Impacts of Climate Variability on Electricity Consumption in the City of Maradi, Niger.

Abstract:

Background: Climate variability is placing growing pressure on electricity systems across the Sahel, yet its relationship with consumption had never been quantified for Maradi, one of Niger's major economic centers and a city already marked by extreme heat, irregular rainfall and rapid urban growth.

Methods: Monthly temperature, precipitation and relative humidity data for 2015–2024, drawn from the Maradi Airport meteorological service and national statistical yearbooks, were combined with NIGELEC electricity consumption records. Interannual trends were assessed by linear regression, climate-consumption relationships by Pearson correlation and multiple linear regression, and future consumption was projected to 2054 under the SSP2-4.5 and SSP5-8.5 climate scenarios.

Results: Mean annual temperature stayed nearly stable (0.97°C range across the decade) despite a pronounced seasonal swing (11.46°C), while precipitation and relative humidity both trended upward. Electricity consumption rose 32% between 2015 and 2022 before falling sharply in 2023 following regional economic sanctions. Temperature correlated strongly with consumption ($r = 0.96$, $p < 0.001$), with each 1°C monthly rise adding 359.11 MWh, while precipitation and humidity showed no meaningful link. By 2054, consumption is projected to grow 65.4–71.8% under SSP2-4.5/SSP5-8.5, driven mainly by structural growth (84–93%) with a smaller but non-negligible thermal contribution (7–16%).

Conclusion: Climate variability, and rising temperature in particular, is a measurable and growing stress factor on Maradi's electrical system. Energy planners should build this thermal effect into infrastructure and demand-forecasting decisions alongside the dominant structural growth trend.

Key words: Climate variability, electricity consumption, temperature, precipitations, relative humidity, Maradi.

Introduction:

Climate variability ranks today among the defining challenges facing the planet, with consequences running deep into ecosystems, human societies and economies alike. The international scientific community has by now documented its signatures at length: shifting and rising temperatures worldwide, changing rainfall patterns, and a growing frequency of extreme climate events [1]. The IPCC identifies sub-Saharan Africa, and the Sahel above all, as among the regions most exposed to these upheavals [2], [3].

Niger embodies this vulnerability about as clearly as any Sahelian country can, marked as it is by sharp rainfall variability and persistently high temperatures [4]. These climatic pressures already weigh heavily on the country's economic activities and infrastructure, nowhere more so than in the energy sector. Niger's electricity system carries one of the lowest access rates on the continent, around 22.5% in 2023, leans on Nigerian imports for nearly 57% of national needs, and runs on aging infrastructure [5], [6]. That precarious position sits at the intersection of two challenges at once: keeping pace with steadily rising consumption driven by population growth and economic development, while also absorbing whatever climate variability throws at that same consumption.

Maradi, one of Niger's major economic centers, makes for a particularly fitting case study. Between its extreme hot-season temperatures, its irregular rainfall [7], and rapid urban growth that keeps pushing electricity consumption upward, especially for thermal comfort uses like air conditioning, ventilation and refrigeration, the city captures the climate-energy relationship about as well as any place could. And yet that relationship, in Maradi specifically, has never really been quantified, which leaves decision-makers with little to go on when trying to anticipate what comes next.

This study sets out to close that gap, with three specific aims: first, tracing how the main climatic parameters and electricity consumption in Maradi have evolved between 2015 and 2024; second, quantifying just how strongly climatic variables and electricity consumption correlate; and third, projecting future consumption under the SSP2-4.5 and SSP5-8.5 climate scenarios.

Materials and Methods:

2.1. Study Area

Maradi sits in the Madarounfa department, at 13° 29′ 30″ N latitude and 7° 05′ 47″ E longitude, and serves as capital of the region that shares its name [8]. With 382,681 inhabitants as of 2022 [9], it ranks among Niger's major economic centers. Its Sahelian climate follows a familiar rhythm: a short rainy season (June to September, 500 to 700 mm annually), a long dry season stretching eight to nine months, and high temperatures that peak between March and June [10]. Maradi's electricity grid, meanwhile, depends almost entirely on imports from Nigeria, a major structural vulnerability in its own right.

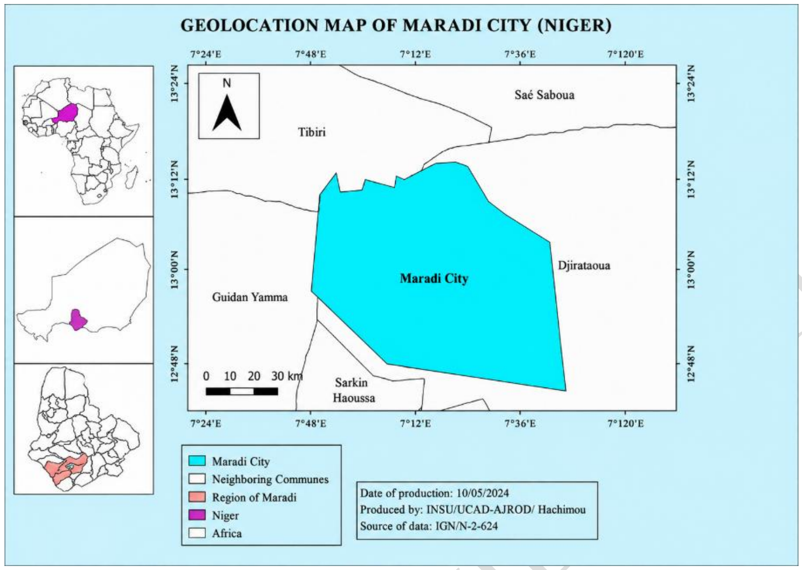


Figure 1. *Location map of the city of Maradi.*

2.2. Data Collected

This study rests on two types of monthly data spanning 2015–2024:

Climate data: mean monthly temperature (°C), monthly precipitation totals (mm), and mean monthly relative humidity (%), drawn from the Monthly Climatological Tables (TCM) supplied by the Maradi Airport meteorological service (2023–2024) and from the Statistical Yearbooks of the National Institute of Statistics, Maradi Regional Office (2015–2022) [9], [11].

Energy data: monthly electricity consumption records (MWh) for the city of Maradi, sourced from the NIGELEC Regional Office.

2.3. Analysis Methods

Raw data were first cleaned and homogenized in Microsoft Excel, after which the following analyses were carried out:

(a) Descriptive analysis and interannual trends: for temperature and relative humidity, we computed monthly and annual means for each year of the decade.

$$X_{mean,mon} = (X_{mean,max} + X_{mean,min})/2 \quad \text{(Eq.1)}$$

where $X_{mean,mon}$ is the monthly mean of variable X; $X_{mean,max}$ / $X_{mean,min}$, the maximum/minimum monthly mean of variable X.

$$X_{mean,yr} = (1/12) \times \Sigma_{(m=1\rightarrow 12)} X_{mean,mon} \quad \text{(Eq.2)}$$

where $X_{mean,yr}$ is the annual mean of variable X, and m is the month.

Precipitation and electricity consumption, being cumulative variables, were instead aggregated as monthly and annual totals.

$$X_{yr} = \Sigma_{(m=1\rightarrow12)}\, X_{mon} \qquad \text{(Eq.3)}$$

where X_{yr} is the annual total of variable X, m is the month, X_{mon} is the monthly total of variable X.

Finally, we determined the interannual monthly means of each parameter across the full 2015–2024 period.

$$X_{mean,mon} = (1/N) \times \Sigma_{(y=1\rightarrow N)}\, X_{m,y} \qquad \text{(Eq.4)}$$

where $X_{mean,mon}$ is the interannual mean of variable X for month (m); $X_{m,y}$ is the value of variable X for month (m) of year (y); N = 10, the number of years in the series.

For each parameter, we analyzed the interannual trend over the decade with a simple linear regression, fitting a trend line of the form $Y = P\cdot X + B$: Y is the variable under study, X is time (years coded 1 through 10), P is the slope, capturing the average yearly rate of change, and B is the intercept. Whether P comes out positive or negative simply tells you the direction of the trend, an increase or a decrease in the parameter over time.

(b) Seasonal correlation analysis: we calculated the Pearson correlation coefficient (r) between each climatic parameter and electricity consumption, based on interannual monthly means (n = 12), where r close to 1 signals a strong positive correlation, r close to −1 a strong negative one, and r close to 0 essentially no relationship. The associated p-value tests significance at $\alpha = 0.05$: below that threshold, the correlation is considered real rather than due to chance; at or above it, chance can't be ruled out.

(c) Analysis of individual effects: to tease apart the individual effect of each climatic variable on monthly electricity consumption (CE), we ran a multiple linear regression using the following model:

$$C_E = \beta_0 + \beta_1\cdot T + \beta_2\cdot Hr + \beta_3\cdot Cp + \varepsilon \qquad \text{(Eq.5)}$$

where CE is electricity consumption (MWh), the dependent variable; T is temperature (°C); Hr is relative humidity (%); Cp is precipitation totals (mm); β0 is the constant (intercept); β1, β2, β3 are the partial regression coefficients, indicating the individual effect of each climatic variable on consumption when all other variables are held constant; ε is the error term, representing the variance not explained by the model.

For each coefficient we calculated the standard error and the associated p-value, to test significance. The model's overall quality rests on the coefficient of determination R^2, which captures how much of the variance in consumption the set of climatic variables actually explains, the closer R^2 sits to 1, the better the fit. Adjusted R^2 penalizes the model for including variables that don't pull their weight, so a value close to 1 there means overfitting isn't a concern. The overall F-test, finally, checks the statistical significance of the model as a whole: the higher the F value, the stronger the model's explanatory power.

(d) Projection of future consumption: since temperature emerged as by far the most influential factor on electricity consumption (sensitivity coefficient β = 359.11 MWh/°C per month), the projection focuses solely on the thermal effect, built from two components:

The structural component: this captures the mean annual growth in consumption, treated as independent of climate variability even though it likely traces back to Maradi's own socio-economic dynamics. We estimate it from the slope of the linear regression (P = 1,529.9 MWh/year) fitted to annual consumption over 2015–2024.

The climatic component: this represents the additional impact of temperature on consumption, calculated by applying the thermal sensitivity coefficient (β1 = 359.11 MWh/°C per month, i.e., 4,309.32 MWh/°C per year), to the temperature trajectories of the SSP2-4.5 (+0.021°C/year) and SSP5-8.5 (+0.049°C/year) scenarios between 2015 and 2100, derived from the NASA CMIP6 climate models, adapted for Niger by the National Council for Environment and Sustainable Development (CNEDD) [6]. Under these scenarios, the rate of temperature increase (ΔT) would be 0.21°C (SSP2-4.5) and 0.49°C (SSP5-8.5) by 2024, hence our reference year.

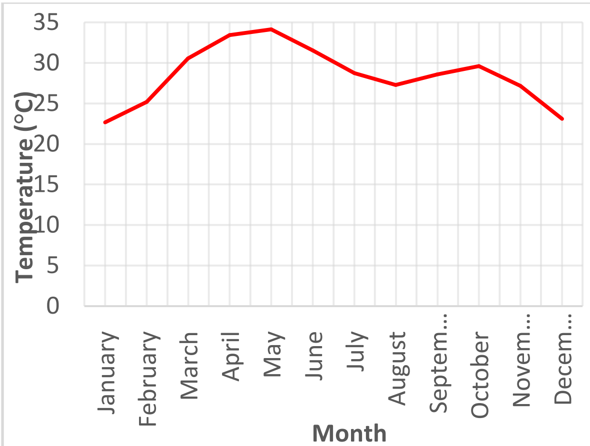
The projection model takes the following form:

$$E_{projected}(n) = E_{2024} + P(n-2024) + \beta_1 \cdot \Delta T(n-2024) \quad \text{(Eq.6)}$$

where Eprojected represents the projected electrical energy (MWh); E2024 is the electrical energy of the reference year 2024 (75,735 MWh); P is the structural growth slope (1,529.9 MWh/year); n is the projection year; β1 is the annual thermal sensitivity coefficient (4,309.32 MWh/°C/year); ΔT is the annual rate of temperature increase under the scenarios (+0.021 and +0.049°C per year).

Results:

3.1. Evolution of Climatic Parameters (2015–2024)



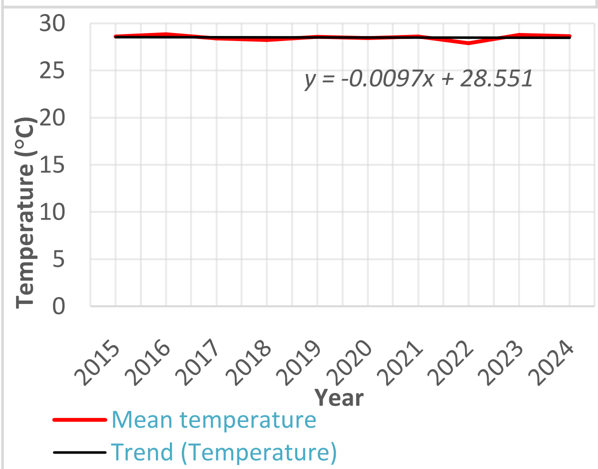
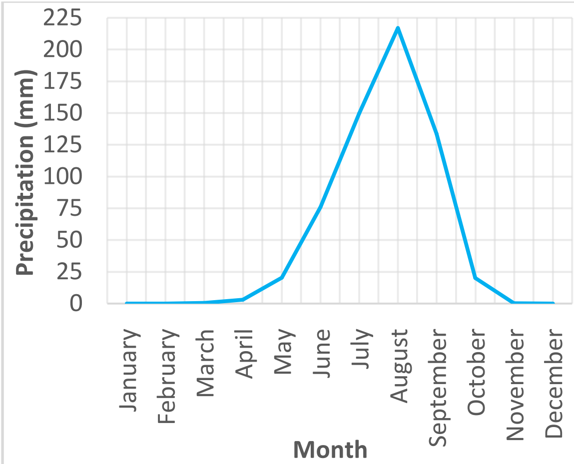


Fig. 1. ***Seasonal variability of mean temperature***

Fig. 2.Interannual evolution of mean temperature (2015- 2024)



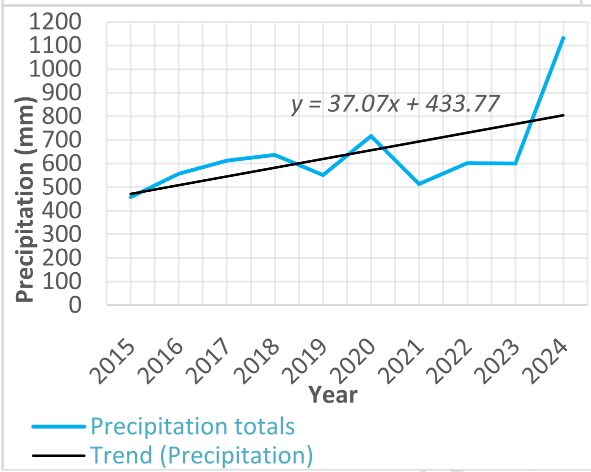
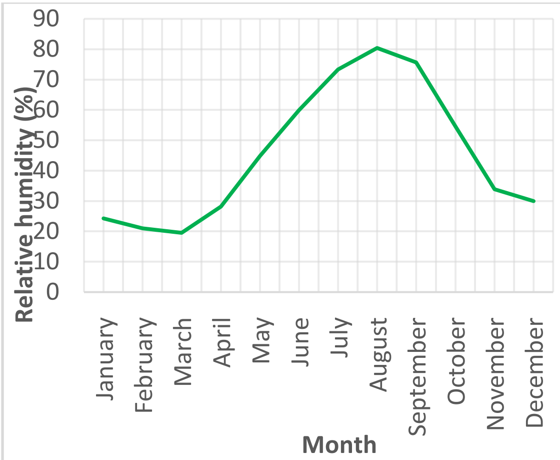


Fig. 3. Seasonal variability of precipitation totals

Fig. 4. Interannual evolution of precipitation totals between 2015 and 2024



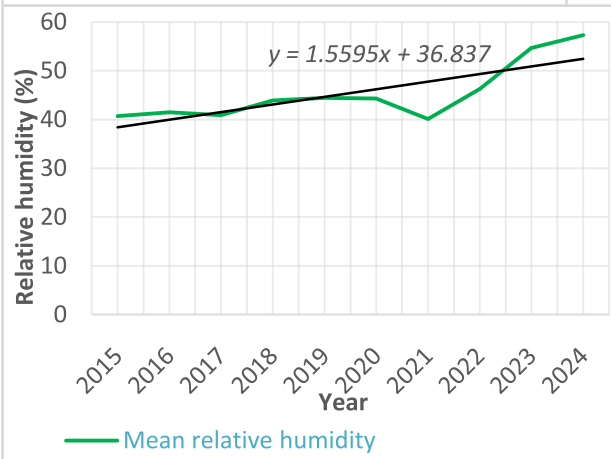


Fig. 5. Seasonal variability of mean relative humidity ***humidity***

Fig. 6. Interannual evolution of mean relative ***between 2015 and 2024***

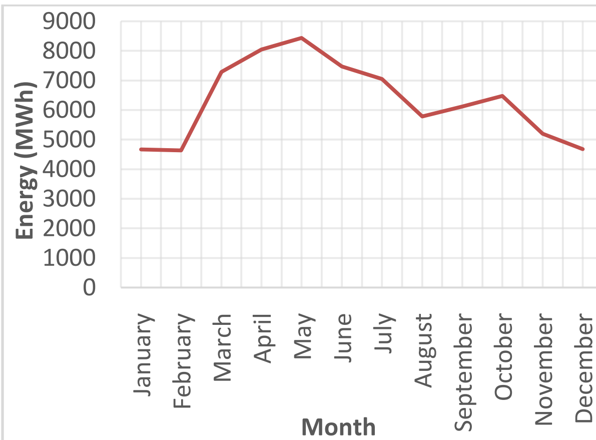
Figures 2 through 7 trace the seasonal variability and interannual evolution of mean temperature, precipitation totals and mean relative humidity for Maradi across 2015–2024; the corresponding charts are referenced below and remain to be inserted once the source plots are available.

Temperature: The monthly temperature profile (Fig. 2) traces a pronounced annual cycle, swinging through a seasonal amplitude of about 11.46°C between a January minimum (22.66°C) and a May maximum (34.12°C). Three thermal seasons emerge from this pattern: an extremely hot stretch from March to June, a moderately hot rainy season from July to October, and a cooler spell from November to February. Zoom out to the decade as a whole, though, and mean annual temperatures (Fig. 3) barely move, a narrow 0.97°C range, from 28.85°C in 2016 down to 27.88°C in 2022, with only a slight downward drift (−0.0097°C/year).

Precipitation: Rainfall concentrates almost entirely into a four-month window, June to September, peaking in August at an average of 216.95 mm (Fig. 4). Year to year, though, the picture is far less tidy (Fig. 5): peaks and troughs alternate sharply, even as an upward trend (+37.07 mm/year) runs underneath the noise. 2024 stands out on its own, with an exceptional total of 1,132.5 mm, 416 mm above the next-highest year on record.

Relative humidity: Relative humidity follows its own seasonal rhythm (Fig. 6): a more humid stretch from June to September, a dry spell from October to May, bottoming out at 19.45% in March and peaking at 80.35% in August. Year over year, though, the trend runs clearly upward (Fig. 7, +1.56%/year), with a particularly sharp rise from 40.13% in 2021 to 57.33% in 2024, a 17.2-point jump in just three years.

3.2. Evolution of Electricity Consumption



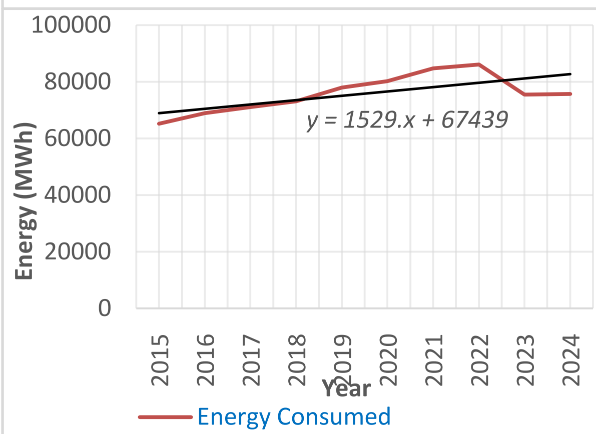


Fig. 7. Seasonal variability of consumption in the city of Maradi

Fig. 8. Interannual evolution of consumption in the city of Maradi, 2015–2024

Electricity consumption swings sharply with the seasons (Fig. 8), tracking the thermal cycle almost exactly: March through June brings peak demand (topping out in May at 8,435.7 MWh), while November through February sees the lowest draw. Zoom out to the interannual picture (Fig. 9) and consumption climbs almost without interruption, from 65,218 MWh in 2015 to a high of 86,063 MWh in 2022, a 32% rise over seven years. Then 2023 breaks the pattern sharply (75,485 MWh, −12.3%). Still, the linear regression (y = 1,529.9x + 67,439) confirms an overall upward trend, with consumption climbing by roughly 1,529.9 MWh a year on average across the period.

3.3. Correlation between Climatic Variables and Electricity Consumption

TABLE I. Seasonal correlation matrix between climatic parameters and electricity consumption in the city of Maradi (interannual monthly means, 2015–2024).

Variables	Pearson correlation coefficient (r)	Significance (p-value)	Interpretation
Temperature and Electricity Consumption	0.961	< 0.001	Very strong and significant correlation
Precipitation and Electricity Consumption	0.093	0.774	Negligible and non-significant correlation
Relative Humidity and Electricity Consumption	0.214	0.504	Weak and non-significant correlation

Table I lays out the seasonal correlation between climatic parameters and electricity consumption over 2015–2024, and one variable stands well apart from the rest: temperature is the only climatic factor showing a significant correlation with consumption (r = 0.961, p-value < 0.001), with a coefficient of determination (R^2 = 0.923) indicating that temperature alone accounts for 92.3% of the seasonal variance in consumption. Precipitation (r = 0.093) and relative humidity (r = 0.214), by comparison, show essentially no relationship at all.

3.4. Individual Effect of Each Climatic Variable on Electricity Consumption

TABLE II. Results of the multiple regression: quantification of the individual effects of each climatic variable on mean monthly electricity consumption.

Explanatory Variables	Coefficient (β)	Standard Error (ε)	t-Statistic	p-value (P)
Constant	-3,748.13	1,017.70	-3.68	0.006
Temperature (°C)	359.11	38.10	9.43	0.00001
Relative Humidity (%)	-6.38	15.18	-0.42	0.686
Precipitation (mm)	2.48	4.48	0.56	0.595

Overall model statistics: R^2 = 0.926; adjusted R^2 = 0.899; standard error = 429.97 MWh; F(3, 8) = 33.5693; P < 0.05.

Table II lays out the results of the multiple regression, and temperature again dominates, with a strongly significant effect on consumption (β_1 = 359.11, p-value << 0.05): holding humidity and precipitation constant, each additional 1°C in monthly temperature adds 359.11 MWh to consumption. Relative humidity (β_2 = −6.38, p-value = 0.686) and precipitation (β_3 = 2.48, p-value = 0.595), meanwhile, contribute nothing statistically meaningful. The model as a whole fits the data well (R^2 = 0.926, adjusted R^2 = 0.899, F(3,8) = 33.57, p-value < 0.05).

3.5. Electricity Consumption Projections to 2054

TABLE III. Results of the projection of annual electricity consumption under the SSP2-4.5 and SSP5-8.5 climate scenarios over the period 2024-2054.

Year	X (years)	ΔT SSP2-4.5 (°C)	ΔT SSP5-8.5 (°C)	No climate impact (MWh)	SSP2-4.5 (MWh)	SSP5-8.5 (MWh)
2024	0	0.21	0.49	75,735	75,735	75,735
2034	10	0.42	0.98	91,034	92,844	95,257
2044	20	0.63	1.47	106,333	109,048	112,668
2054	30	0.84	1.96	121,632	125,252	130,078

Table III sets out the projected annual electricity consumption under both climate scenarios, and the numbers point to substantial growth: 65.4% under SSP2-4.5, rising to 71.8% under SSP5-8.5, by 2054 relative to 2024. The gap between the two scenarios starts out negligible in 2024 but widens steadily, reaching 4,826 MWh by 2054. Over the full thirty years, the climate-independent structural component, a steady 1,529.9 MWh/year, accounts for the lion's share of that growth on its own, some 45,897 MWh, or roughly 84 to 93% of the total, while the additional thermal effect makes up the remaining 7 to 16% under the SSP2-4.5 and SSP5-8.5 scenarios respectively.

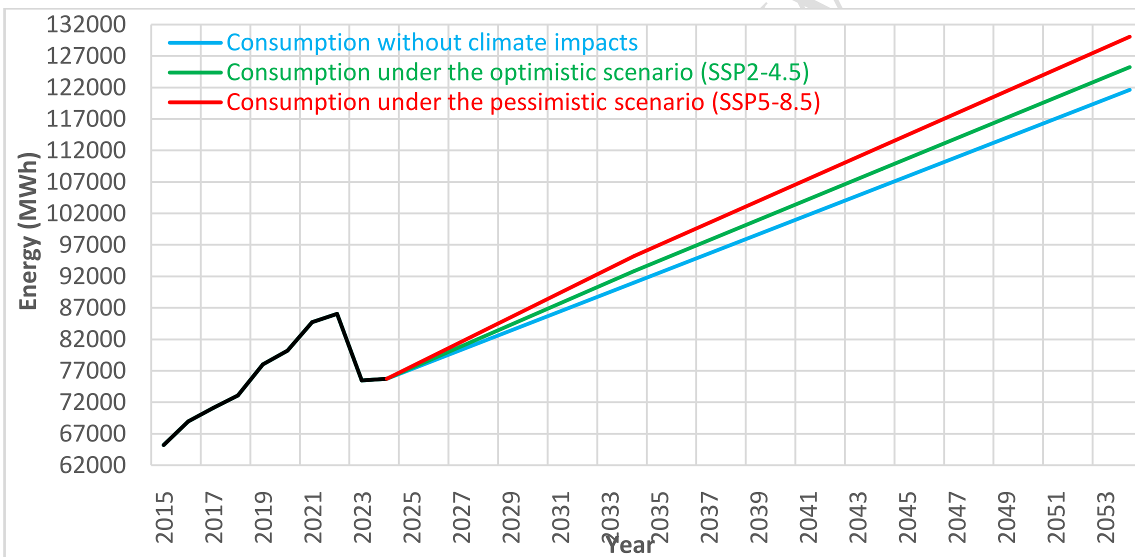


Fig. 9. Historical (2015-2024) and projected future (2024-2054) electricity consumption under the SSP2-4.5 and SSP5-8.5 scenarios.

Discussion:

The relative stability observed in mean annual temperatures over 2015–2024 deserves a note of caution rather than a confident conclusion. A decade is a short window for capturing the long-term climate signal, and the literature on climate trend detection is fairly insistent that reliable detection needs a longer observation period [12]. That apparent interannual stability, though, doesn't erase the strong seasonal variability underneath it, if anything, it may mask increasingly pronounced extreme heat during the critical March-to-June window, in keeping with what is already known about Maradi's broader regional context [13]. The pronounced variability in precipitation, meanwhile, fits squarely within the well-documented climatic profile of the Sahel, where rainfall variability stands as the principal expression of climate vulnerability, per [14]. And the upward trend in relative humidity lines up with recent findings on Sahelian climate change from [15], which likewise document rising humidity across the Sahel between 2014 and 2024.

The sharp 12.3% drop in electricity consumption recorded in 2023 marks a real break in the growth trajectory Maradi had followed since 2015, and climate has nothing to do with it. The cause lies elsewhere entirely: the July 26, 2023 military coup in Niger, which triggered ECOWAS economic and energy sanctions, chief among them the suspension of Nigerian electricity supply.

The strong correlation between temperature and electricity consumption ($r = 0.96$; $p < 0.001$) comes down to a fairly intuitive seasonal rhythm at work in Maradi: during the hottest months, March through June, the grid faces peak demand from thermal comfort uses, air conditioning, ventilation, refrigeration, while consumption eases off again once the cooler seasons arrive. That is what drives the sharp sensitivity of consumption to temperature captured in the significant coefficient ($\beta 1 = 359.11$ MWh/°C/month), and it echoes findings from [16] and [17], covering respectively the IUT Maradi site and the electrical grid spanning the Niamey, Dosso and Tillabéry regions, both of which found a strong temperature influence on consumption. It also sits comfortably alongside [18]'s work across twelve cities in West and Central Africa, which reports temperature explaining anywhere from 25 to 70% of the variability in electricity consumption.

The lack of a significant correlation between electricity consumption and either relative humidity ($r = 0.21$) or precipitation ($r = 0.09$) is worth unpacking rather than simply noting. On humidity, the international literature makes clear that its effect on consumption depends heavily on local climatic context: in humid regions where humidity stays high and roughly constant year-round, it contributes meaningfully to cooling demand [19]. Maradi runs the opposite pattern structurally, the humid months (June–September) coincide with lower temperatures, so cooling demand actually falls as humidity rises ($\beta 2 = -6.38$ MWh/%/month), a finding that echoes [20]'s work on the Sahel-Sudan zone reporting a negative correlation between the two variables in arid regions. Precipitation's weak link with consumption, meanwhile, likely owes to two things at once: it concentrates into just four months of the year (June–September), which limits its reach across the annual consumption cycle, and those same months coincide with moderate temperatures, when cooling demand is naturally lower anyway, masking whatever independent effect rainfall might otherwise have. That puts this result at odds with [19]'s finding for Togo, where precipitation and consumption correlated at 73% in a humid context.

The projected 65.4 to 71.8% rise in electricity consumption by 2054 lines up with [21]'s forecast of strong energy-demand growth across tropical regions between 2010 and 2050, with climate change contributing a meaningful share. It also fits with [22]'s projection of a fourfold increase in Africa's cooling-related energy demand by 2030, and with [23]'s estimate that cooling equipment worldwide will more than double its current consumption by 2050, growing especially fast across Africa and South Asia. Breaking the projected growth down reveals the more important point: socio-economic dynamics, population growth, economic development, drive most of the increase (84–93%), which means energy planning in Maradi needs to respond first and foremost to this structural demand, itself a reflection of the city's exceptionally rapid growth. Still, the thermal contribution (7–16%), though the smaller share, is not one to write off in a warming climate. It adds one more layer of stress onto an already strained electrical system, and it argues for building cooling-related energy needs into how Maradi plans its electrical infrastructure investments. The widening gap between the SSP2-4.5 and SSP5-8.5 scenarios, 4,826 MWh by 2054, suggests, further, that climate mitigation policy really can move the needle on Maradi's future electricity demand, even if only modestly, which is itself an argument for folding climate projections systematically into national energy planning.

Conclusion:

This study set out to trace the interaction between climate variability and electricity consumption in Maradi over 2015–2024, and to project what that interaction might mean through 2054. The results answer the questions we started with, and they point to several conclusions worth underlining. The decade itself shows mean annual temperatures holding relatively stable, precipitation swinging considerably from year to year with an upward drift, and relative humidity climbing steadily. Electricity consumption in Maradi grew 32% between 2015 and 2022, only to break sharply in 2023 under ECOWAS economic sanctions that suspended Nigerian electricity imports, an exogenous shock that exposes just how structurally vulnerable Niger's electrical system really is, and one that makes a strong case for diversifying supply sources and building out local renewable energy. The study's central finding, though, is the exceptionally strong seasonal correlation between mean temperature and electricity consumption: the multiple regression shows a 1°C rise in monthly temperature adding 359.11 MWh to monthly consumption, while precipitation and relative humidity contribute nothing statistically meaningful. Looking ahead to 2054, consumption is projected to keep rising under both the SSP2-4.5 and SSP5-8.5 scenarios, driven mainly by socio-economic structural growth with a real but secondary contribution from the climatic thermal effect. Altogether, these results confirm that energy planning in Maradi has to answer, first and foremost, to this growing structural demand, while still building in the non-negligible, and growing, effect of climate warming on thermal comfort demand.

This study is, as far as we know, the first to examine the climate-electricity consumption relationship for Maradi specifically, which leaves plenty of room for follow-up work. Bringing in additional climatic variables, wind, solar irradiation, and the like, building more sophisticated projection models that fold in demographics, economic growth, technological change and energy policy, and breaking consumption down by sector (residential, commercial, industrial) would all be valuable next steps.

Acknowledgments:

The authors wish to thank the Maradi Airport Meteorological Service, the Maradi Regional Office of the Nigerien Electricity Company (DR/NIGELEC), and the Maradi Regional Office of the National Institute of Statistics (DR/INS) for providing the data that made this study possible.

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