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Analysis of electricity usage evolution in Madagascar from 2008 to 2021 using utility data and statistical methods

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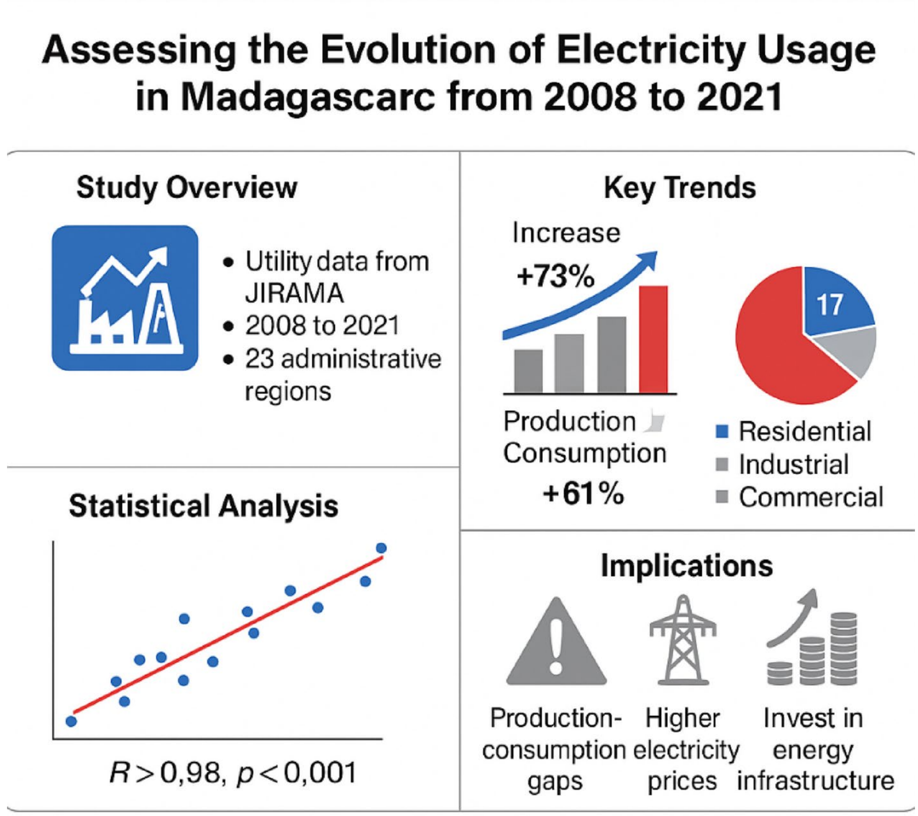
Abstract
This study investigates the evolution and sectoral dynamics of electricity usage in Madagascar from 2008 to 2021, using exclusive operational data from Jiro sy Rano Malagasy (JIRAMA), the national electricity utility. Covering over 50 power plants across the country's 23 administrative regions, the dataset includes monthly statistics on electricity production, consumption, losses, costs, and customer profiles segmented by residential, industrial, commercial, and lighting sectors. Using R and Python, the data were cleaned and analyzed through time series, descriptive statistics, linear regression, and correlation methods. The results reveal a consistent increase in electricity production (+73%) and consumption (+61%), especially in the residential sector (+82%), driven by a 54% rise in customer numbers. Industrial and commercial sectors also saw significant demand growth, while the lighting sector showed a decline in consumption despite stable subscriber numbers. High correlation coefficients ($R > 0.98$) confirm strong linear relationships between consumption, cost, and customer growth across all sectors. However, persistent gaps between production and consumption point to technical inefficiencies and infrastructure limitations. Electricity prices have more than doubled, with marked surges observed after 2015, reflecting rising operational costs and network expansion. The findings underline the urgent need for targeted investments in energy infrastructure, loss reduction strategies, and equitable pricing policies to ensure sustainable and inclusive energy access across Madagascar's diverse regions.

Keywords Electricity consumption, Energy access, Madagascar, Utility data

1 Introduction

Over the past twenty years, the global shift toward cleaner and more sustainable energy sources has gained critical momentum, largely driven by the urgent imperative to mitigate climate change and promote long-term sustainable development. Electricity generation and consumption have steadily increased worldwide, reflecting a persistent rise in energy demand that dates back to the early 1980s. Recent forecasts suggest that global energy consumption is reaching unprecedented levels. According to the International Energy Agency [1], global energy demand grew by 2.2% in 2024 alone—surpassing

Graphical Abstract



global GDP growth and outpacing the average annual increase observed between 2013 and 2023. This surge has been primarily fueled by emerging and developing economies, which accounted for over 80% of the increase [1]. Electricity plays a pivotal role in the functioning of both households and economic sectors. A significant portion—approximately 56.2%—of total electricity generation is directed toward the residential and commercial domains, which include public institutions and agricultural activities [2]. In contrast, around 42.3% of electrical output is allocated to industrial operations, where it powers machinery, servers, and other energy-intensive equipment that require regular calibration and maintenance [3, 4]. Meanwhile, the transportation sector accounts for a mere 1.5% of electricity consumption, due to its continued reliance on fossil fuels such as gasoline [2, 3]. Acquiring a foundational understanding of how electricity is distributed across these sectors is crucial for designing strategies aimed at mitigating greenhouse gas (GHG) emissions. Indeed, emissions linked to electricity generation remain a substantial contributor to global climate change.

Electricity generated from renewable sources has experienced significant growth. World Bank statistics show a 6% year-over-year increase in renewable electricity usage in 2021, bringing its share to 28.2% of total global electricity consumption [5]. However, stark inequalities in access and consumption remain. High-income nations continue to dominate global energy use, while low-income countries—particularly in Sub-Saharan

Africa—contribute only marginally to total consumption [6, 7]. Over 600 million individuals in Africa still lack access to electricity, with the continent's average electrification rate hovering just above 40%, the lowest globally [6]. In Sub-Saharan Africa (excluding South Africa), the per capita annual electricity consumption is estimated at roughly 180 kWh, compared to more than 13,000 kWh in the United States and approximately 6500 kWh in Europe [7]. Africa's energy challenges extend well beyond generation capacity and include critical issues related to infrastructure, energy conversion, distribution networks, and efficient end-use [7]. Although fossil fuels and nuclear energy remain dominant in the current power mix, renewable resources such as hydroelectricity, solar, wind, geothermal, and biomass offer promising alternatives. Yet, these sources collectively represent only about 20% of the continent's installed electricity capacity [7]. Between 1984 and 2004, global primary energy demand rose by 49%, accompanied by a 43% increase in CO_2 emissions—underscoring the continued reliance on carbon-intensive energy systems [8]. To better understand these dynamics, an expanding body of academic research has focused on regional energy transitions. Mazorodze [9], for example, analyzed data from 22 Sub-Saharan African countries spanning 1990 to 2019 and concluded that while renewable energy adoption contributes to reductions in CO_2 emissions, it does not consistently translate into green economic growth. In the case of Madagascar, Nematchoua [10] revealed that over 80% of the island's renewable energy potential remains untapped despite recent policy initiatives. Similarly, comparative research by da Silva et al. [11] examining energy transition frameworks in Austria, Germany, and Brazil highlighted the varied approaches and innovations involved in expanding renewable energy systems.

Madagascar—the world's fourth-largest island—is endowed with abundant natural energy resources, particularly in hydropower, solar, and biomass. Nonetheless, access to electricity remains critically low, with an electrification rate below 30% and heavy reliance on imported fossil fuels. Rapid population growth and accelerated urbanization continue to place additional pressure on electricity demand, while infrastructure development struggles to keep pace. At this pivotal moment, Madagascar's energy sector stands at a strategic crossroads, requiring substantial investment and bold policy reforms to unlock its renewable potential and ensure inclusive energy access for its population. This study makes several original contributions to the existing body of research on electricity systems in Madagascar and Sub-Saharan Africa. First, it constitutes the first comprehensive, long-term analysis of electricity usage in Madagascar based entirely on official operational utility data from JIRAMA, covering 14 years and more than 50 power plants across 23 administrative regions. The dataset provides monthly, sector-disaggregated information on electricity production, consumption, losses, customer profiles, and pricing. Such detailed, utility-level datasets are extremely rare in Sub-Saharan Africa, where most studies rely on national aggregates, projections, or short-term surveys. The exceptional temporal depth and geographical coverage of this dataset enable a far more accurate and granular analysis of the evolution of Madagascar's electricity system, offering insights that were previously unattainable in the literature. Unlike previous studies that relied on national estimates, short-term surveys, or partial datasets, this work provides high-resolution, sector-specific insights into consumption dynamics, pricing trends, technical losses, and regional disparities. Second, the study introduces a robust statistical framework—combining time-series modeling, correlation analysis, and regression techniques using R and Python—that offers a replicable methodological approach for low-income countries with limited energy data infrastructures. Finally, the research provides evidence-based recommendations for infrastructure investment, loss-reduction strategies, and equitable pricing policies, thereby filling a critical gap in the literature and offering practical guidance for national energy planning and sustainable development in Madagascar. The remainder of this article is structured as follows: Sect. 2 details the data sources and methodological framework. Section 3 presents the main findings through statistical and graphical analysis. Section 4 discusses the implications of these results for policy and planning. Finally, Sect. 5 outlines the study's limitations and proposes directions for future research.

2 Methodology

2.1 Data source

This study relies on an exclusive dataset provided by *Jiro sy Rano Malagasy (JIRAMA)*, Madagascar's national electricity and water utility. The dataset contains monthly operational statistics recorded between January 2008 and December 2021, covering more than 50 power plants—diesel, hydroelectric, hybrid, and small-scale generating units—distributed across the country's 23 administrative regions. JIRAMA operates both interconnected and isolated grids, enabling analysis across network typologies and socio-economic contexts. Raw data were obtained directly from JIRAMA's regional directorates, where local technical teams routinely compile operational logs, billing records, and customer information. The national utility aggregates and digitizes these reports into monthly statistical summaries that form the basis of this study. Because such long-term, utility-level datasets are extremely rare in Sub-Saharan Africa, special attention was given to assessing data quality, consistency, and completeness.

2.2 Geographic and energy context

Madagascar's electricity system spans a geographically diverse territory characterized by highly uneven infrastructure development. (i) Eastern regions (e.g., Atsinanana, Analanjirofo) experience high humidity, heavy rainfall, and cyclones, affecting distribution networks. (ii) Central highlands (e.g., Analamanga, Vakinankaratra) concentrate economic activities, exhibit higher electricity demand, and host most hydroelectric stations. (iii) Western and southern regions (e.g., Menabe, Androy) are arid, sparsely populated, and dependent on isolated diesel systems.To characterize this diversity, each plant in the dataset was assigned to its administrative region and climatic zone. Spatial variability in demand, losses, and customer growth was analyzed using descriptive statistics and geospatial visualizations.

2.3 Data collection and indicators

The dataset contains monthly values for the following indicators: Electricity production (MWh) from diesel, hydro, and hybrid facilities; Electricity consumption and billed energy (MWh); Technical and non-technical losses (MWh and %); Customer counts by category (residential, commercial, industrial); Monthly electrification access rates (%); Electricity prices and operational costs (MGA) where available.

Electrification access rate

The regional electrification access rate was calculated using the standard utility formula:

$$\text{Access Rate} \quad \frac{\text{Total Number of Customers}}{\text{Total Number of Households}} * 100 \tag{1}$$

Household figures were obtained from official national census reports (INSTAT). This metric reflects *connection-based* access rather than consumption-based access.

2.4 Data cleaning and quality assessment

To ensure reproducibility and transparency, a detailed data-cleaning workflow was applied.

(i) Detection and Treatment of Missing Values: Missing values occurred sporadically due to delayed reporting or damaged logbooks. Three rules were applied: (a) Short gaps (≤ 2 consecutive months): Filled using linear interpolation:

$$Xt = Xt - 1 + \frac{Xt + 1 - Xt - 1}{2} \tag{2}$$

(b) Long gaps (> 2 months): Reconstructed using: regional averages, plant-type averages (diesel/hydro), or consumption ratios from similar regions. (c) Entirely missing regions for a given year: These were flagged, documented, and excluded from analyses requiring continuous time series.

(ii) Identification and correction of anomalies
Anomalies were defined as: Sudden jumps exceeding ± 3 SD relative to the regional monthly mean; Reported negative consumption values; Production < billed consumption; Loss rates exceeding 60% (physically implausible). Corrections were applied as follows: Typographical errors were corrected using original paper logs validated by JIRAMA technicians. Implausible values were replaced by the median of the preceding and following months. Outliers caused by generator failures, cyclone impacts, or rolling blackouts were retained, but flagged, because they reflected genuine operational conditions.

(ii) Harmonization and Validation: All energy values were converted to MWh, Customer categories were standardized across years to correct for changes in JIRAMA classification, Cross-validation was performed by triangulating production–consumption–loss relationships.

This rigorous cleaning process ensures that the dataset is internally consistent and analytically robust.

2.5 Statistical analysis tools

All statistical analyses were conducted using R (version 4.4.1) and Python (libraries: pandas, numpy, scipy, matplotlib, seaborn). The analytical workflow included: Time series decomposition to identify long-term trends, seasonal patterns, and anomalies. Descriptive statistics (mean, SD, SE, CV); Pearson correlation and linear regression to assess relationships between consumption, cost, and customer dynamics; Geospatial mapping using shapefiles from INSTAT and QGIS for regional disparities; Trend comparison across pre- and post-2016 periods (growth slowdown). Analyses were performed at national, regional, and sectoral levels.

2.6 Statistical indicators and formulas

Rather than listing formulas in isolation, they are integrated here within their analytical context.

Mean and variability

To assess central tendencies and dispersion:

$$\mu = \frac{1}{n}\sum xi, \quad SD = \sqrt{\frac{1}{n-1}\sum (xi-\mu)^2}, \quad SE = \frac{SD}{\sqrt{n}} \tag{3}$$

where μ (mu): The arithmetic mean (average) of the dataset; n: The total number of observations (sample size); x_i: The value of the *i*-th observation in the dataset; SD: The standard deviation of the dataset; $n-1$: Degrees of freedom, used for the unbiased estimate of the population variance in a sample; $x_i - \mu$: The deviation of each observation from the mean; $(x_i - \mu)^2$: The squared deviation, ensuring all differences are positive; SE: Standard error of the mean.

2.7 Reproducibility

To ensure full reproducibility:

All scripts used for cleaning, transformation, and analysis were written in R and Python; A publicly available version of the code is archived on Zenodo. https://doi.org/10.5281/zenodo.17804199. Each figure in the Results section includes references to the corresponding statistical methods and exact n values.

3 Results

3.1 Trends in electricity production, consumption, and pricing in Madagascar

The Fig. 1 demonstrates a trends of electricity consumption and production in Madagascar.

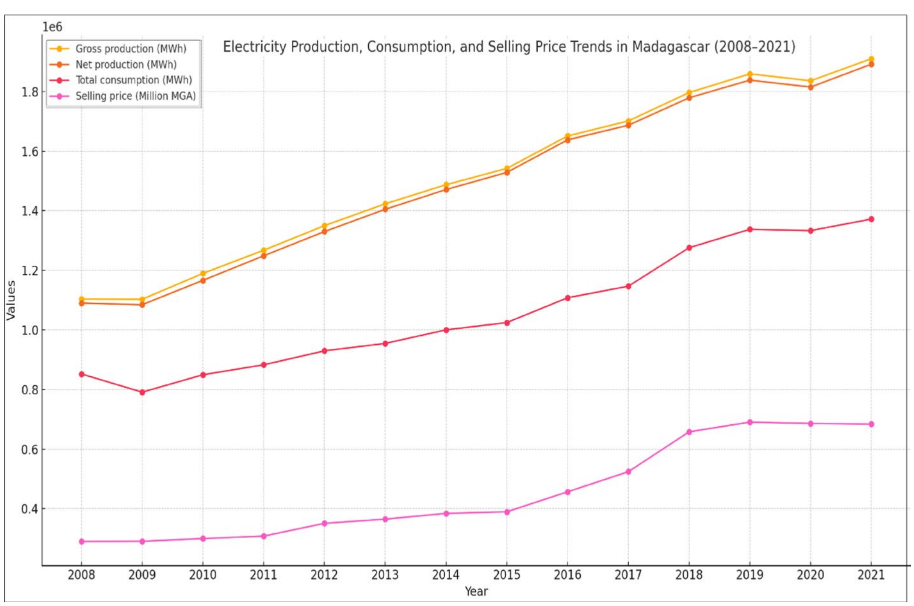


Fig. 1 Trends in gross and net electricity production, total electricity consumption, and average selling price in Madagascar from 2008 to 2021. Gross and net production and total consumption are expressed in megawatt-hours (MWh, left axis), while the average selling price of electricity is expressed in million Malagasy Ariary (MGA).

Between 2008 and 2021, gross electricity production in Madagascar experienced steady growth, increasing from 1,103,746 MWh to 1,910,682 MWh. The average annual gross production was 1,500,365 MWh, with a standard deviation (SD) of 269,565, indicating moderate variability around the general trend. Net production, which accounts for system losses, followed a parallel trend with an average of 1,475,765 MWh and a standard deviation of 264,025. Total consumption remained lower than production, with an average of 1,092,385 MWh, a standard deviation of 203,397, and a significant increase from 852,237 MWh in 2008 to 1,372,138 MWh in 2021, representing an increase of nearly 61%. Finally, the electricity sales price in millions of MGA (Malagasy Ariary) more than doubled, rising from 289,764 to 683,959 million, with an average of 461,171 million MGA, a standard error of 39,292, and a standard deviation of 146,896, reflecting a significant tariff increase linked to growing demand and operating costs. Statistical analysis reveals very strong correlations between the different variables. The Pearson correlation coefficient (R) between net production and total consumption is 0.994, indicating a nearly perfect linear relationship (p-value < 0.001). This suggests that the increase in production closely follows the growth in domestic demand. Similarly, the correlation between sales price and consumption is also strong ($R = 0.981$, $p < 0.001$), indicating that tariff increases are potentially linked to rising demand or infrastructure improvements. In terms of relative differences, the Mean Relative Difference (MRD) between gross and net production is low at 1.63%, indicating good conversion efficiency. Between net production and total consumption, the MRD is more significant (25.42%), which may be attributed to technical losses, low grid efficiency, or limited storage or distribution capacity in certain geographic areas. Statistically, all observed trends are significant at the 95% confidence level ($p < 0.05$). The 95% confidence intervals confirm a steady increase in production and consumption, although the increase in sales price has been more pronounced since 2015, particularly between 2016 and 2018 (+ 44.2%). This likely coincides with structural reforms, increased production costs, or expansion of the network's territorial coverage. In conclusion, these data highlight sustained growth in electricity in Madagascar, both in terms of production and consumption, with overall improvement in system efficiency. However, the persistent gap between net production and consumption indicates that losses or inefficiencies remain and need to be addressed. The ongoing rise in electricity prices also calls for fair regulation to ensure access to energy for vulnerable households. These findings suggest the need for investment in storage, smart distribution, and the integration of renewable energy sources to support this momentum while strengthening the country's energy resilience. Residential electricity is presented in the Fig. 2.

3.2 Dynamics of residential and industrial electricity in Madagascar

Only CTR subscriber customers are counted in this study (prepaid meter subscription or under special control). As shown in the Fig. 2, the data on residential electricity in Madagascar from 2008 to 2021 reveal a clear upward trend in terms of number of customers, costs, and electricity consumption. The number of customers increased from 386,947 to 595,628 (+ 54%), electricity consumption rose from 433,806 MWh to 790,921 MWh (+ 82%), and the total cost went up from 154,808 million MGA to 368,248 million MGA (+ 138%). The annual average number of customers is 481,650 with a standard deviation (SD) of 64,476 and a standard error (SE) of 17,224. For electricity consumption, the

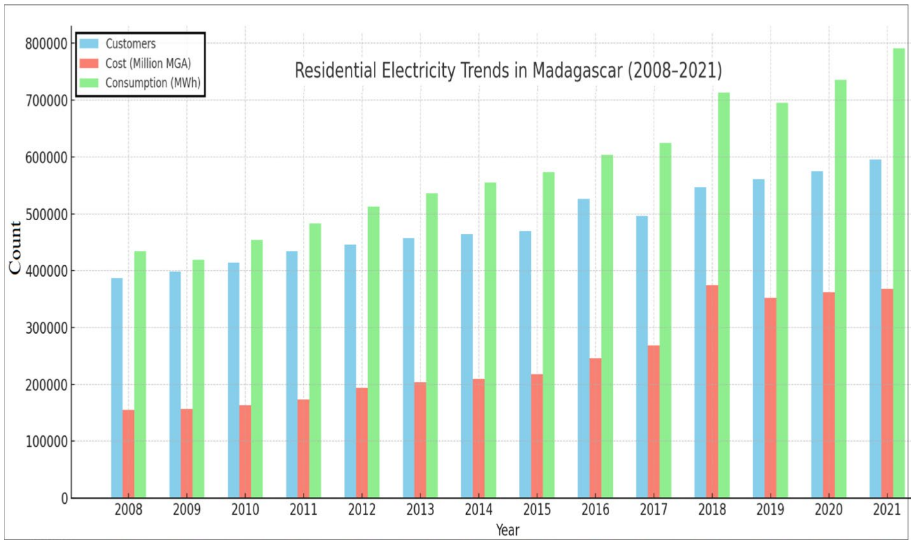


Fig. 2 Residential electricity trends in Madagascar from 2008 to 2021, including the annual number of residential customers, total electricity consumption (MWh), and total billed cost (million Malagasy Ariary, MGA). The figure illustrates the steady growth of the customer base, the increasing electricity demand, and the corresponding rise in residential billing

average is 586,195 MWh with an SD of 118,639 and an SE of 31,699. The average cost is 255,539 million MGA (SD = 78,162; SE = 20,891). Electricity consumption is highly correlated with the number of customers ($R = 0.991$) and with costs ($R = 0.983$), indicating that increased demand is closely linked to customer growth. The time trend in electricity consumption shows a strong linear correlation ($R = 0.992$) with a statistically significant p-value of 5.4×10^{-11}, confirming a consistent and non-random growth. The 95% confidence interval for the annual consumption growth rate is estimated between 23,649 and 30,883 MWh per year. The mean relative difference (MRD) also indicates significant increases: 43% for customers, 85% for costs, and 61% for consumption. These results highlight a growing energy dynamic in Madagascar's residential sector, driven by progressive improvements in electricity access, although the rising costs could present economic accessibility challenges. Industry trends is given in the Fig. 3.

The industrial electricity data from Madagascar between 2008 and 2021 (see Fig. 3) show clear upward trends in consumption, number of customers, and associated costs, despite some fluctuations. Over the 14-year period, electricity consumption increased from 353,439 MWh in 2008 to 491,123 MWh in 2021 (+ 39%), while the number of industrial customers grew from 993 to 1417 (+ 43%), and the cost rose from 107,210 million MGA to 258,503 million MGA (+ 141%). The mean electricity consumption was 408,032 MWh, with a standard deviation (SD) of 83,486 and a standard error (SE) of 22,309. The average number of customers was 1133 (SD = 170; SE = 45), and the average cost was 181,867 million MGA (SD = 65,419; SE = 17,475). The Pearson correlation coefficient between electricity consumption and cost is very strong ($R = 0.985$), and the correlation between consumption and number of customers is also high ($R = 0.980$), indicating a strong linear relationship among these variables. A linear regression of electricity consumption over time yields an $R = 0.970$ and a highly significant p-value of 1.2×10^{-8}, confirming a statistically significant growth trend. The 95% confidence interval for the annual increase in consumption lies between 10,468 and 15,625 MWh per year. The Mean Relative Differences (MRD) were 43% for customers, 39% for consumption,

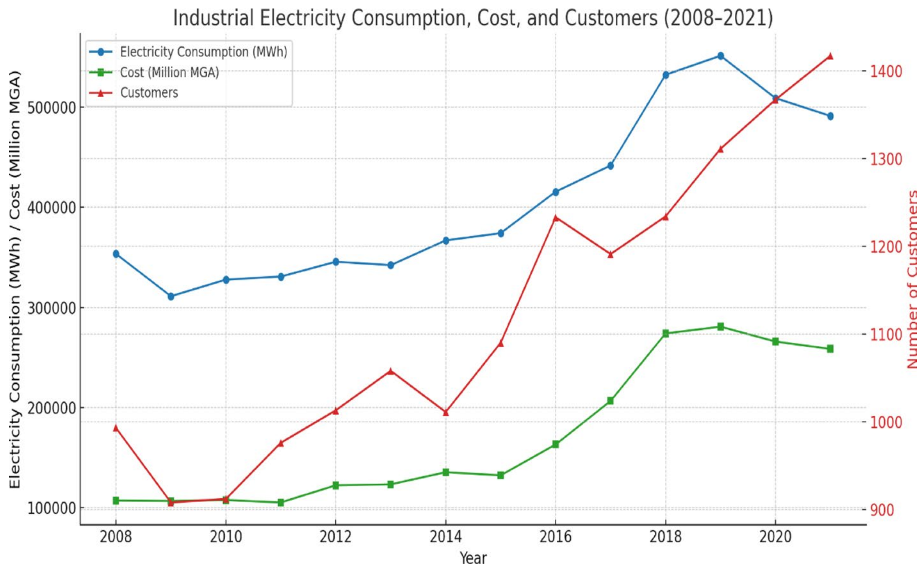


Fig. 3 Industrial electricity consumption, total billed cost, and number of industrial customers in Madagascar from 2008 to 2021. Electricity consumption (MWh) and cost (million Malagasy Ariary, MGA) are shown on the left y-axis, while the number of industrial customers is displayed on the right y-axis. The figure highlights the progressive increase in industrial energy demand and electricity pricing, along with the growth of the industrial customer base during the period

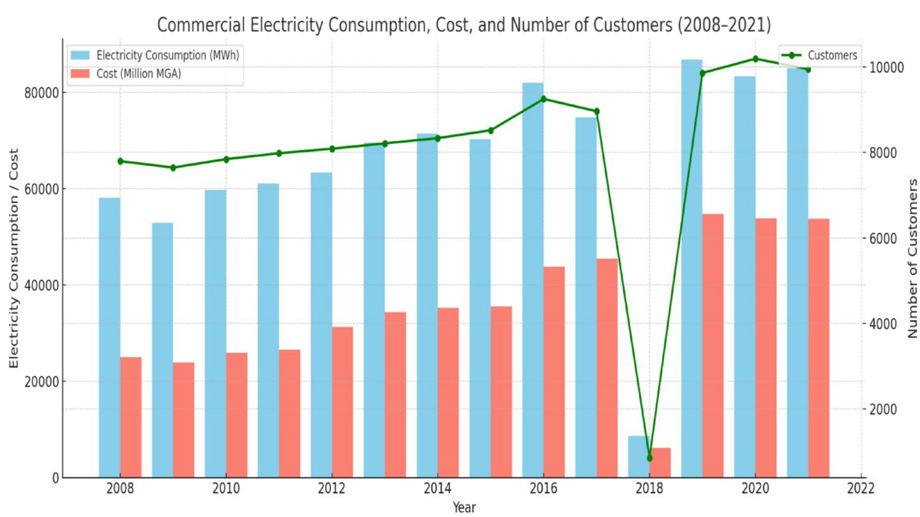


Fig. 4 Commercial electricity consumption, total billed cost, and number of commercial customers in Madagascar from 2008 to 2021. Electricity consumption (MWh) and cost (million Malagasy Ariary, MGA) are displayed on the left y-axis, while the number of commercial customers is plotted on the right y-axis. The figure highlights the progressive growth in commercial electricity demand and billing over time, as well as notable fluctuations in the commercial customer base, including the sharp temporary decline observed in 2018

and 141% for costs, showing that while customer growth and energy demand were steady, the costs grew disproportionately faster. These findings suggest that Madagascar's industrial electricity demand has expanded significantly, driven by gradual industrial growth and electrification, though cost escalation may affect industrial productivity and sustainability if not accompanied by improved energy efficiency or renewable alternatives. Other sectors as commercial and onroad, shown a similar trend such as industrial (see Figs. 4 and 5).

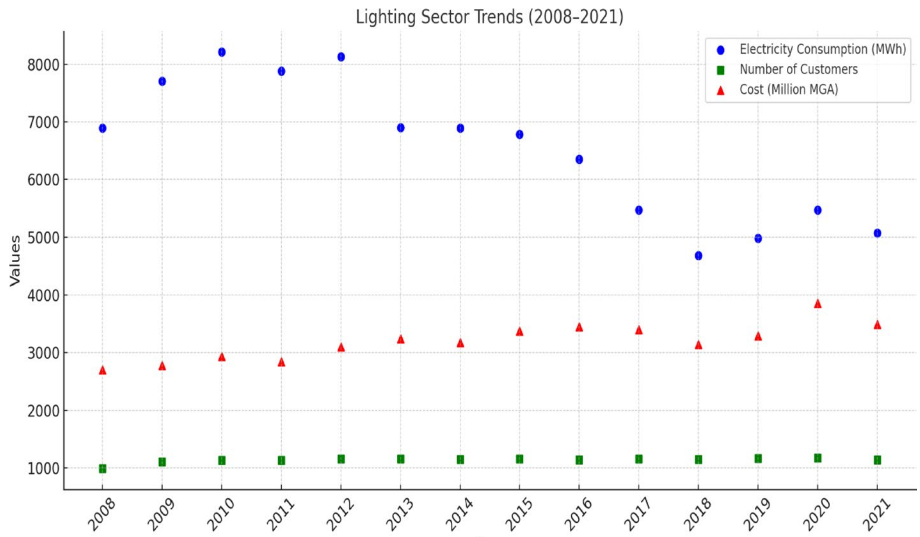


Fig. 5 Trends in electricity consumption, number of customers, and total billed cost in the lighting sector in Madagascar from 2008 to 2021. Electricity consumption (MWh), number of lighting customers, and total billed cost (million Malagasy Ariary, MGA) are presented on the same axis to illustrate their relative temporal evolution. The figure shows fluctuations in consumption over time, moderate growth in the number of lighting-sector customers, and a steady increase in billed cost across the study period

3.3 Dynamics of commercial and onroad electricity in Madagascar

Figure 4 demonstrates the trend of commercial electricity consumption, cost, and number of Customers.

The data reveal as demonstrates in Fig. 4a significant dynamic in the commercial electricity sector in Madagascar over the period from 2008 to 2021. The average annual electricity consumption for this sector is 65,435 MWh, with a standard deviation of 17,466 MWh, indicating considerable variation over the years. The average number of customers is approximately 8547, with slight variation (standard deviation of 929), while the average annual cost of electricity consumption is estimated at 36,225 million MGA, with a standard deviation of 11,098 million MGA. Pearson's correlation coefficient shows a strong positive correlation between electricity consumption and cost ($R = 0.93$, $p < 0.001$), indicating that increases in consumption are strongly linked to increases in cost. A moderate correlation is also observed between consumption and the number of customers ($R = 0.71$, $p = 0.005$), suggesting a parallel growth in customer base and demand. Similarly, there is a moderate correlation between cost and number of customers ($R = 0.70$, $p = 0.006$).The Mean Relative Difference (MRD) for electricity consumption is 10.25%, and for cost 10.95%, reflecting relatively moderate year-to-year fluctuations. The Standard Errors (SE) indicate the precision of the mean estimates: 4668 MWh for consumption, 248 for number of customers, and 2967 million MGA for cost. The 95% confidence intervals for the annual averages confirm the robustness of these findings. For example, the average electricity consumption is estimated within the range of 55,638 MWh to 75,233 MWh, while the cost ranges between 29,983 and 42,468 million MGA, with high statistical certainty. The Lighting sector is presented in the Fig. 5. The data on electricity usage for lighting in Madagascar from 2008 to 2021 reveal a declining trend in consumption, despite relatively stable customer numbers. The average annual electricity consumption is 6425 MWh with a standard deviation (SD) of 1206 MWh, indicating moderate year-to-year variability.

The average number of customers is 1143, with a low SD of 54 customers, showing strong stability in the customer base. The average annual cost is 3231 million MGA, with an SD of 357 million MGA, reflecting minor cost fluctuations over time. The Pearson correlation coefficient (R) between electricity consumption and number of customers is 0.14 ($p = 0.63$), indicating a very weak and statistically insignificant correlation, suggesting that the decline in consumption is not due to a reduction in customer numbers. However, the correlation between consumption and cost is moderately positive ($R = 0.60$, $p = 0.026$), meaning that cost somewhat follows consumption trends, although not proportionally. The Mean Relative Difference (MRD) for electricity consumption is 16.26%, while for cost it is 11.05%, which indicates a more pronounced year-to-year fluctuation in consumption than in cost. This could be due to fixed infrastructure costs or minimum billing policies that maintain relatively steady revenues for the utility provider even with decreasing usage. The Standard Error (SE) of the mean is 322 MWh for consumption, 14.3 for number of customers, and 95 million MGA for cost, suggesting a high precision in the estimates of customer numbers and acceptable precision for the other metrics. The 95% confidence interval (CI) for annual electricity consumption ranges from 5725 to 7126 MWh, for the number of customers from 1111 to 1174, and for cost from 3015 to 3447 million MGA. These intervals confirm the reliability of the averages. Generally, while the number of lighting customers has remained stable, the steady decline in electricity consumption, particularly after 2012, suggests behavioral changes, possibly due to energy efficiency improvements, economic constraints, or increased use of alternative lighting solutions (e.g., solar lamps). Despite this decline, costs remained relatively stable, indicating resilience or fixed pricing structures in the electricity market for lighting in Madagascar.

4 Discussion

The results outlined in Sect. 3 confirm strong and sustained growth in electricity production and consumption in Madagascar during the period 2008–2021. All major sectors—residential, industrial, and commercial—experienced increasing electricity usage, consistent with broader electrification trends in Sub-Saharan Africa [12]. This upward momentum reflects both expanding access and rising demand in urban and peri-urban regions. The extremely high correlation between net production and total consumption ($R > 0.98$) demonstrates that electricity supply capacity has largely kept pace with consumption growth, consistent with findings from Hailu et al. [13], who stressed the importance of matching infrastructure development to rapidly evolving energy needs in low-income countries. However, a deeper contextual analysis reveals several structural constraints, including persistent transmission and distribution losses, escalating electricity costs, uneven sectoral growth, and emerging technological transitions that reshape consumption behavior.

4.1 Electricity production, system losses, and network constraints

Despite substantial gains in electricity generation, the gap between gross production, net production, and billed consumption remains significant, as indicated by an MRD of approximately 25%. This points to serious inefficiencies within the transmission and distribution (T&D) network. Generation losses remain modest (MRD ≈ 1.6%), but the distribution system continues to suffer from technical failures, aging infrastructure, and logistical barriers related to Madagascar's geographic diversity. The reliance on diesel-based isolated grids, particularly in the western and southern regions, contributes heavily to operational inefficiencies. High fuel transportation costs, poor road infrastructure, generator aging, and maintenance delays exacerbate these losses. Non-technical losses—including billing inaccuracies and electricity theft—are also prevalent due to limited deployment of smart metering technologies. When compared with better-performing grids in South Africa, where T&D losses are typically below 10%, it becomes evident that Madagascar's network requires large-scale modernization [8, 14]. These infrastructure gaps represent a critical barrier to improving service quality and reducing system-wide inefficiencies.

4.2 Sectoral dynamics, rising electricity costs, and economic implications

Sectoral analysis highlights important differences in consumption trends and cost dynamics. The residential sector experienced the most substantial growth in both consumption (+ 82%) and customer numbers (+ 54%). Yet, this period also saw a dramatic increase in supply costs, estimated at roughly 138%. Multiple contextual factors likely contributed to this surge. National tariff revisions attempted to offset chronic financial deficits within the utility. Madagascar's dependence on imported diesel made the sector highly vulnerable to international price fluctuations, and the depreciation of the Malagasy Ariary between 2014 and 2020 substantially increased the cost of fuel imports, generator components, and other essential materials. These economic pressures explain the rapid escalation of costs to consumers. Although national consumption increased, this does not contradict affordability concerns. The coexistence of newly connected households with very low consumption levels indicates what the literature describes as "shallow access," where households have electricity connections but use electricity minimally due to price sensitivity or unreliable service [15]. In the industrial and commercial sectors, the mismatch between moderate consumption growth and disproportionate increases in electricity costs—reaching up to 140%—suggests structural tariff pressures and operational inefficiencies. High electricity tariffs can reduce industrial competitiveness and constrain economic productivity, as documented in other island economies such as Mauritius and Fiji [16]. These sector-specific observations underscore the need to interpret electricity consumption growth within the broader context of economic constraints, tariff structures, and supply instability.

4.3 Lighting sector transitions: behavior, technology, and off-grid alternatives

The lighting sector presents a contrasting dynamic, marked by declining electricity consumption despite stable customer numbers. This trend indicates a shift in both consumer behavior and technological adoption. Several contextual factors help explain this decline. Madagascar has undergone a rapid expansion in off-grid solar solutions, including solar lanterns and solar home systems supplied through donor-supported initiatives such as the World Bank's Off-Grid Market Development Fund, and large-scale commercial operations by companies such as HERi Madagascar and Aptech. These technologies have become increasingly affordable due to pay-as-you-go financing models, making them attractive substitutes for grid-based lighting, particularly in regions experiencing frequent outages. Additionally, the widespread availability of LED bulbs has significantly reduced per-household electricity consumption for lighting. The weak correlation between customer count and lighting-sector consumption (R = 0.14) further supports the idea that consumers are progressively complementing or substituting grid electricity with off-grid alternatives. Similar transitions have been reported in Kenya and Rwanda, where solar adoption has reshaped rural lighting patterns [17]. This decline in grid-based lighting demand reflects more than simple behavioral change; it represents a structural energy transition that should be integrated into national electrification strategies.

4.4 Reconciling growth, access quality, and policy implications

The simultaneous increase in national electricity consumption and persistent stagnation in consumption per customer reveals a critical paradox. While electrification efforts have expanded the number of households connected to the grid, many users continue to experience low-quality access characterized by poor reliability, frequent outages, voltage fluctuations, and insufficient supply capacity. This suggests that increases in the number of connections do not necessarily translate into meaningful improvements in welfare or productivity. Thus, electricity-sector development must focus not only on expanding access but also on improving service quality, affordability, and the enabling conditions for productive energy use.

These findings carry substantial implications for national energy policy. Reducing the large production-to-consumption gap requires targeted investments in specific transmission corridors, particularly those linking the central hydropower zones to the diesel-dependent southwestern regions. Addressing the surge in electricity costs necessitates a careful review of tariff structures, combined with targeted subsidies for low-income or low-consumption households. The decline in lighting-sector consumption highlights an ongoing structural transition toward solar solutions, which should be formally recognized in national electrification planning by reducing import taxes on solar components and expanding incentives for energy-efficient technologies such as LED bulbs. Strengthening the monitoring of service quality through reliability indicators would also improve the allocation of resources and enhance transparency. Overall, the evolution of Madagascar's electricity sector reflects both progress and persistent structural barriers. Addressing these interconnected challenges requires a coordinated, data-driven national energy strategy that integrates grid modernization, tariff reform, decentralized renewable energy solutions, and improved reliability across regions [18, 19].

5 Practical implications and policies

The long-term analysis of electricity consumption and customer dynamics in Madagascar from 2008 to 2021 highlights several critical implications for national energy policy and planning. Contrary to the earlier misinterpretation, the results clearly show a substantial national increase in electricity consumption (+61%) and production (+73%) over the 14-year period. However, this expansion has not been uniform across regions or customer segments. A closer inspection of the data reveals a noticeable slowdown in consumption growth after 2016, accompanied by persistent disparities in access and usage. This nuance is essential for interpreting national demand patterns and designing adaptive energy policies.

First, while residential, industrial, and commercial sectors all experienced growth, the average consumption per customer remains low, and in some regions has stagnated or even declined despite an expanding subscriber base. This suggests that increases in connection rates do not automatically translate into meaningful improvements in electricity usage or living standards. Affordability constraints, frequent outages, poor infrastructure quality, and limited productive use of electricity likely restrict effective consumption. Policies must therefore go beyond grid expansion and prioritize tariff reforms, targeted subsidies, and actions to improve service reliability, particularly for low-income households and rural communities.

Second, the cost of electricity supply (MGA/kWh) has increased sharply over the study period, outpacing customer growth and placing additional financial pressure on both the utility and consumers. This rising cost structure underscores the need to invest in operational efficiency, network modernization, and loss-reduction programs, especially given the high technical and commercial losses reported in multiple regions. Expanding the share of renewable energy—particularly hydropower and solar—could mitigate dependence on diesel-based generation and enhance resilience to price volatility in global fuel markets.

Third, the plateau in subscriber growth observed after 2016 may reflect structural challenges such as limited grid capacity, insufficient investment in rural electrification, and administrative barriers to new connections. To overcome this stagnation, policymakers should intensify efforts toward grid reinforcement, decentralized energy systems (including solar mini-grids and standalone systems), and public–private partnerships capable of accelerating last-mile electrification.

Finally, the findings emphasize the urgent need for a nationally coordinated, data-driven energy strategy. Comprehensive planning must integrate long-term demand forecasting, fiscal sustainability, renewable energy potential, and regional equity considerations. By leveraging robust operational data—such as those used in this study—Madagascar can strengthen its capacity for evidence-based policy design, promote inclusive energy access, and advance its commitments under national development agendas and global climate frameworks.

6 Conclusion

This study provides the first long-term, data-driven assessment of electricity consumption trends in Madagascar across 22 regions from 2008 to 2021. Using a high-resolution operational dataset from the national utility, we analyzed sectoral consumption patterns, customer growth, pricing evolution, and system performance indicators through descriptive statistics, correlation analysis, and time-series visualizations. The findings reveal a substantial increase in electricity production (+73%) and consumption (+61%) over the 14-year period, driven largely by strong growth in the residential, industrial, and commercial sectors. However, this national expansion masks important nuances: after 2016, consumption growth slows considerably, and average usage remains low for many customers despite rising connection rates. These patterns point to persistent structural constraints—including affordability challenges, frequent outages, infrastructure limitations, and limited productive use of electricity—that restrict effective consumption across several regions.

The study also highlights pronounced regional inequalities, with urban areas benefiting from higher and more stable levels of electricity use, while many rural regions show stagnation or minimal gains. This continued urban–rural divide underscores the need for spatially targeted policies and differentiated electrification strategies. Furthermore, the sharp increase in electricity supply costs during the study period, despite improvements in consumption, raises concerns about the efficiency and financial sustainability of the current energy system.

Taken together, the results underscore the urgency of rethinking national energy strategies in Madagascar. Policy reforms must not only seek to expand grid connections but also ensure that electricity is affordable, reliable, and efficiently delivered. Priorities should include investments in grid modernization, loss-reduction initiatives, and decentralized renewable energy solutions, as well as pro-poor tariff structures that enhance meaningful electricity use among low-income households. By linking empirical evidence to actionable policy recommendations, this study offers a robust analytical foundation for advancing equitable, resilient, and sustainable energy development in Madagascar.

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