting, a bottom-up model was introduced to simulate appliance-level load shifting. This model estimates hourly electricity demand for each customer based on appliance ownership, the frequency of use of these appliances, and operating period. It is the study of how the cutomers connected to IMG and how their use of common household appliances could be shifted to periods when solar energy is more available.

The model considers the eligible household group from Tier 3 to Tier 5 that was grouped based on how much electricity they typically use in a day. A list of shiftable appliances in these households were created, each one with the details on how much power it uses, how long it ran and how often it was used each week [17][18]. The average daily usage hours and power for various household appliances were obtained from a structured questionnaire survey of 326 urban households in Lagos, Nigeria, conducted as part of a study on energy services demand for residential solar photovoltaic (RSPV) systems [19]. This is representative of appliance use patterns for the location under consideration.

Instead of the assumption that all appliances run at the same time, the model used probability distribution to decide when each appliance is likely to be used during the day based on the likelihoods of it being used in a day.

Table 4 shows the summary of shiftable appliances including their energy use per cycle, their typical duration, frequency of weekly use and the potential load shifting window. While most of these data were obtained from existing research work, conservative values were assumed for the shifting windows, based on findings from literature.

Table 4: Shiftable household appliance profile

Appliance	**Energy per Use (kWh)**	**Duration (h)**	**Uses per Week**	***Shifting Window (hours)***
Washing Machine	3.36	1.6	2	*06:00–08:00, 18:00–20:00[15]*
Iron	0.24	1.5	5	*07:00–21:00[20]*
Water Pump	1.902	1.7	5	*05:00–20:00*
Water Heater	0.575	0.3	7	*05:00–09:00, 21:00 -23:00*
Blender	0.045	0.1	5	*6:00 – 9:00, 12:00 – 20:00*

Air Conditioner	4.326	2.9	7	*10:00 – 22:00[20]*

To model a realistic load shifting, each appliance was assigned a usage probability profile based on the literature and typical household behavior (see Table 4). Probability weight was applied over specific windows to reflect when appliances are most likely used.

4.8 Model process flow

Figure 5 shows the logic used to model appliance-level load shifting for eligible households. The model iterates through each household, determines its energy consumption tier (Tiers 3–5), and assigns shiftable appliances based on ownership and use probability profiles.

If the appliance is scheduled to be used on a given day, a start time is selected within the typical usage period. If the use falls within non-solar hours, the model shifts the appliance operation by up to 4–6 hours earlier or later to align with solar generation periods.

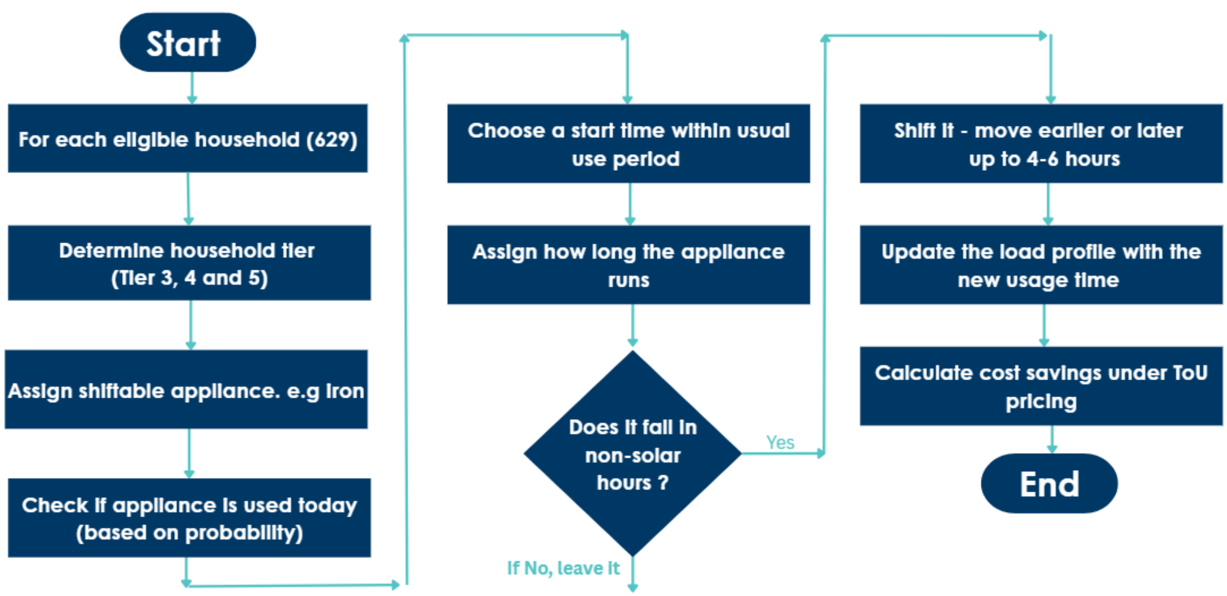

Figure 5: Process flow chart

5 Results, Analysis and Discussion

Using the bottom-up appliance-level simulation approach, the model assigns shiftable appliances to each household based on ownership, schedules them to start at a realistic time and runs them at their expected duration, reflecting typical daily routines. Figures 6 (a, b, c) shows the resulting distribution representative of Tier 3, Tier 4, and Tier 5 households. This bottom-up approach is crucial for capturing the realistic diversity of appliance ownership and usage patterns across the three customer segments. Considering the daily energy consumption of Tier 3 households, they have the lowest number of shiftable loads. Tier 4 households have increased number of shiftable loads compared with Tier 3, and Tier 5 households have the highest number of shiftable loads.

A major assumption of this model is that each household appliance's power draw is constant for the period of its use (see Table 4).

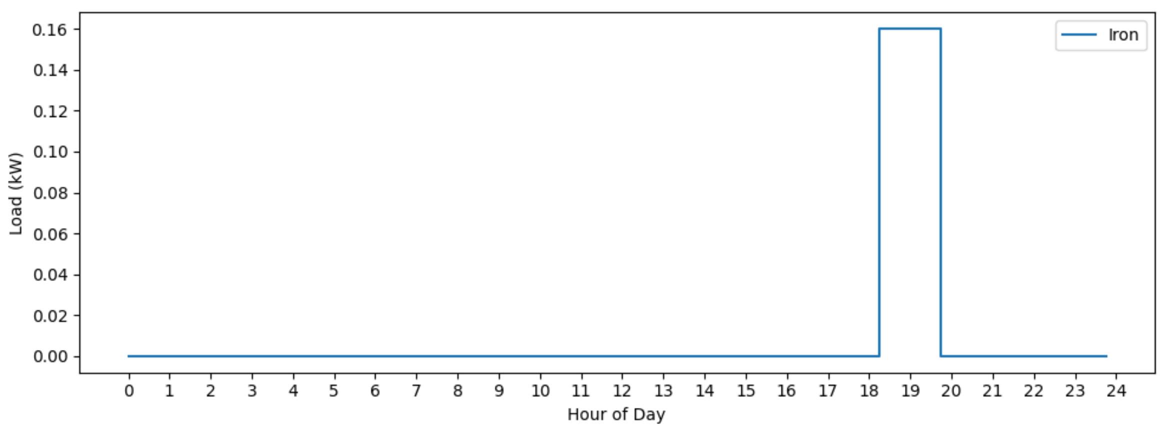

Figure 6a: Shiftable appliance profile - a Tier 3 household

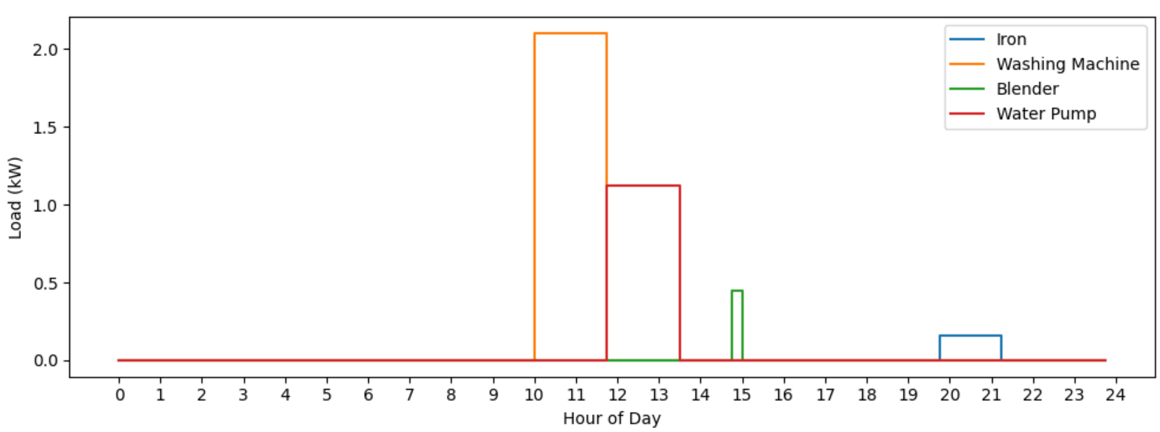

Figure 6b: Shiftable appliance profile - a Tier 4 household

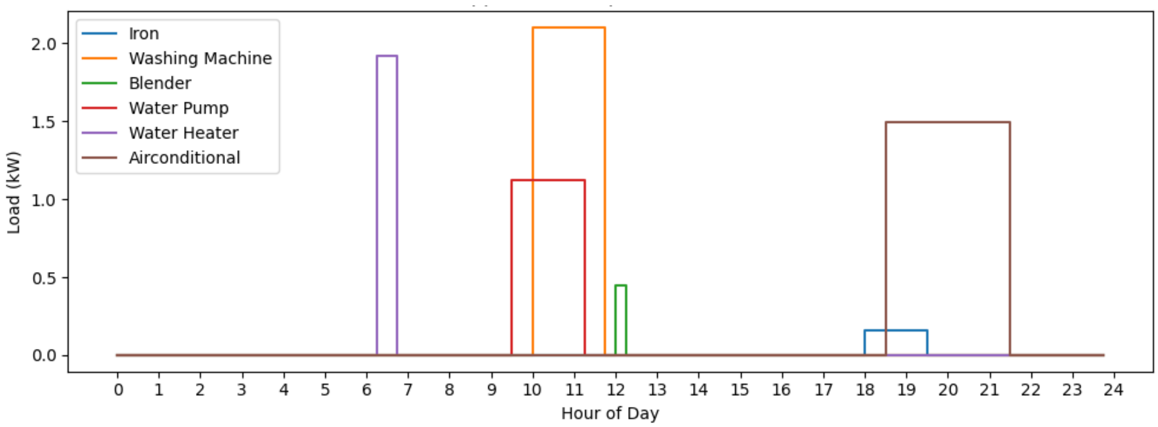

Figure 6c: Shiftable appliance profile - a Tier 5 household

To progress from the micro-level analysis of individual households, the aggregate of all load profiles over a 24-hour period was obtained. This approach produces a shiftable appliance load profile (see Figure 7). These outputs confirm that the model captures realistic appliance diversity and patterns of use across tiers, forming the foundation for the Time-of-Use shifting scenarios tested later in this study.

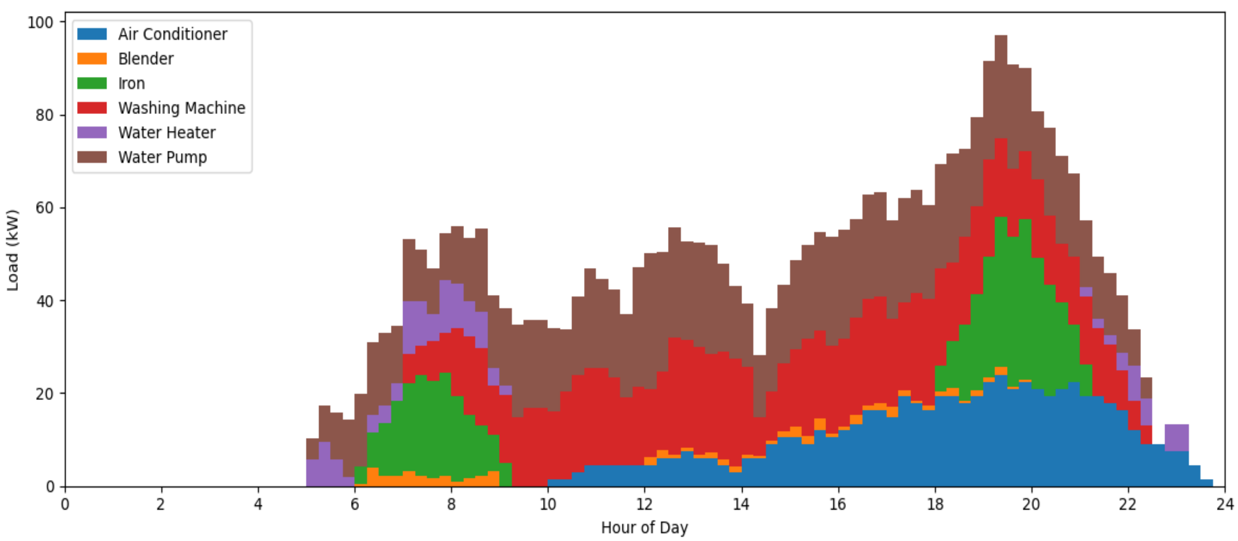

Figure 7: Aggregate load profile of shiftable appliances

Figure 7 shows the total electricity demand from these specific household appliances with load shifting potential before the demand-side management (DSM) strategies are applied. Each colored section of the plot shows a different appliance, and their heights are stacked to show their individual contribution to the total load at any given time. This study considers this load profile as the baseline to determine the potential for shifting households' electricity demand solar-rich hours, directly addressing the issue of solar energy curtailment.

5.1 Time-of-Use tariff design and load shifting

To incentivize demand-side flexibility and align electricity consumption with periods of renewable energy availability, a static Time-of-Use (ToU) tariff plan was introduced. The 24-hour day is divided into three tariff periods, each reflecting the expected grid conditions and solar PV generation potential (see Figure 3).

Table 5: Time-of-Use (TOU) tariff plan

Period Type	**Hours**
Off-Peak (off solar)	00:00 – 09:59
Midday (solar PV peak)	10:00 – 15:59
Peak (off solar)	16:00 – 23:59

This day division is the operational baseline for carrying out the load shifting. The shift simulation is such that certain appliance use is shifted away from "off solar hours" (before 10 a.m. and after 3 p.m.) and into solar hours (10 a.m. to 3 p.m.). This approach models what could happen if a Time-of-Use (ToU) tariff, with a tariff reduction during peak solar hours, were used to encourage people to use electricity when solar power is available.

Shifting was done in a realistic way, keeping the appliance run-time the same and not stacking too many at once. The model focuses on specific, highly flexible appliances like washing machines and dishwashers, which are well-suited for a shift of several hours. By comparing energy use before and after shifting, the model showed how much electricity was moved into solar hours.

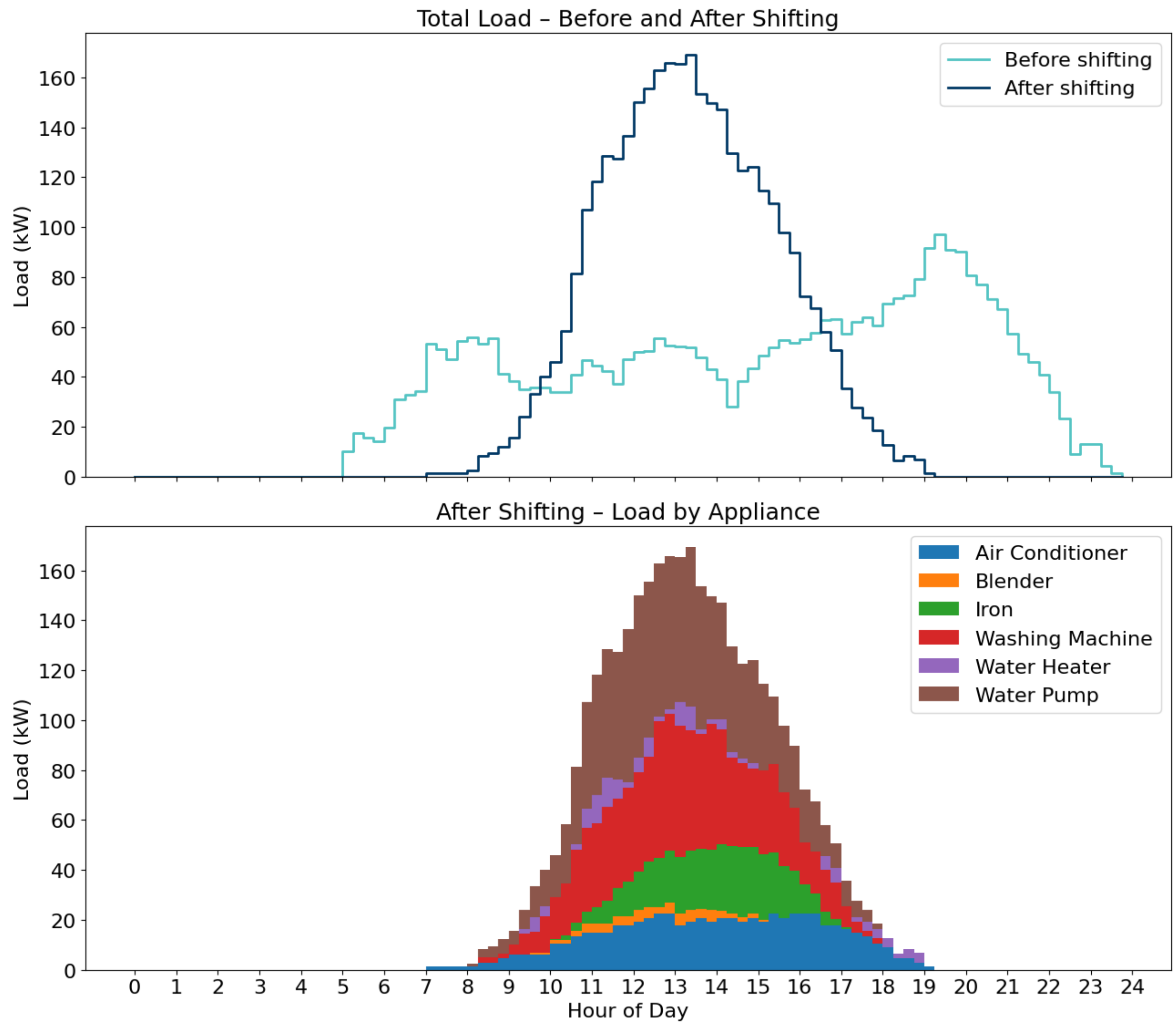

Figure 8a,8b: Aggregate load profile of shifted appliances

The implementation of the demand-side management program is seen in Figure 8a, which compares the aggregate electricity consumption of all households before and after the load-shifting intervention. Before the shift, there were two peaks: a small one in the morning and a large one in the evening. After the load shifting, the large evening peak is reduced, and the electricity use is redistributed to the afternoon, between 10 AM and 4 PM where there is sufficient supply of solar power.

Figure 8b provides additional insight with a breakdown of the new afternoon peak by appliance type. It shows that appliances like the washing machine, water pump, and iron are the main reasons for the new peak. This confirms that these appliances were successfully shifted during the day when solar power is available.

The table below shows the energy consumption across the three periods of the day before and after load shifting. All (100%) shiftable appliances outside *solar hours* are shifted in such a way that at least part of the consumption falls in the solar hours.

Table 6: Energy consumption shift across different time periods

Period Type	**Before Shifting (kWh)**	**After Shifting (kWh)**	**Δ Shifted (kWh)**
Off-Peak (off solar)	182.96	37.97	-144.99
Midday (solar PV peak)	219.80	649.74	+429.94
Peak (off solar)	485.39	200.44	-284.95

The *Δ Shifted* (kWh) is used to quantify the change in energy consumption for each period of the day. The negative values show a substantial reduction in energy consumption during these non-solar hours. Conversely, the midday period shows a significant increase of +429.94 kWh. This data shows that a total of 429.94 kWh of electricity use was successfully shifted from non-solar periods into midday hours.

5.2 Estimating savings

A detailed cost analysis was carried out to quantify the financial benefits of load-shifting under Time-of Use tariffs to both customers and minigrid developers. The analysis considers both the system-level savings for developers and customer-level savings for participating households. All calculations are based on the aggregate energy consumption profile of the shiftable appliances obtained from the simulation.

A time-of-use (TOU) tariff was proposed to incentivize load shifting, with a reduced rate of ₦100/kWh during the solar hour and a maintained standard rate of ₦150/kWh for all other hours (the current tariff)[3]. The major assumption for the system-level analysis is that any load not met by the grid during non-solar periods would be supplied by diesel generators. The pricing schedule is seen on Table 7.

Table 7: Time-of-Use (TOU) tariff structure based on solar availability

Period Type	**Hours**	**Current Tariff ₦/kWh($/kWh)**	**ToU Tariff ₦/kWh($/kWh)**
Off-Peak (off solar)	00:00 – 09:59	150 (US$0.09)	150 (US$0.09)
Midday (solar PV peak)	10:00 – 15:59	150 (US$0.09)	100 (US$0.06)
Peak (off solar)	16:00 – 23:59	150 (US$0.09)	150 (US$0.09)

5.2.1 System-level savings

The system-level savings were estimated by quantifying the reduction in IMG's reliance on fossil fuel (diesel) generation because of load shifting. This also includes possible reduction in the cost of purchasing energy from the grid to meet off solar hours demand. The savings on diesel were obtained by estimating the total energy consumed during off-solar hours for both the baseline and load shifted scenarios. The analysis assumes that any electricity load not supplied by the grid during the peak (16:00-23:59) and morning (00:00-09:59) periods would have been generated by diesel generators. The total energy consumed during off solar hours was measured before and after the load-shifting program. The difference between these two values represents the total amount of energy that was successfully shifted away from these periods.

The simulation result shows a 64% reduction in diesel cost with daily consumption falling from 180 litres to about 64 litres. Figure 9 compares daily diesel consumption before and after load shifting for three diesel generator scenarios: 40%, 70% and 100%.

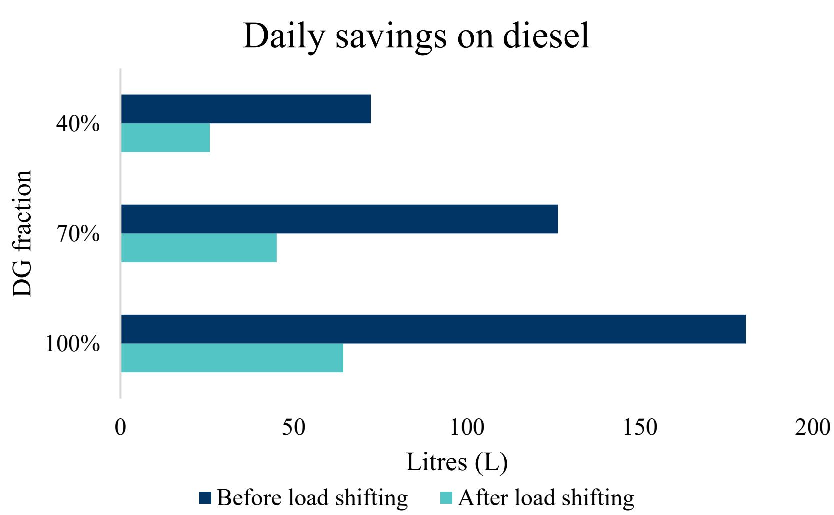

Figure 9: Savings on diesel generation (DG)

As illustrated in this Figure 9, savings are achieved, demonstrating that shifting appliance use into solar hours provides economic benefits regardless of the diesel generator's share in meeting non-solar hour demand.

5.2.2 Customer level savings

The customer level savings were estimated by first establishing a baseline cost obtained from calculating the total daily electricity consumption of all households before any load was shifted. This energy consumption was then multiplied by a standard flat-rate tariff of ₦150/kWh to represent an actual electricity bill. Following the simulated load shift, a new billing total was estimated based on the TOU tariff. This tariff applied a discounted rate of ₦100/kWh for all energy consumed during the solar peak hours (10:00-16:00) and the standard rate of ₦150/kWh for all other hours. The difference between the baseline cost and the new TOU-based cost represents the total financial savings achieved by all customers.

The simulation results show a 24% reduction in customer electricity bills when shifting from the standard flat tariff to the ToU tariff structure. Customers benefit from moving part of their consumption into solar hours.

5.2.3 Carbon emissions

To consider the environmental benefits of the proposed load-shifting strategy, CO_2 emission reductions were estimated from the reduction in diesel fuel consumption. Based on the simulation, daily savings of about 116 litres corresponds to an avoidance of 114 tonnes of CO_2 annually.

5.2.4 Energy curtailment

Considering that one of the objectives of this study is to reduce energy curtailment, shifting 492 kWh into solar hours results in approximately a 24.6% reduction in daily curtailment.

6 Conclusions

This study demonstrates the potential of appliance-level load shifting, supported by Time-of-Use (ToU) tariffs, to deliver significant operational and economic benefits in interconnected mini-grid (IMG) systems. Using consumption data from a first-of-its-kind IMG site in Nigeria, the modelling shows that both customers and minigrid developers can benefit from strategic demand reallocation into solar production hours. Customers can reduce their electricity bills by operating flexible appliances such as electric irons, water pumps, and other shiftable loads during periods when tariffs are lower. For the developer, reduced demand during non-solar hours translates into lower reliance on diesel generators, resulting in fuel savings, significant cost reductions, and reduced CO_2 emissions.

The results highlight a clear win-win outcome for both customers and minigrid developers. For customers, replacing a flat tariff with a ToU tariff structure led to a 24% reduction in daily electricity bills and for the minigrid developers, the outcome shows a 64% decrease in diesel consumption as a result of load shifting, therefore increasing the commercial viability and revenues of their operations. From the environmental perspective, about 114 tonnes of CO_2 will be reduced annually.

With all these benefits in place, the effectiveness of ToU pricing depends largely on customers' willingness to adjust their appliance use and consumption pattern. Following this, education of customers on the benefit of this programme, and offering financial incentives could improve participation rates and contribute to the impact of load shifting strategies.

While the current study provides strong indicative results, the next step lies in validating these findings through real-world pilots and household level data collection. This would provide empirical evidence necessary to guide wider adoption of ToU-based demand management in rural electrification projects across similar contexts.

In conclusion, appliance-level load shifting supported by ToU tariffs, although often underestimated by developers, project designers or implementers - offers a cost-effective and environmentally beneficial pathway for improving the sustainability of interconnected mini-grid operations.

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