

Electricity Consumption in Rural African Microgrids—A Review

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Abstract

Microgrids are key to rural electrification in Africa. While previous studies have mainly addressed microgrid sizing, techno-economic performance, and energy management, electricity consumption has received limited attention despite its central role in system design. The goal of this study is to review, harmonize and analyse publicly available electricity consumption data from rural microgrids across Africa. The analysis reveals a median of 44.5 consumers per microgrid, with most microgrids serving a few dozen to a small hundred consumers. The most frequently reported domestic loads are lighting, televisions, radios and fans while schools, health centers, places of worship, water pumps, and mills are the most frequently reported community-wide loads. The median consumption per consumer is 0.7 kWh/day. Moreover, a significant difference is observed between existing and hypothetical (e.g., used in the frame of conceptual design studies) microgrids, with median consumption per consumer values of 0.13 and 2.85 kWh/day, respectively, suggesting a tendency to overestimate demand during the microgrid planning phase. These findings are complemented by further insights, particularly into variability patterns and reporting practices. As new studies become available, we will continue to expand the compiled database. This work can notably be useful to microgrid developers and policymakers.

Keywords: microgrids; electricity consumption; rural electrification; Africa; energy access

1. Introduction

In September 2015, the United Nations adopted the 2030 Agenda for Sustainable Development, a set of guidelines encompassing the 17 Sustainable Development Goals (SDGs) [1,2]. Among these goals, SDG7 aims to ensure universal access to clean, reliable, sustainable, modern, and affordable energy services [3,4]. However, this goal remains far from being achieved, particularly in Sub-Saharan Africa, where nearly 600 million people still lacked access to electricity in 2022 [5,6]. For instance, in the Central African Republic, the electricity access rate was as low as 6.1% in 2022 [7]. This lack of access is highly detrimental, as electricity enables many key services essential for socio-economic development, such as water pumping [8,9], public lighting [10], and vaccine refrigeration [11]. Confronted with this concerning reality, autonomous microgrids are emerging as a viable and complementary solution to traditional grid extensions, offering the possibility of supplying electricity to remote rural villages in the short term [12,13]. According to [14], the total number of microgrid connections across Africa increased from 40,000 to over 78,000 between 2019 and 2021.



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In the scientific literature, several articles focus on microgrids, particularly in isolated areas of Africa. These articles address various challenges encountered in the implementation and operation of microgrids, among which several categories of studies can be distinguished.

A first widely addressed category is microgrid design, particularly their initial sizing. For instance, Bacha et al. [15] propose an optimization of microgrid sizing in Algeria using both solar and wind energy sources. Their objective is to minimize the cost of energy while ensuring a reliable power supply. Alagbu et al. [16] study a methodology for microgrid sizing with a focus on integrating photovoltaic (PV) renewable energy and improving electricity quality in isolated areas. Al Abri et al. [17] address the optimization of microgrid sizing in Oman, minimizing costs while considering environmental impacts, and employ the HOMER Pro software tool [18]. Diab et al. [19] compare the performance of three recent metaheuristic algorithms (bat optimization, black hole optimization, and equilibrium optimizer) to determine the optimal sizing of standalone microgrid components, including PV panels, hydrogen fuel cells, and batteries. They apply their algorithms to a case study in Egypt.

A second major category of studies focuses on techno-economic analyses of microgrids. For example, Williams et al. [20] examine a hybrid PV/diesel microgrid, taking into account uncertainties related to fuel prices and electricity demand. The main objective is to assess how these uncertainties affect the profitability and investment risks associated with microgrids. Gabra et al. [21] present a techno-economic analysis of standalone wind microgrids in Africa, comparing them to PV and diesel systems for rural electrification. The results show that PV and diesel systems are generally the most cost-effective options for rural electrification in Africa, while wind systems can only be advantageous in specific regions, such as the Horn of Africa. Adefarati et al. [22] investigate the economic and environmental performance of microgrids integrating renewable energy sources and storage. They carry out MATLAB R2016b simulations to quantify load-shedding costs in isolated rural contexts.

A third widely discussed category in the literature is energy control and management within microgrids. For instance, Aatabe et al. [23] propose a stochastic energy management strategy for an autonomous PV microgrid, designed to handle sudden fluctuations in electricity demand. Their approach relies on dynamic programming to optimize energy use in real time. Lampiao et al. [24] implement a control system based on PI regulators (with dq transformation) to maintain voltage stability and reduce energy losses in a hybrid PV/diesel/battery microgrid supplying a village. Safder et al. [25] develop a rule-based energy management system for a voltage-controlled DC microgrid composed of PV panels, batteries, and supercapacitors. Other studies further explore advanced inverter control, including coordinated voltage-power control [26], self-coordinated control of storage and distributed-generation inverters [27], and sliding-mode-based approaches for enhanced robustness under parameter perturbations [28]. Load forecasting and demand-side management (DSM) are also key aspects of this category. Based on four years of measurements from an off-grid Kenyan microgrid, Pisaneschi et al. [29] show that machine-learning techniques can improve short-term load forecasting compared with baseline methods. Otieno et al. [30] also develop forecasting approaches for rural Kenyan microgrids, showing that demand prediction can support system operation and expansion. Regarding DSM, Thiaux et al. [31] propose a DSM strategy for a stand-alone PV/diesel/battery microgrid and highlight that DSM reduces energy costs by 11.3% in the considered case. Finally, Wang et al. [32] develop a machine learning-based DSM framework for a rural microgrid in Tanzania that classifies household consumption behaviours and provides tailored interventions to extend supply time.

Certain articles also carry out literature reviews on microgrids. In particular, Mandelli et al. [33] conduct a literature review on microgrids in developing countries, organized in two parts. The first part defines a reference framework for these systems, detailing the role of microgrids and typical loads installed. The second part presents a literature review of articles published between 2000 and 2014, categorized into five domains: technology and components, modelling and simulation, techno-economic analyses, case study analysis, and policy analyses. Jabari et al. [34] review converter topologies, control strategies, and fault management approaches in AC, DC, and hybrid AC/DC microgrids, with a focus on stability, interlinking converters, and advanced control methods for enhancing microgrid reliability. Ahmad et al. [35] present a review of energy management approaches in microgrids, focusing on optimizing distributed energy resources to enhance stability, reduce operational costs, and minimize greenhouse gas emissions. They also explore real-time optimization techniques and discuss relevant IEEE standards to standardize energy management mechanisms in microgrids. Martin-Martinez et al. [36] present a literature review on microgrids considering physical devices, communication protocols, intelligent control systems, and economic models. The goal is to provide a clear and organized view of key concepts and technologies related to microgrids while identifying current challenges and potential solutions for their deployment and management.

Although electricity consumption is often mentioned in these studies, it is usually addressed as the load to be satisfied for system sizing. It is rarely the primary focus of the study and is therefore generally not described or analysed in detail. Some articles still pay closer attention to electricity consumption.

Some studies focus in detail on consumption data for specific sites. For example, Kirubi et al. [37] analyse the different loads within a microgrid in Kenya and study its contribution to rural economic development. They highlight that access to electricity improves the productivity of small businesses, increases incomes, and facilitates the provision of social and commercial services. Few et al. [38] explore the impact of rurality and climatic conditions on electricity demand among populations accessing electricity for the first time. They also analyse the implications for microgrid design. Notably through two case studies (one in a peri-urban area in Rwanda and the other in a rural area in India), they propose a framework to estimate electricity demand, optimize PV microgrid sizing, and evaluate costs and greenhouse gas emissions, taking into account variations in domestic and non-domestic demand based on peri-urban or rural contexts. The influence of climatic conditions and socio-economic context on electricity demand in low-income areas is emphasized by Poblete-Cazenave and Pachauri [39], who highlight that household electricity demand varies strongly with financial resources, climate, seasonality, and regional characteristics. In line with this perspective, Dagnachew et al. [40] underline that regional differences can shape both household electricity demand and electricity use for productive activities. Dominguez et al. [41] further point out that rural appliance ownership is influenced by numerous variables, including household size, income, proximity to roads or population centres, education and employment status, as well as temperature and precipitation.

Other articles analyse consumption data from several microgrids within a country or region. For instance, Blodgett et al. [42] analyse consumption data from eight microgrids in Kenya. They compare the results of preliminary surveys with actual measurements and with follow-up surveys conducted after the microgrids were implemented. The analysis reveals significant discrepancies between the estimated consumption during preliminary surveys and the actual consumption observed in the microgrids of this study. Otieno et al. [43] explore how to segment microgrid customers in East Africa using demographic and behavioural data collected from sites in Tanzania. Using machine learning

models, they identify characteristics to predict electricity consumption habits, helping microgrid developers target potential customers for whom profitability is more likely to be achieved and thus improve the financial viability of microgrids. Li et al. [44] analyse data collected by the company Sparkmeter (based in Washington, DC, USA) across 36 microgrids in Africa based on criteria defined by the Quality Assurance Framework (QAF). The criteria include energy quality (voltage, frequency, power factor), energy availability (consumption scales), and energy reliability (number and duration of power outages).

However, to the best of our knowledge, no study compiles and analyses the available microgrid consumption data in Africa. In light of this gap, this study aims to provide a harmonized review and analysis of publicly available electricity consumption data from rural African microgrids. More specifically, this study pursues three main objectives, which also constitute its main contributions:

1. To compile publicly available electricity consumption data from rural microgrids across Africa into a standardized database that provides both an overview of the available evidence and a resource for those seeking consumption data for specific analyses (e.g., in a given country).
2. To investigate consumption variation between microgrids by establishing consumption ranges and visualizing how the different studies are distributed within these ranges, after defining common denominators and a standardized terminology to enable comparison across studies.
3. To discuss the differences between studies using data from existing microgrids and those based on planned/hypothetical microgrids and to analyse the nature of loads implemented as well as the types of energy sources and storage usually deployed to fulfil microgrid consumption.

In this article, after carefully reviewing the literature, we managed to find sufficiently detailed consumption data for 78 microgrids. The remainder of this article is structured as follows. Section 2 describes the architecture of a typical autonomous microgrid, presents consumption sources in a microgrid, and outlines the method used to compile and process consumption data in microgrids. Section 3 presents the data gathered and Section 4 analyses these data. Section 5 presents the conclusions of this work, discusses its implications for microgrid planning and policy, and outlines future perspectives.

2. Method

2.1. Microgrid Definition

This article focuses on isolated microgrids, i.e., those that are not connected to the main grid. This is a very common situation in rural and even peri-urban areas of Sub-Saharan Africa [45,46]. In general, these microgrids are located several kilometres, or even tens of kilometres, away from the country's main grid [47,48].

A microgrid has one or more primary energy sources, which are usually renewable, particularly photovoltaic (PV) [49], wind [21] or hydroelectric [50]. Batteries are also commonly installed to mitigate the variability of renewable sources and ensure a continuous power supply [51]. A diesel generator may also be implemented for the same purpose [52]. Electricity is distributed to consumers via a power network, which can be either AC or DC [53,54]. The generation sources, storage components, and loads are interfaced through one or more converters [55,56], which also handle energy management [56,57]. Figure 1 illustrates the typical architecture of an isolated photovoltaic microgrid, while Figure 2 provides an aerial view of a microgrid deployed in Madagascar.

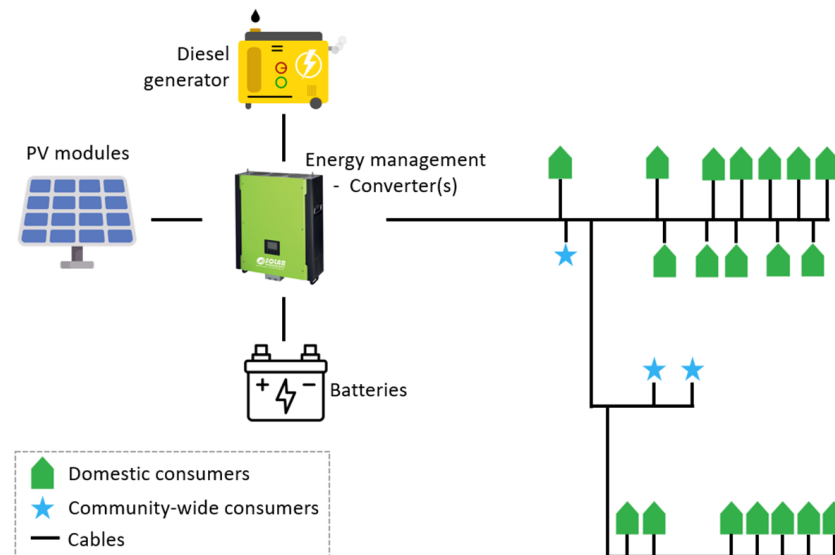


Figure 1. Typical architecture of an isolated photovoltaic microgrid. Adapted from [58].

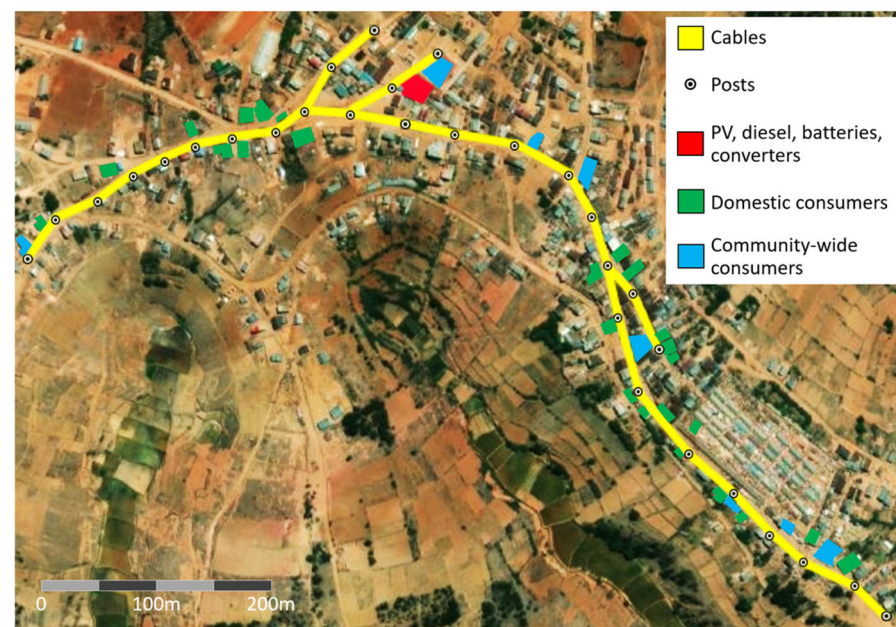


Figure 2. Aerial view of a microgrid, Madagascar. Adapted from [58]. Background © Esri World Imagery.

2.2. Microgrid Consumers

Two main types of consumers from the microgrid can be distinguished:

- **Domestic consumers:** This category refers to residential households, where examples of loads include lighting and electronic devices such as televisions, radios, and ventilation systems [59,60].
- **Community-wide consumers:** This category covers loads and buildings that can serve the entire community. Examples include income-generating activities such as sawmills, rice mills, and mechanical workshops [37,61], as well as public utility buildings like schools, basic health centers, and places of worship [38,62]. A community-wide consumer typically consumes more than a domestic one [63].

2.3. Data Source Identification, Extraction, and Processing

This section focuses on the methodology used to identify relevant publicly available sources and extract the data included in the database, whereas the literature review in the Introduction (Section 1) was used to position the contributions of this study.

Source identification. A review methodology was adopted to identify publicly available sources reporting electricity consumption data for rural African microgrids. More specifically, the search was conducted using Google Scholar, Google, Web of Science and Scopus. The search strategy combined keywords related to (i) microgrids or mini-grids, (ii) electricity consumption or energy use, (iii) African rural contexts. Boolean operators were used to construct search strings such as: (“microgrid” OR “mini-grid”) AND (“electricity consumption” OR “energy use”) AND (“Africa” OR “Sub-Saharan Africa” OR specific country names). Inclusion criteria were: (i) isolated microgrids located in Sub-Saharan Africa, (ii) rural contexts, (iii) availability of quantitative consumption data, with no restrictions imposed on the type of documents considered (e.g., scientific articles, PhD manuscripts, reports from governmental or international energy access agencies, and NGO reports). The screening process involved the initial keyword search, followed by manual review of document relevance, data completeness, source documentation, and consistency with the inclusion criteria described above. Each retained reference was carefully read and assessed before data extraction. Data were included only when the source provided sufficiently clear and documented information and when the corresponding microgrid fell within the scope of the study. Sources or values that were insufficiently documented, unclear, outside the scope, or internally inconsistent were not included in the database. We also searched for existing publicly available databases but did not find any that provided relevant consumption data for our study.

Data extraction and harmonization. Upon reviewing the relevant references, we extracted the information described in Table 1 for each microgrid. These are information commonly available in the identified references and that we consider relevant for characterizing microgrids and their consumption. Examples include the number of consumers per microgrid and the consumption of the microgrid. Three important observations could also be made when reviewing the literature. First, the microgrids mentioned in the literature fall into two categories: (i) Existing microgrids, for which actual consumption measurements are provided [30,42] (labelled as “existing”), (ii) planned or hypothetical microgrids, for which studies have been conducted (e.g., sizing of the generation and storage components) but the system has not been deployed (it might or might not be in the future). In these latter cases, consumption figures are based on estimates and the microgrids are labelled as “hypothetical”. Second, the nature of the reported consumption data varies across references. In particular, consumption values may be reported over different timeframes, such as per day [64], per month [37], or per year [14]. To enable comparison across studies, all consumption values were converted into average daily values, both for the total microgrid consumption and for the consumption per consumer. When values were reported on a monthly or yearly basis, they were divided by the corresponding number of days in the reporting period. Note that seasonal variations could not be analysed because most references did not provide sufficiently detailed seasonal consumption data. In the few cases where consumption values were reported separately for different seasons, these values were averaged to obtain the annual daily average. Third, in most cases, the total consumption of the microgrid and the number of consumers were provided, allowing us to derive the consumption per consumer by division. In rarer cases, we had access to the consumption per consumer and the number of consumers, which enabled us to calculate the total consumption of the microgrid through multiplication.

Table 1. Parameters considered in the literature review.

Column	Description and Example Entry
Microgrid number	The microgrid number <i>Example: 3</i>
Reference	The reference from which the microgrid is sourced. <i>Example: [42]</i>
Microgrid name	The name given to the microgrid in the article. <i>Example: Barsaloi</i>
Type of microgrid	Existing/Hypothetical <i>Example: Existing</i>
Country	The country where the microgrid is located. <i>Example: Kenya</i>
Percentage of electricity access in rural areas of the country (%)	Percentage of electricity access in rural areas of the country where the microgrid is located. These data are obtained from [65]. <i>Example: 65%</i>
GDP per capita in the country (\$)	Gross domestic product (GDP) per capita of the country where the microgrid is located. These data are obtained from [66]. <i>Example: \$1224</i>
Number of consumers	The number of consumers connected to the microgrid. <i>Example: 65</i>
Type of loads in domestic consumers	Type of loads implemented in domestic consumers of the microgrid <i>Example: Lighting, TV, radio</i>
Community-wide consumers	Information on community-wide consumers present in the microgrid. <i>Example: 1 school, 1 health center, 30 streetlights</i>
Microgrid consumption (kWh/day)	The average daily consumption of the microgrid (kWh/day). <i>Example: 10.7 kWh/day</i>
Consumption per consumer (kWh/day)	The average daily consumption per microgrid consumer (kWh/day). <i>Example: 0.24 kWh/day</i>
Type and size of energy source	The type of energy source used to power the microgrid and its installed power (if available). <i>Example: PV (30 kW), diesel (7.5 kW)</i> <i>Note: When there are two energy sources, including a diesel generator, the non-diesel source is generally more utilized [15].</i>
Type and size of energy storage	The type of energy storage and its size (if available). <i>Example: Lead-acid battery (1164 kWh)</i> <i>Note: In some cases, no information is available on the storage system, which does not necessarily mean that there is no storage system.</i>

3. Collected Data

The database developed and used in this study is available in open access in Supplementary Material (Excel file within a .zip folder) as well as through the following Zenodo link: <https://doi.org/10.5281/zenodo.21324725>. An excerpt of some of the information from the database is presented in Table 2. A total of 78 microgrids providing sufficient infor-

mation on consumption were identified. These microgrids are located in various countries such as South Africa, Tanzania, Kenya, Benin, Ivory Coast, and the Democratic Republic of the Congo. However, microgrids with sufficient information were not encountered for several countries with a high need for rural electrification, such as the Central African Republic or Malawi. The database will be updated as further sufficiently documented studies are identified, and the updated data will be made available through the Zenodo link.

Table 2. Sample of collected data.

Microgrid Number	Reference	Type of Microgrid	Country	Number of Consumers	Consumption per Consumer (kWh/Day)	Type and Size of Energy Source	Type and Size of Energy Storage
1	[32]	Existing	Tanzania	44	0.24	PV (4.8 kW)	None
2	[37]	Existing	Kenya	221	0.25	Diesel (267 kVA)	
3	[42]	Existing	Kenya	58	0.06	PV	Lead-acid battery
4	[42]	Existing	Kenya	27	0.08	PV	Lead-acid battery
5	[42]	Existing	Kenya	63	0.23	PV	Lead-acid battery
6	[42]	Existing	Kenya	29	0.1	PV	Lead-acid battery
7	[42]	Existing	Kenya	27	0.1	PV	Lead-acid battery
8	[42]	Existing	Kenya	19	0.04	PV	Lead-acid battery
9	[42]	Existing	Kenya	29	0.12	PV	Lead-acid battery
10	[42]	Existing	Kenya	26	0.08	PV	Lead-acid battery
11	[42]	Hypothetical	Kenya	58	0.43	PV	Lead-acid battery
12	[42]	Hypothetical	Kenya	27	0.17	PV	Lead-acid battery
13	[42]	Hypothetical	Kenya	63	0.25	PV	Lead-acid battery
14	[42]	Hypothetical	Kenya	29	0.82	PV	Lead-acid battery
15	[42]	Hypothetical	Kenya	27	0.63	PV	Lead-acid battery
16	[42]	Hypothetical	Kenya	19	2.1	PV	Lead-acid battery
17	[42]	Hypothetical	Kenya	29	0.13	PV	Lead-acid battery
18	[42]	Hypothetical	Kenya	26	0.13	PV	Lead-acid battery
19	[43]	Existing	Tanzania	45	0.21	PV, diesel	
20	[43]	Existing	Tanzania	90	0.18	PV, diesel	

Table 2. *Cont.*

Microgrid Number	Reference	Type of Microgrid	Country	Number of Consumers	Consumption per Consumer (kWh/Day)	Type and Size of Energy Source	Type and Size of Energy Storage
21	[43]	Existing	Tanzania	88	0.22	PV, diesel	
22	[43]	Existing	Tanzania	54	0.18	PV, diesel	
23	[48]	Hypothetical	South Africa	50	16.18	Wind (300 kW), diesel (100 kW)	
24	[59]	Hypothetical	South Africa	50	13.84	PV	
25	[62]	Hypothetical	Senegal	18	2.63	PV, wind	
26	[62]	Hypothetical	Senegal	25	2.46	PV, wind	
27	[62]	Hypothetical	Senegal	31	3.05	PV, wind	
28	[62]	Hypothetical	Senegal	47	3.67	PV, wind	
29	[62]	Hypothetical	Senegal	56	2.82	PV, wind	
30	[62]	Hypothetical	Senegal	83	2.57	PV, wind	
31	[62]	Hypothetical	Senegal	23	3.37	PV, wind	
32	[62]	Hypothetical	Senegal	32	3.02	PV, wind	
33	[62]	Hypothetical	Senegal	38	3.19	PV, wind	
34	[62]	Hypothetical	Senegal	57	2.84	PV, wind	
35	[62]	Hypothetical	Senegal	97	2.85	PV, wind	Battery (42 kWh)
36	[62]	Hypothetical	Senegal	146	2.6	PV, wind	
37	[62]	Hypothetical	Senegal	19	4	PV, wind	
38	[62]	Hypothetical	Senegal	26	3.76	PV, wind	
39	[62]	Hypothetical	Senegal	35	3.62	PV, wind	
40	[62]	Hypothetical	Senegal	52	3.74	PV, wind	
41	[62]	Hypothetical	Senegal	51	4.59	PV, wind	
42	[62]	Hypothetical	Senegal	77	4.03	PV, wind	
43	[30]	Existing	Kenya	34	0.03	PV, diesel	
44	[30]	Existing	Kenya	28	0.06	PV, diesel	
45	[30]	Existing	Kenya	21	0.16	PV, diesel	Battery (172.8 kWh)
46	[30]	Existing	Kenya	26	0.15	PV, diesel	Battery (400 kWh)
47	[30]	Existing	Kenya	32	0.31	PV, diesel	Battery (72 kWh)
48	[30]	Existing	Kenya	75	0.22	PV, diesel	Battery (36 kWh)
49	[30]	Existing	Kenya	30	0.11	PV, diesel	Battery (637 kWh)
50	[67]	Hypothetical	Cameroon	103	4.19	PV (3 kW), hydro (32.2 kW)	Gel lead-acid battery (900 kWh)
51	[68]	Existing	Tanzania	264	5.79	Hydro (120 kW)	

Table 2. Cont.

Microgrid Number	Reference	Type of Microgrid	Country	Number of Consumers	Consumption per Consumer (kWh/Day)	Type and Size of Energy Source	Type and Size of Energy Storage
52	[69]	Hypothetical	Nigeria	15	18.92	Wind (60 kW), diesel (10 kW)	
53	[70]	Existing	South Africa	300	2.44	PV (14 kW), wind (140 kW), diesel (50 kW)	
54	[71]	Hypothetical	Cameroon			Hydro (5 kW), biogas (10 kW)	
55	[71]	Hypothetical	Cameroon			PV (3 kW), biogas (10 kW)	
56	[72]	Hypothetical	Benin	333	2.04	PV (150 kW), diesel (62.5 kVA)	
57	[73]	Hypothetical	Ivory Coast	96	6.9	PV (189 kW), hydro (20 kW), diesel (25 kW)	
58	[74]	Hypothetical	Algeria	20	2.35	PV (11.4 kW), diesel (6 kW)	
59	[75]	Hypothetical	Nigeria	232	1.82	PV, wind, hydro	
60	[76]	Hypothetical	Rwanda	500	2.84	PV, diesel	
61	[77]	Existing	Kenya	30	0.04		
62	[77]	Existing	Kenya	71	0.13		
63	[77]	Existing	Kenya	32	0.12		
64	[77]	Existing	Kenya	25	0.08		
65	[77]	Existing	Kenya	21	0.13		
66	[77]	Existing	Kenya	28	0.04		
67	[77]	Existing	Kenya	33	0.02		
68	[77]	Existing	Tanzania	70	0.02		
69	[77]	Existing	Tanzania	109	0.07		
70	[77]	Existing	Tanzania	52	0.23		
71	[77]	Existing	Tanzania	92	0.95		
72	[78]	Hypothetical	Nigeria	12	12.5	PV (30 kW), diesel (7.5 kW)	
73	[79]	Hypothetical	Rwanda	212	0.76	PV (5 kW), hydro (11 kW)	
74	[80]	Existing	Namibia	364	4.67	PV (304 kW), diesel (300 kVA)	Lead-acid battery (2400 kWh)

Table 2. *Cont.*

Microgrid Number	Reference	Type of Microgrid	Country	Number of Consumers	Consumption per Consumer (kWh/Day)	Type and Size of Energy Source	Type and Size of Energy Storage
75	[80]	Existing	Namibia	610	1.2	PV (292 kW), diesel (300 kVA)	Lead-acid battery (2600 kWh)
76	[81]	Existing	Madagascar	230	5.27	PV, diesel	
77	[82]	Hypothetical	The Gambia	29	10.8	PV (79.8 kW), diesel (60 kW)	Lead-acid battery (1164 kWh)
78	[83]	Existing	Uganda	300	0.12	PV (3 kW), biogas (3 kVA)	Lead-acid battery

4. Data Analysis and Discussion

In this section, we analyse and discuss the main trends emerging from the data. It should be noted that all microgrids included in the Supplementary Excel File, and therefore satisfying the inclusion criteria defined in Section 2, were considered in the analyses presented below, including for the computation of descriptive statistics (e.g., median, first and third quartiles). Thus, particularly low or high values of the indicators were not removed from the statistical analysis. They were only omitted from some figures (see Sections 4.1 and 4.2), for readability, while of course remaining available in the raw database. This choice to retain all values in the statistical analysis was motivated by the fact that high or low values may reflect genuine heterogeneity among rural African microgrids, such as differences in consumer composition, productive uses, and whether the microgrid is existing or hypothetical.

4.1. Number of Consumers and Implemented Loads

Figure 3 shows a boxplot presenting the collected data for the number of consumers per microgrid. Note that the boxplots in Section 4 were plotted using Tukey's method (function 'boxplot' in Matplotlib v. 3.7.0 in Python v. 3.10.19). In this representation, the central line of the box corresponds to the median value, while the lower and upper edges of the box represent the first (Q1) and third (Q3) quartiles, respectively. The whiskers extend to the most extreme values located within 1.5 times the interquartile range ($IQR = Q3 - Q1$) from the quartiles. Moreover, for the sake of clarity and to focus on the most relevant area, particularly the box representing Q1 and Q3, we did not display the values that fall outside the whiskers when such values exist (e.g., in the case of Figure 3, 11 values exceeded the upper whisker (these 11 values correspond to the ones for microgrid numbers 2, 51, 53, 56, 59, 60, 73, 74, 75, 76, 78, see Table 2)), but these values remain, of course, accessible in the raw data provided in Table 2. Figure 3 highlights that the median value of the number of consumers is 44.5 and, more generally, that a microgrid supplies electricity to a few dozen or up to a small hundred consumers.

Regarding the type of loads and consumers, the most frequently cited loads in domestic consumers (i.e., cited by 11 or more references) are lighting, TV, radio and fan. The other reported loads vary (e.g., mobile phone charging, computer, refrigerator). Community-wide consumers are explicitly described in 40% of the microgrids. The most frequently cited ones (i.e., cited by 5 or more references) are schools, health centers, places of worship, water pumps and mills. Other community-wide consumers are also mentioned but are highly diverse, such as a cotton ginnery, a metal workshop, a barbershop and a casino.

However, while the types of domestic and community loads are generally reported, the data typically provide limited information on their usage patterns. As a result, it was not possible to quantify their respective contribution to total electricity consumption or to reliably assess whether specific load combinations are associated with higher consumption levels. Future studies should therefore report load types together with typical usage patterns whenever possible.

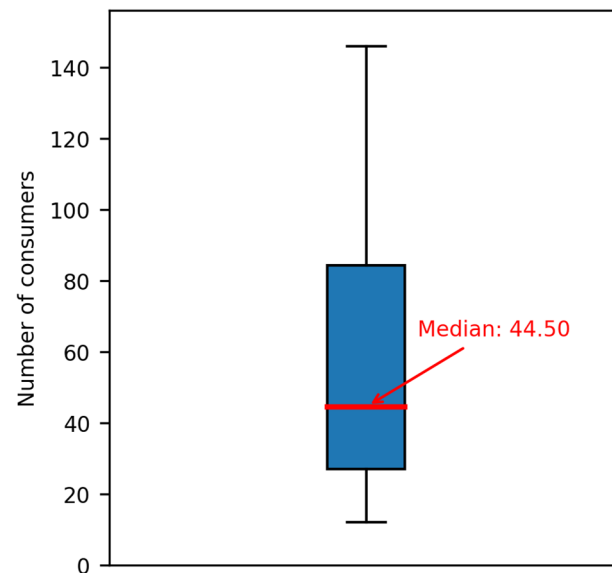


Figure 3. Boxplot of the number of microgrid consumers.

4.2. Consumption per Consumer

A boxplot showing the collected data for the consumption per consumer is plotted in Figure 4 (as explained in the previous section, 5 values above the upper whisker are not plotted for the sake of clarity but are available in the raw data (these 5 values correspond to the ones for microgrid numbers 23, 24, 52, 72, and 77, see Table 2)). The median consumption per consumer is found to be 0.7 kWh/day (mean value: 2.38 kWh/day). This consumption also exhibits significant variations between microgrids, as highlighted by the first quartile (Q1) of 0.13 kWh/day and the third quartile (Q3) of 3.09 kWh/day. These consumption levels can be compared to those in higher-income countries, such as France, where the average electricity consumption per household is 15.6 kWh/day [84], or the United States, where it reaches 29.5 kWh/day [85]. This stark contrast highlights that electricity consumption in rural African microgrids is significantly lower than in higher-income countries. One key factor behind this difference is the nature of the deployed loads. Indeed, in rural African microgrids, high-consuming loads such as air conditioning, space heating, and electric cooking systems are rarely used. Instead, as seen in Section 4.1, the deployed loads are mainly lighting, TV, radio and fan, which consume much less.

It is also interesting to note the difference between measured data from existing microgrids and estimated data from hypothetical microgrids. For existing microgrids, the median consumption per consumer is 0.13 kWh/day (with Q1 = 0.08 kWh/day and Q3 = 0.23 kWh/day), whereas, for hypothetical microgrids, it is 2.85 kWh/day (with Q1 = 2.06 kWh/day and Q3 = 3.94 kWh/day). This difference suggests that energy consumption may be overestimated during the microgrid conceptual design phase, in line with the findings of [42], which examined this issue for a case study in Kenya.

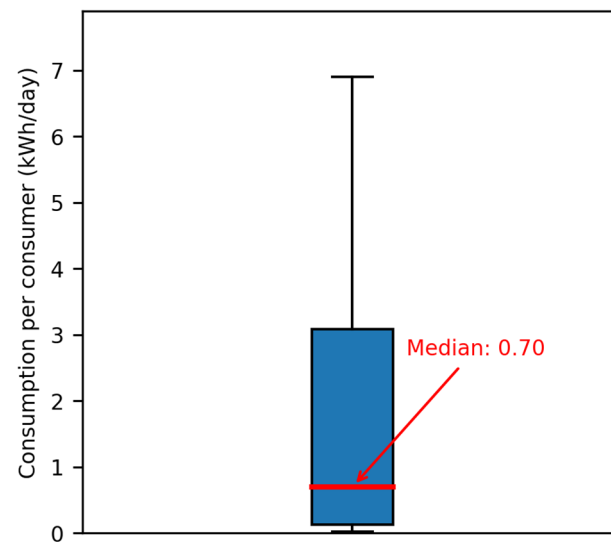


Figure 4. Boxplot of the consumption per consumer.

One possible explanation of this difference is the inherent difficulty in estimating electricity needs and future electrical appliance adoption for populations that previously had no access to electricity [38,86]. Moreover, hypothetical studies, particularly those focusing on microgrid optimal sizing, may rely on conservative or aspirational demand assumptions to ensure that the designed system is able to meet future needs. Conversely, consumption in existing microgrids may be constrained by users' ability to pay [87], limited appliance ownership [38], supply reliability issues [32], or operational constraints such as load shedding [32]. For instance, the existing Ngurudoto microgrid in Tanzania, reported by Wang et al. [32] and serving 44 consumers, exhibits an average consumption of 0.24 kWh/day per consumer. This value is low compared with the median of 0.7 kWh/day per consumer for the whole dataset, which pools existing and hypothetical microgrids. According to the authors, more than two-thirds of households remained relatively under-equipped in terms of electrical appliances after the installation of the microgrid, reflecting the low purchasing power and limited economic activity of the community. This echoes the findings of Blodgett et al. [42], who reported that more than half of surveyed users considered electricity prices to have a high or very high impact on their electricity use. Similarly, Azimoh et al. [70] highlighted that the Lucingweni pilot microgrid in South Africa ceased operation only a few months after commissioning because electricity costs exceeded users' willingness to pay, and that shortages of spare parts, limited local technical capacity, and insufficient financial resources for maintenance can strongly reduce service reliability. Finally, existing microgrids with publicly available consumption data may also not be fully representative of all operating rural African microgrids, (e.g., if lower consumption existing microgrids were more likely to be studied). In future research, we will further investigate the respective contribution of these different factors to better understand the mechanisms explaining the gap between estimated and measured consumption across rural African microgrids.

4.3. Generation Sources, Storage and Comparison with Consumption

Figure 5 presents the energy sources used in the microgrids. It appears that a wide range of configurations have been considered. The most prevalent energy source is photovoltaic (PV) energy, which is present in 93% of microgrids (for which the energy source is mentioned). It is also noteworthy that diesel is included in a large number of configurations, but almost never as the sole energy source. This aligns with the logical role of diesel in rural isolated microgrids, which is to serve as a backup source to compensate for the temporal

variability of renewable energy sources [88,89]. Furthermore, when comparing the type of energy source with the total consumption of the microgrid (see data in the Supplementary Excel File), it is observed that photovoltaic energy is used for both low consumption microgrids (<10 kWh/day [42]) and high-consumption microgrids (>100 kWh/day [59]).

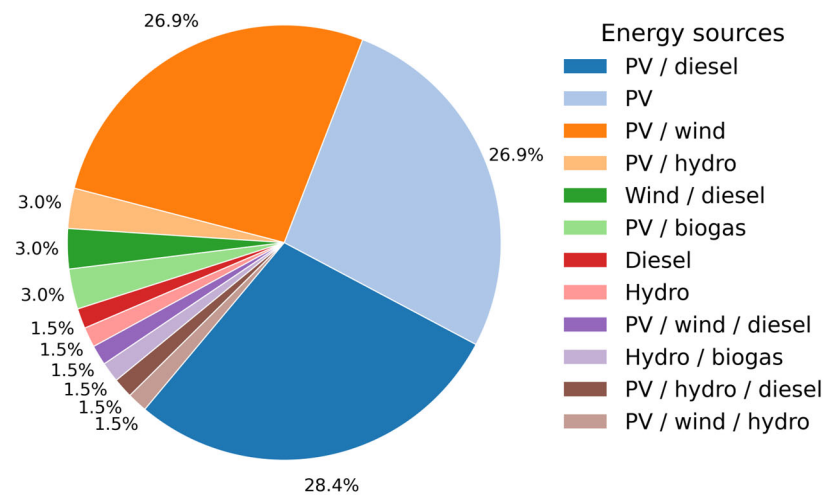


Figure 5. Distribution of energy sources. Note: the percentages were calculated based on the 67 out of the 78 microgrids in the database that report the energy source (see Table 2).

When analysing the energy sources separately for existing and hypothetical microgrids, it appears that 65% of hypothetical microgrids consider an energy source other than photovoltaic and diesel, whereas this percentage drops to only 11% for existing microgrids. This highlights that, while alternative energy sources are frequently considered and studied for optimal microgrid conceptual sizing in rural Africa, they are rarely implemented in practice, where photovoltaic and diesel (usually as backup) remain the preferred choices. This contrast can be illustrated by comparing two examples from the database. The Gam microgrid in Namibia is an existing installation serving 610 consumers and powered by photovoltaic energy, supported by battery storage and diesel generation [80]. In contrast, the hypothetical Elebu case in Nigeria serves 232 consumers and is based on a configuration combining photovoltaic, wind and small hydropower as generation sources [75].

The frequent use of photovoltaic energy as an energy source can be explained by several factors. In recent years, the cost of photovoltaic energy has dropped significantly, making it competitive with other renewable and non-renewable energy sources [90,91]. Additionally, Africa has a very high solar potential [92,93], and the modular nature of photovoltaic systems (which can range from a few watts to more than several megawatts) [94], makes them particularly well-suited for isolated African villages, where electricity demand is expected to grow over the years [38,95].

Regarding storage systems, they are rarely explicitly mentioned in Table 2. When they are, batteries are always the chosen storage solution, and lead-acid is favoured. However, lithium-ion batteries may become increasingly favoured in future rural microgrid deployments owing to their declining prices [96,97].

By analysing the Supplementary Excel File, it appears that the articles providing sufficiently detailed information on electricity consumption (which is at the core of our study), rarely mention the installed power of the generation system and the storage capacities. More specifically, the size of the generation system is reported for only 18 microgrids, and the storage capacity is given for only 10 microgrids. As a result, even though it would have been of great interest to analyse the relationship between electricity consumption, user loads, generation capacity and storage capacity, and potentially reveal sizing trends

or matching rules depending on demand, the available data are too limited to perform such a correlation analysis in a robust way. This represents an important area for further research and highlights the need for subsequent studies to systematically report electricity consumption data together with generation and storage system sizes. In the same vein, the AC/DC architecture is insufficiently reported, preventing a robust comparison of consumption features between AC and DC microgrids. Future studies should thus also report grid architecture together with electricity consumption.

5. Conclusions, Implications for Microgrid Planning and Policy, and Perspectives

This review compiled, standardized and examined publicly available data on electricity consumption in rural African microgrids, a key yet insufficiently documented dimension of system design, operation, and long-term sustainability. The analysis of the compiled database highlighted several key findings:

- The median number of consumers per microgrid is 44.5. More broadly, the identified microgrids typically serve a few dozen to a small hundred consumers.
- Lighting, television, radio and fan are the most commonly mentioned domestic loads, while high-consumption appliances like air-conditioning or space heating are rarely mentioned.
- The most commonly cited community-wide loads are schools, health centers, places of worship, water pumps and mills.
- The median electricity consumption per microgrid consumer is 0.7 kWh/day (mean value: 2.38 kWh/day). The consumption per consumer also varies significantly between microgrids (first quartile: 0.13 kWh/day, third quartile: 3.09 kWh/day). These consumption levels remain far below those commonly observed in high-income countries (e.g., mean value of 15.6 kWh/day in France [84] and 29.5 kWh/day in the United States [85]).
- The median electricity consumption per consumer is 0.13 kWh/day for existing microgrids, whereas it reaches 2.85 kWh/day for hypothetical (e.g., used in the frame of conceptual design studies) microgrids, thus tending to suggest that energy consumption may be overestimated during the microgrid design phase.
- Photovoltaic energy is the dominant energy source, present in 93% of the microgrids. We also found that 65% of hypothetical microgrids consider an energy source (e.g., wind energy) other than photovoltaic and diesel, whereas this proportion drops to just 11% for existing microgrids. This highlights that while alternative energy sources are often considered in theoretical studies (notably for optimal microgrid sizing in rural Africa), they are rarely implemented in practice, where photovoltaic and diesel (typically as backup) remain the preferred choices.
- Our review also shows that studies providing sufficiently detailed information on electricity consumption (which is the main focus of our study) rarely report the corresponding generation or storage capacities. Future studies should aim to systematically link consumption data with system sizing parameters, as this would improve understanding of how microgrids are designed in response to electricity demand.

Regarding microgrid planning and design implications, these findings suggest that electricity demand is best considered as a central but uncertain component of system design. The difference observed between existing and hypothetical microgrids points to the relevance of using several demand scenarios instead of relying on a single estimated consumption level. This also supports the use of stochastic or robust optimization approaches for microgrid design, as they can explicitly account for demand uncertainty within the optimal sizing process. In practice, the orders of magnitude of consumption reported

here, as well as the fact that different values are provided each time (i.e., median, Q1, Q3), can both help microgrid developers assess whether the results of their future site-specific electricity demand surveys are broadly consistent with the consumption ranges reported in this review. It can also help them define several demand scenarios, which can then be incorporated into stochastic and robust optimization methods such as [98,99]. Furthermore, in this context of demand uncertainty, modular microgrid designs also appear particularly relevant, as they allow generation and storage to be expanded progressively as electricity consumption evolves. The inherently modular nature of photovoltaic arrays and batteries is particularly valuable in this respect, as it facilitates staged deployment and future system upgrades.

In terms of policy implications, public authorities (e.g., rural electrification agencies, ministries) and funding institutions could encourage detailed and robust demand assessment procedures before microgrid deployment, as well as the use of stochastic optimal design approaches accounting for demand uncertainty, particularly within tendering processes. Moreover, they could encourage more systematic monitoring, public reporting, and open access to essential microgrid data in future studies. In particular, electricity consumption, load composition, usage patterns, generation capacity, storage capacity, and grid type (AC or DC) should be documented jointly and in a consistent format whenever possible, for example using a standardized reporting table promoted by funding agencies, public authorities, or industry associations. This would improve project benchmarking and support more evidence-based rural electrification policies.

Beyond these planning and policy implications, this review also highlights broader challenges and future research directions for rural microgrids in Africa. A first challenge is to move from static and aggregated consumption indicators toward a more detailed understanding of electricity usage patterns across sub-Saharan Africa, including a quantitative assessment of how these patterns are shaped by factors such as regional climate, appliance ownership, tariff structures, service quality, and local economic conditions. A second challenge is to better document and analyse how demand evolves throughout the microgrid lifetime, since temporal load evolution remains rarely reported despite its importance for long-term microgrid planning. Finally, future research should more systematically combine consumption data with operational information and socio-economic impacts, in order to identify more robust links between electricity use, system performance, and project outcomes.

The work carried out in this review can be useful to several stakeholders, including microgrid developers, rural electrification agencies, non-governmental organizations, and researchers aiming to improve microgrid design. By compiling and harmonizing dispersed data on electricity consumption in rural African microgrids, it provides a consolidated empirical basis to benchmark demand assumptions, identify typical consumption ranges, highlight key data gaps, and support more evidence-based planning. Moreover, as we continue to expand the database with new quantitative data in the future, its usefulness for comparative analyses and future research should further increase over time.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/en19143292/s1>.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating Current
DC	Direct Current
NGO	Non-Governmental Organization
PV	Photovoltaic
SDGs	Sustainable Development Goals

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