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Assessment of Energy Consumption and Associated Carbon Footprint of Households in Bauchi Metropolis, Nigeria

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ABSTRACT: The escalating impacts of global warming have raised concerns at local and global levels, necessitating urgent mitigation efforts, particularly among households in urban settings. However, limited information on household energy consumption and its associated carbon footprint may constrain effective climate mitigation and policy development in Bauchi metropolis. This study assessed household energy consumption in Bauchi metropolis to establish its carbon footprint and inform policy development amid evident climate change. The study adopted a descriptive survey approach involving questionnaires and observational field measurements using a weighing scale to establish the average unit weight of energy sources across six wards. A two stage sampling technique involving cluster and purposive sampling was adopted. Descriptive statistics and the Intergovernmental Panel on Climate Change (IPCC) guidelines were used to analyse the data and estimate the related carbon footprint. The result of 403 analysed responses revealed that the average annual carbon footprint from firewood, charcoal, grid electricity, LPG, petrol, diesel, kerosene, and sawdust was 6.61 tCO_2 per household, with firewood and charcoal identified as priority areas for emission reduction. The study concluded that household energy consumption contributes to carbon emissions in the Bauchi metropolis and therefore recommends targeted interventions should reduce dependence on firewood and charcoal and promote cleaner household energy sources.

Keywords: Energy consumption; Carbon footprint; Greenhouse gas; Climate change mitigation; Urban households

1. Introduction

The building sector's significant contribution to global warming has garnered heightened interest among researchers, prompting a focus on analysing energy consumption in residential buildings to quantify greenhouse gas (GHG) emissions, which can serve as a basis for policy formulation towards carbon reduction. The building sector alone accounts for around 40% of total energy consumption and more than one-third of global carbon emissions [1], with residential buildings constituting a substantial share of this contribution [2]. This contribution becomes more critical in urban residential settings, where urban dwellers typically spend most of their time indoors, consequently increasing household energy demand [3]. The concentration of energy demand within residential bufrildings, therefore, positions the sector as a critical area for carbon emission reduction [4–6]. However, the increasing energy demand associated with rapid urbanisation and industrialisation raises concern because continued growth in residential energy consumption directly reinforces carbon emissions [7,8]. Thus, the sustainability challenge is not simply the growth in residential energy consumption but the continued dependence on energy sources whose consumption intensifies GHG emissions. This relationship has strengthened global concern over the role of energy consumption in climate change and the need for coordinated strategies to reduce global warming and its detrimental effects [9], including drought, flooding, delayed or excessive rainfall, extreme heat conditions, rising sea levels, and hurricanes [10]. Consequently, the residential sector represents not only a major energy-consuming sector but also a strategic point of intervention for reducing carbon emissions and advancing sustainable energy use.

However, Nigeria presents a particularly critical energy and environmental dilemma because energy demand is increasing while supply remains insufficient, unreliable, and on a downward trend. Although fossil fuels are environmentally damaging and non-renewable, they continue to dominate the country's energy sector [11]. The dominance of conventional energy sources is evident in household energy use, which accounts for 74.24%, compared with only 25.76% for modern energy sources [12]. This imbalance exposes a fundamental contradiction in Nigeria's energy transition: the country possesses substantial renewable energy resources, yet household energy consumption remains strongly dependent on conventional sources. Addressing this contradiction requires diversification of the energy portfolio through infrastructure development and public sensitisation to harness Nigeria's vast renewable resources and enhance supply security [11]. Nigeria's abundant solar radiation, rivers and streams for hydropower, biomass for biogas, extensive coastline, and wind potential in the Sahel provide opportunities for such diversification. Nevertheless, the continued dominance of fossil fuels for cooking and electricity remains a significant source of GHG emissions and a contributor to climate change [13]. The issue, therefore, extends beyond energy availability to the composition of household energy consumption and its associated environmental consequences.

Therefore, carbon emissions remain a significant concern in Nigeria as the country continues to experience the effects of climate change. Despite interventions by the Nigerian government, international bodies, and non-governmental organisations through laws, policies, programmes, and projects aimed at curtailing this scourge, the country's carbon footprint continues to rise [14]. This persistent increase raises questions about the effectiveness of existing interventions and the extent to which carbon-emitting activities within individual sectors and settings are being adequately quantified. The consequences are evident across essential sectors, including agriculture, health, power generation, and security, while changes in rainfall and temperature patterns have produced excessive rain and heat in some areas [14] and rising temperatures, sea levels, flooding, drought, desertification, and land degradation in others [9]. Against this background, researchers have increasingly assessed carbon emissions associated with academic institutions [15,16] and the hospitality industry [17,18] in Nigeria. However, comparatively limited attention has been given to other energy-consuming sectors, particularly residential settings [19]. This represents an important evidence gap because household energy consumption constitutes a direct source of carbon emissions, yet its contribution remains less established in the Nigerian context. Similar household carbon emission assessments have been undertaken in countries with substantial carbon emissions, including China [20], the United States [21], and India [22,23], demonstrating the relevance of household-level assessment to carbon accounting and reduction strategies.

Furthermore, Bauchi metropolis in northeastern Nigeria exemplifies the broader global and national energy and climate challenges [24]. The city is experiencing rapid population growth and urbanisation, consistent with trends across Nigeria [25,26], thereby increasing household energy demand. This demand is predominantly met through traditional energy sources such as biomass, kerosene, and electricity generated from fossil fuels [27,28]. However, the increasing household energy demand is not matched by equivalent evidence on its carbon emissions, creating a critical information gap for carbon reduction planning in the metropolis. The significance of this gap is reinforced by evidence confirming climate change in Bauchi State [24] and by the Bauchi State Government's commitment through the Ministry of Housing and Environment to addressing climate change [29]. Without empirical evidence of the energy sources contributing to household carbon emissions, however, such policy commitment is constrained in its capacity to identify and prioritise household-level emission reduction opportunities. Given these dynamics, the study aimed to assess household energy consumption from the use of firewood, charcoal, liquefied petroleum gas (LPG), diesel, petrol, kerosene, sawdust, and grid electricity in Bauchi metropolis, with a view to establishing their associated carbon footprint as an evidence base for policy formulation towards carbon reduction.

2. Methodology

This section presents the procedures adopted to achieve the research objective. It outlines the research design, study area, population, sampling techniques, method of data collection, data analysis, and method of data presentation as discussed in the following sub-sections below.

2.1. Research Design

The study adopted a quantitative research design. To achieve the objective of the study, it involved measurement using a weighing scale, a designed record sheet, and a semi-structured questionnaire to obtain data on household demographics and their estimated monthly energy consumption. Descriptive statistics (percentage, frequency, and mean) were used to analyze the data using IBM SPSS version 23. The carbon footprint was determined from the households estimated monthly energy consumption using the default emission factors provided by the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines [30] also retained by the 2019 IPCC refinement [31] for firewood, charcoal, diesel, kerosene, petrol, LPG, and sawdust while for electricity grid in Nigeria, country-specific emission factor was adopted from [18] to calculate the associated carbon emissions. Therefore, data were presented using frequency distribution tables, graphs, and a narrative summary.

2.2. Population

The population consists of households in six (6) wards of the Bauchi metropolis as identified by the National Population Census (NPC) in Bauchi state. The 2006 census population for the wards was obtained and projected to 2024 using Newman's method of population projection [32], given as:

$$P_n = P_o + \left(\frac{1 + R}{100} \times P_o\right) n \tag{1}$$

where: P_n = Population in the recent year

P_o = Population in the base year

R = Annual growth rate

n = Number of intermediary years

R = 2.89 was derived from the NPC report as applied to Bauchi state. Likewise, the household size (HHS) of 5.5 [33] was used. This is summarized in Table 1.

Table 1. Population of the study.

S/No.	Wards	2006 Census Population	Projected 2024 Population	2024 Projected Population of Houses
i	Makama	77,957	135,575	24,650
ii	Dan'amar	64,066	111,417	20,258
iii	Dan'iya	36,491	63,461	11,538
iv	Dawaki	35,396	61,557	11,192
v	Dan'kade	28,299	49,215	8948
vi	Hardo	5460	9495	1726
	TOTAL	247,669	430,720	78,312

Table 1 presents the total estimated population of 78,312 households.

2.3. Sample Size

The sample size was determined by adopting the widely used sample size formula for household studies, as applied by [34] in Equation (2).

$$S = \frac{NP(1-P)}{\left(\frac{B}{C}\right)^2 (N-1) + P(1-P)} \tag{2}$$

where, S is the required sample size;

N, the population size;

P, the population proportion expected to answer (0.5);

B, the degree of accuracy expressed as a proportion (0.05); and

C, the Z statistic value based on the confidence level (e.g., 1.96 for 95% confidence)

Therefore,

$$S = \frac{NP(1-P)}{\left(\frac{B}{C}\right)^2 \cdot (N-1) + P(1-P)}$$

$$S = \frac{78{,}312 \times 0.5(1-0.5)}{\left(\frac{0.05}{1.96}\right)^2 \cdot (78{,}312-1) + 0.5(1-0.5)}$$

= 19,578/[(0.000651)·(78,311) + 0.25]

= 19,578/51.23

= 382.16

= 382 Households

However, 10% buffer was added to the sample size, 382 + (0.10 × 382) = 420 households. The proportionate distributions according to the wards are presented in Table 2.

Table 2. Sample Size.

S/No.	Wards	2024 Projected Population of Houses	Proportion of the Pop. (%)	Calculated Sample Size	10% Buffer	Adjusted Sample Size
i	Makama	24,650	31.48	120	12	132
ii	Dan'amar	20,258	25.87	99	10	109
iii	Dan'iya	11,538	14.73	56	6	62
iv	Dawaki	11,192	14.29	55	5	60
v	Dan'kade	8948	11.43	44	4	48
vi	Hardo	1726	2.20	8	1	9
	Total	78,312	100	382	38	420

Table 2 presents the 2024 projected population of the households, the proportion of households' distribution, the calculated sample size, and 10% buffer added for all the respective wards to arrive at the total adjusted sample size of 420 households. This includes 132, 109, 62, 60, 48, and 9 for the wards Makama, Dan'amar, Daniya, Dawaki, Dankade, and Hardo, respectively. This is proportionately distributed to ensure the sample accurately represents the population, thereby increasing accuracy, reliability, and generalization of the findings. Finally, 403 questionnaires were validated for analysis with 123, 106, 57, 60, 48, and 9 responses from Makama, Dan'amar, Dan'iya, Dawaki, Dankade, and Hardo wards, respectively.

2.4. Sampling Techniques

The study used a two-stage sampling technique. First, cluster sampling was used to target the six wards of Bauchi metropolis: Makama, Dan'amar, Daniya, Dawaki, Dankade, and Hardo. Secondly, given the urban setting and the fact that larger buildings consume more energy [35], purposive sampling was used to target conventional flats and apartments, specifically selecting households within these wards to obtain representative samples, as shown in Table 2.

2.5. Study Area

Bauchi metropolis is located in North-eastern Nigeria with geographical coordinates of latitudes 10°16′0″ N and 10°23′0″ N and longitudes 9°47′30″ E and 9°53′0″ E as presented in Figure 1. It is the largest city in Bauchi state, which serves as both the state capital and the capital of the Bauchi Local Government Area [36]. The metropolis blends traditional and modern elements, reflecting its growth in infrastructure, commerce, and residential development. As a key hub for governance and economic activities in the region, Bauchi metropolis is vital to the state's economy. The study focuses on the six wards within the metropolis: Dan'iya, Dan'amar, Dawaki, Dankade, Hardo, and Makama [37,38].

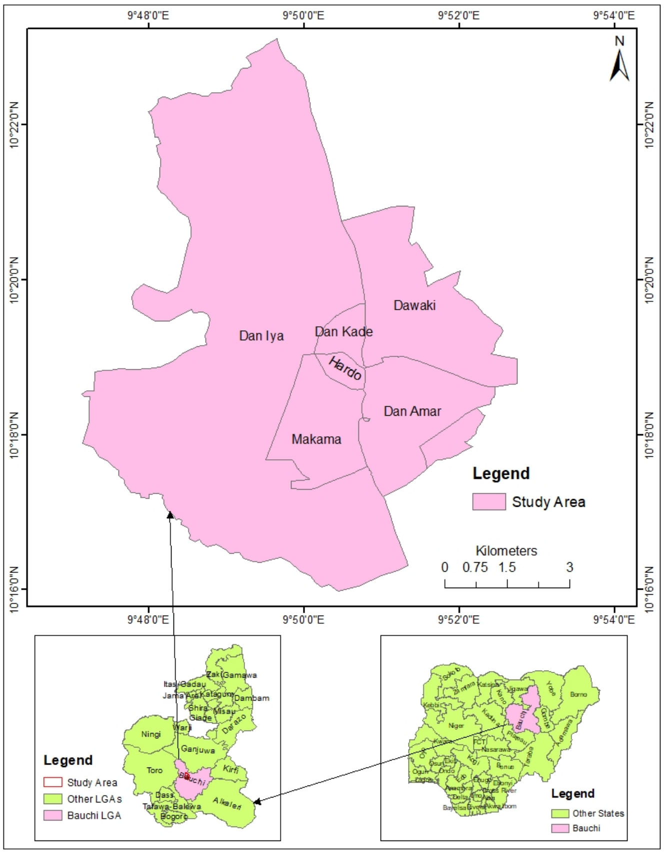

Figure 1. Map of the study area.

2.6. Data Collection

Data collection employed a robust, complementary dual-method approach to ensure that total consumption estimates were empirically grounded. The methods were a questionnaire survey and physical measurement using a weighing scale. The major advantage of the adopted approach is its applicability in settings where detailed household energy-monitoring infrastructure is unavailable. Combining questionnaire-based consumption information with physical measurement of locally used biomass-fuel units provides a practical means of converting locally reported fuel quantities into standardized mass and energy units. The approach also permits multiple energy sources to be assessed within a common analytical framework.

2.6.1. Questionnaire Survey

Semi-structured questionnaire were used to obtain the households demographic data and the estimated monthly energy consumption of these households, including the scope 1: charcoal in plastic bag (Kg); LPG in Kg; petrol in gallon; diesel in gallon; kerosene in gallon; firewood in Kg and sawdust in bacco sag (Kg) and the scope 2 emission source: electricity in kWh as commonly used within the households in the wards.

The questionnaires were researcher administered to the household heads or their representative in the respective wards. This allows any doubts the respondents may have about the questions to be clarified, ensuring that responses are accurate and complete.

2.6.2. Measurement

Using a weighing scale, physical measurements were carefully carried out to estimate the unit weight of firewood in Figure 2, charcoal in Figure 3, and sawdust in Figure 4, all measured in kilograms (Kg), as identified for use by households in the respective wards. To ensure consistency and reliability, all measurements were carried out by trained personnel, and each weighing scale was set to zero before measurements were carefully taken. The results were recorded and computed to obtain their respective average weights, which were then used in the study to determine the equivalent annual energy consumption for each energy source.

Figure 2. Weighing of firewood.

Figure 3. Weighing of charcoal.

Figure 4. Weighing of sawdust.

2.7. Data Analysis

The data analyses employed in the study were:

i. Descriptive statistics
ii. Carbon footprint analysis

2.7.1. Descriptive Statistics

Using IBM SPSS version 23, percentages, means, frequency distribution tables, and graphs were used to summarize and interpret the survey data, facilitating the achievement of the research objective.

2.7.2. Carbon Footprint Analysis

The carbon footprint analysis was achieved using data obtained from the estimated monthly household energy consumption as obtained from the households. The estimated monthly energy consumption was multiplied by twelve (12) months to obtain the estimated annual energy consumption. Meanwhile, the relevant conversion factors presented in Table 3 were used to convert these estimated quantities of energy sources used by households to energy equivalents.

Despite the 2019 refinement to the 2006 IPCC Guidelines, the default carbon emission factors remain largely unchanged from the 2006 Guidelines. Therefore, the 2006 IPCC emission factors and methodology as applied to the 2019 refinement [30,31] were employed to estimate the carbon emissions associated with the consumption of petrol, diesel, kerosene, LPG, firewood, charcoal and sawdust by the households as presented in Table 4 while, country specific emission factor for Nigeria electricity grid was adopted from [18] of 0.439 $KgCO_2$/kWh to estimate the carbon emissions associated with the consumption of electricity.

Table 3. Conversion factors.

S/No.	Energy	Energy Equivalent	Source
i	Electricity	3.6 MJ/kWh	[39]
ii	LPG	49.50 MJ/Kg	[39]
iii	Kerosene	36.6 MJ/L	[39]
iv	Charcoal	30.0 MJ/Kg	[39]
v	Fuel wood	16.20 MJ/Kg	[40]
vi	Diesel	38 MJ/L	[40]
vii	Petrol	34.2 MJ/L	[41]

Table 4. Default emission factor for residential.

S/No.	Fuel	Kg of GHG per TJ on a Net Calorific Basis		
		CO_2	CH_4	N_2O
i	Motor Gasoline	69,300	10	0.6
ii	Other Kerosene	71,900	10	0.6
iii	Gas/Diesel Oil	74,100	10	0.6
iv	Liquefied Petroleum Gases	63,100	1.5	0.1
v	Wood/Wood Waste	112,000	300	4
vi	Charcoal	112,000	200	1
vii	Other Primary Solid Biomass	100,000	300	4

To estimate the carbon footprint from the average energy equivalent of the respective energy sources by the households, Equation (3) was adapted from [30]. This is given as:

$$CF_{(\text{Energy source})} = QEC \times EF_{CO2} \tag{3}$$

where, CF: Carbon Footprint of a particular energy source; QEC: Quantity of energy consumed; and EF: Emission Factor of a particular energy source

3. Results

3.1. Household Demographics

Table 5 presents the sociodemographic data, including gender, marital status, age, educational level of household heads, and the number of household members (household size). The findings indicated that 338 (83.9%) of the household heads are male, while 65 (16.1%) are female, indicating that most of the household heads are male. The marital status indicated that 309 (76.7%) household heads were married, 42 (10.4%) were single, 34 (8.4%) were widows, 8 (2%) were divorced, and 10 (2.5%) were separated, indicating that the assessed households were predominantly headed by married persons. The age ranges indicated that young adults aged 18–44 years constituted the highest proportion, with 199 (49.4%), followed by those aged 45–64 years, with 161 (40%), indicating that most household heads were within the young and middle-aged groups. The educational levels indicated that those with tertiary education constituted the highest proportion, with 247 (61.3%), indicating that most household heads had relatively high educational attainment. The results also revealed that 146 (36.2%) households had 6–10 household members, followed by 127 (31.5%) households with 1–5 members, indicating that medium-sized households were the most prevalent among the assessed households.

Table 5. Household socio-demographic data.

S/No.	Factors	Options	Frequency	Percentage (%)
i	Gender	Male	338	83.9
		Female	65	16.1
		Total	403	100
ii	Marital status	Single	42	10.4
		Married	309	76.7
		Widow	34	8.4
		Divorced	8	2
		Separated	10	2.5
		Total	403	100
iii	Age	18–44 Years	199	49.4
		45–64 Years	161	40
		≥65 Years	43	10.7
		Total	403	100
iv	Educational Level	None	9	2.2
		Informal	22	5.5
		Primary	28	6.9
		Secondary	97	24.1
		Tertiary	247	61.3
		Total	403	100
v	Household size	1–5	127	31.5
		6–10	146	36.2
		11–15	67	16.6
		16–20	43	10.7
		≥21	20	5.0
		Total	403	100

3.2. Estimation of Average Annual Energy Consumption

This section presents the analysis of the estimated average annual energy consumption of the various energy sources identified by the households. Data were extracted from the questionnaire on the households' estimated monthly energy consumption, which was multiplied by twelve (12) months to obtain the annual energy consumption. The monthly and annual energy consumptions were presented in Tables 6 and 7, respectively.

3.2.1. Monthly Energy Consumption

Table 6 presents the estimated average monthly quantity of the different energy sources used by households for different tasks. Results revealed that 40 households consume 187 gallons of diesel, with a mean of 4.68 gallons per household; 349 households reported consuming 27,039 plastic bags of charcoal (15,682.62 kg) per month (commonly sold at 200 naira per plastic bag and weighing an average of 0.58 kg each). On average, each household consumes 77.48 plastic bags of charcoal (44.94 kg) per month. 316 households reported consuming 19,219 bundles of firewood (68,227.45 kg) per month (commonly sold at 300 naira per bundle and weighing 3.55 kg each). The mean consumption was 60.82 bundles (215.91 kg) per household per month. 50 households consume 159.2 gallons of kerosene, with a mean of 3.18 gallons per household; 86 households consume 545.7 gallons of petrol, with 6.35 gallons of petrol per household; 366 households consume 55,303.15 kWh of electricity, with a mean of 151.10 kWh per household; 162 households consume 3419.3 kg of LPG, with a mean of 21.11 kg per household; and 1 household consumes 140.94 kg of sawdust (three bacco sags, 46.98 Kg each), with a mean of 140.94 kg per household per month. These findings indicate a substantial reliance on electricity and biomass energy sources among the assessed households.

Table 6. The quantity of energy consumed per month.

S/No.	Energy Source	Frequency	Sum	Mean	Unit
i	Diesel	40	187.0	4.68	Gallon
ii	Charcoal	349	15,682.62	44.94	Kg
iii	Firewood	316	68,227.45	215.91	Kg
iv	Kerosene	50	159.2	3.18	Gallon
v	Petrol	86	545.7	6.35	Gallon
vi	Grid electricity	366	55,303.15	151.10	KWh
vii	LPG	162	3419.3	21.11	Kg
viii	Sawdust	1	140.94	140.94	Kg

3.2.2. Annual Energy Consumption

The estimated monthly energy consumption obtained in Section 3.2.1 was computed in this section to obtain the estimated annual energy equivalent and the average annual energy equivalent consumption for various energy sources identified. Conversion factors in Table 3 were used to convert each of the estimated energy sources to energy equivalent. The estimated monthly energy equivalent was multiplied by twelve (12) months to obtain the estimated annual energy equivalent consumption for the respective energy sources in mega joules (MJ). Furthermore, the annual energy equivalents for the respective energy sources were divided by the number of households that consumed each to obtain the estimated annual energy-equivalent consumption for each energy source. The computed results were presented in Table 7.

Table 7. Computation of average annual energy equivalent consumption.

S/No.	Energy Sources	Frequency	Quantity per Month	12 Months per Year	A.E.E. (MJ)	A.A.E.E. per HH (MJ)
i	Firewood	316	68,227.45 Kg	818,729.4 Kg	13,263,416.28	41,972.84
ii	Sawdust	1	140.9 Kg	1690.80 Kg	27,390.96	27,390.96
iii	Charcoal	349	15,682.62 Kg	188,191.44 Kg	5,645,743.20	16,176.91
iv	Petrol	86	2480.75 L	29,769.00 L	1,018,099.80	11,838.37
v	LPG	162	3419.3 Kg	41,031.6 Kg	2,031,064.2	12,537.43
vi	Diesel	40	850.10 L	10,201.20 L	387,645.60	9691.14
vii	Grid electricity	366	55,303.15 kWh	663,637.8 kWh	2,389,096.08	6527.58
viii	Kerosene	50	723.72 L	8684.64 L	317,857.82	6357.16
	Total				25,080,313.94	132,492.39

HH = Household; A.E.E. = Annual Energy Equivalent; A.A.E.E. = Average Annual Energy Equivalent per household.

Table 7 presents the computation of the annual energy consumption for the various energy sources identified as used by households in the Bauchi metropolis. This is further explained in Figures 5 and 6.

Figure 5 presents the estimated average annual quantity of the respective energy sources consumed per household in a common unit of energy, megajoules (MJ). These results were presented in descending order, where firewood (41,972.84 MJ), sawdust (27,390.96 MJ), and charcoal (16,176.91 MJ) had higher energy equivalents consumed per household, while the least consumed energy sources were diesel (9691.14 MJ), grid electricity (6527.58 MJ), and kerosene (6357.16 MJ) per household. However, the estimate of solar energy consumption was excluded because of its zero-emission nature. These findings indicate that firewood, sawdust, and charcoal constituted the major energy sources in terms of energy equivalent consumed per household.

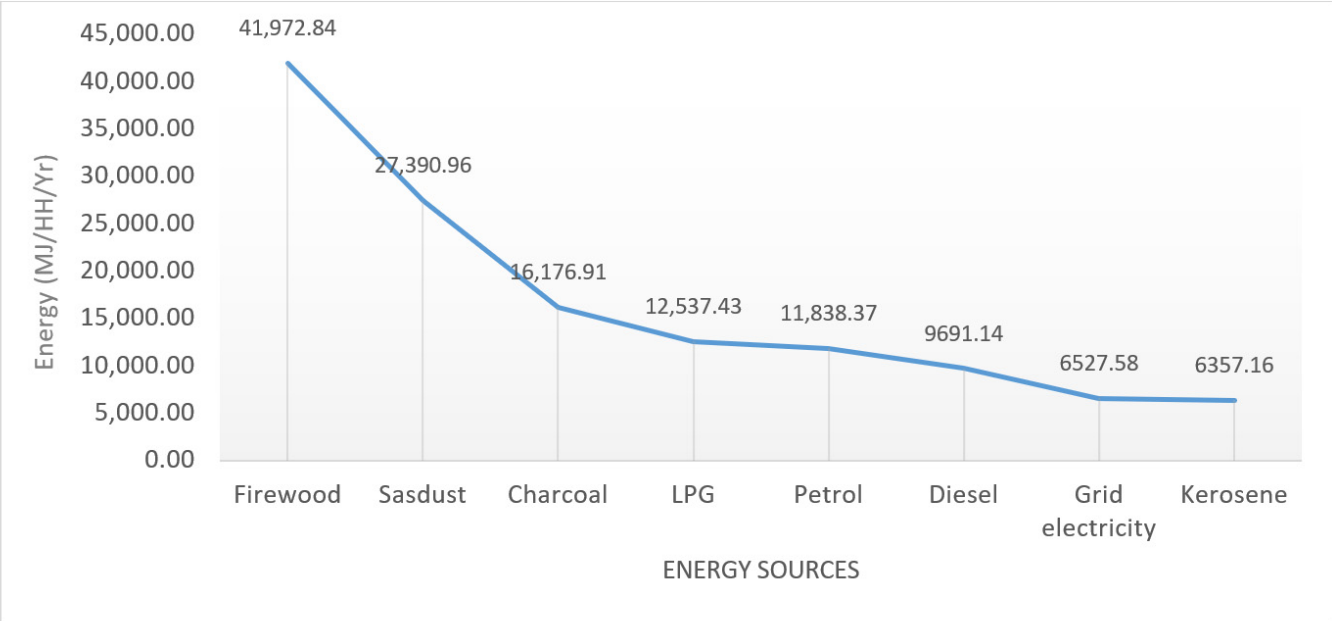

Figure 5. Average annual energy equivalent consumption of the different energy sources per household.

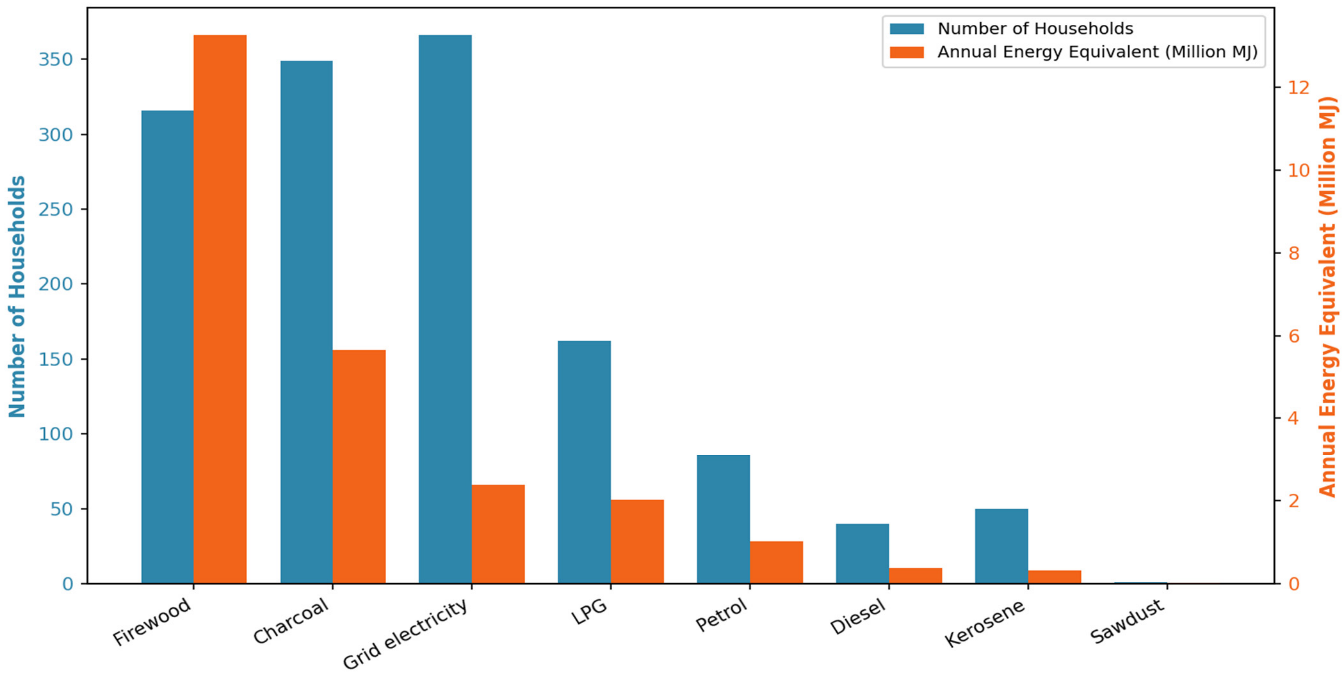

Figure 6. Annual energy equivalent consumption.

Table 7 also presents the annual energy equivalent consumption by households. These present that 316 households consumed 13,263,416.28 MJ of firewood, 349 households consumed 5,645,743.20 MJ of charcoal, 366 households consumed 2,389,096.08 MJ of grid electricity, 162 households consumed

2,031,064.20 MJ of LPG, 86 households consumed 1,018,099.80 MJ of petrol, 40 households consumed 387,645.60 MJ of diesel, and 1 household consumed 27,390.96 MJ of sawdust. This is graphically presented in Figure 3. These findings indicate that firewood accounted for the highest annual energy equivalent consumption among the assessed households, followed by charcoal and grid electricity.

Therefore, to obtain the average annual energy consumption per household in the Bauchi metropolis from the consumption of the various energy sources identified, the total annual energy equivalent (25,080,313.94 MJ) was divided by the total number of 403 households analysed. This gives an average annual energy consumption of 62,234.03 MJ per household from the consumption of firewood, charcoal, grid electricity, LPG, petrol, diesel, kerosene, and sawdust.

3.3. Analysis of Carbon Footprint Associated with Households Energy Consumption

The carbon footprint associated with household energy consumption was analyzed based on the types and quantities of energy sources consumed by households. The analysis presents the estimated average annual carbon emissions attributed to each energy source and the overall average annual carbon emissions per household. These are presented below in Sections 3.3.1 and 3.3.2, respectively.

3.3.1. Average Annual Carbon Emission per Household by Energy Source

The study aimed to establish the carbon footprint of households associated with their energy consumption. Using the estimated average annual energy equivalent consumption per household obtained in Table 7 for the various energy sources, the associated carbon footprint was estimated using the 2006 IPCC provisional guide [30] for firewood, charcoal, sawdust, petrol, LPG, diesel, and kerosene. While for the grid electricity, a specific emission factor for Nigeria was adopted from [18] of 0.439 $KgCO_2$/Kwh. The computed results are presented in Table 8.

Table 8. Average annual carbon emission by each energy source.

S/No.	Energy Source	Frequency	A.A.E.E./HH (MJ)	A.A.E.E./HH (TJ)	tCO_2/HH/Yr
i	Firewood	316	41,972.84	0.0420	4.70
ii	Sawdust	1	27,390.96	0.0274	3.07
iii	Charcoal	349	16,176.91	0.0162	1.81
iv	Petrol	86	11,838.37	0.0118	0.82
v	Grid electricity	366	6527.58	0.0065	0.80
vi	LPG	162	12,537.43	0.0125	0.79
vii	Diesel	40	9691.14	0.0097	0.72
viii	Kerosene	50	6357.16	0.0064	0.46
	Total			0.1325	13.17

A.A.E.E. = Average Annual Energy Equivalent; HH = Household; MJ = Megajouls; TJ = Terajouls; Yr = Year.

Table 8 shows the estimated average annual quantity of carbon emissions associated with the consumption of the various energy sources by households for each of the energy sources. These showed firewood (4.70 tCO_2), sawdust (3.07 tCO_2), charcoal (1.81 tCO_2), LPG (0.79 tCO_2), diesel (0.72 tCO_2), and kerosene (0.46 tCO_2) had the least emissions per household annually. This is further explained in Figure 7, in descending order.

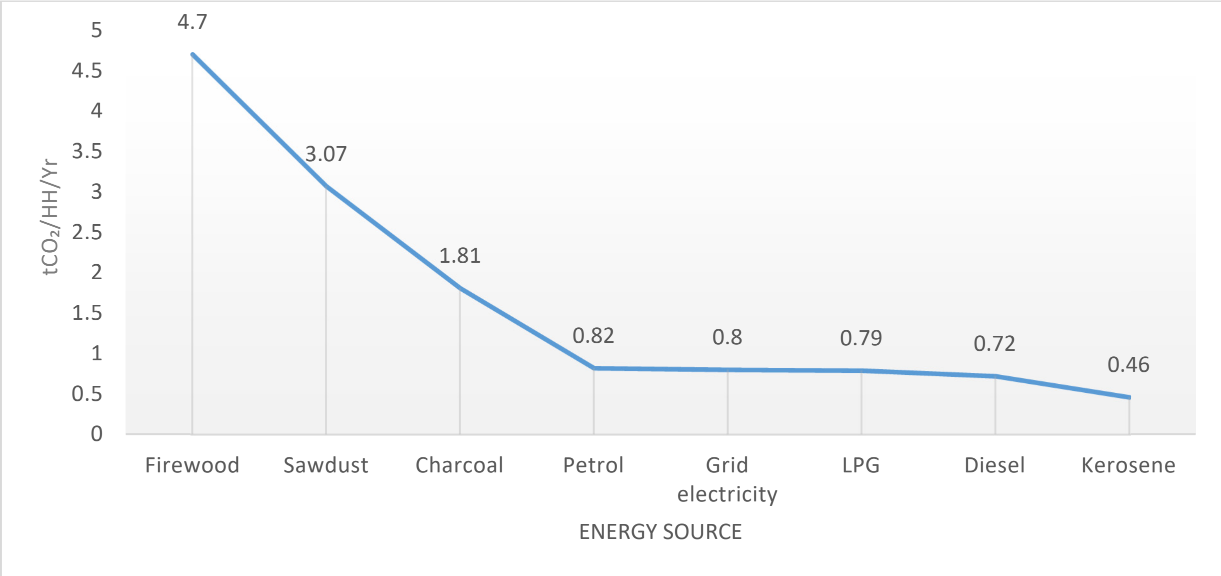

Figure 7. Average annual carbon dioxide emission.

3.3.2. Average Annual Carbon Emission per Household

To obtain the average annual carbon emission per household from the eight energy sources identified and the quantities obtained, using a weighted average, the average annual carbon emission by each of the energy sources was multiplied by the number of households using them. The total carbon emission from these energy sources was divided by the total of 403 households assessed. Table 9 presents the various energy sources and their respective quantity of carbon emissions. This shows that 316 households emit 1485.20 tCO_2 of firewood, 349 households emit 631.69 tCO_2 of charcoal, 366 households emit 292.80 tCO_2 of grid electricity, 162 households emit 127.98 tCO_2 of LPG, 86 households emit 70.52 tCO_2 of petrol, 40 households emit 28.80 tCO_2 of diesel, 50 households emit 23.00 tCO_2 of kerosene, and 1 household emits 3.07 tCO_2 of sawdust annually. The total carbon emission by the households was 2663.06 tCO_2 per annum. Therefore, the average carbon emissions per household from the use of these energy sources were estimated at 6.61 tCO_2 annually.

Table 9. Average annual carbon footprint.

S/No.	Energy Source	Frequency	Average per Household	Total tCO_2/Yr
i	Firewood	316	4.70	1485.20
ii	Charcoal	349	1.81	631.69
iii	Grid electricity	366	0.80	292.80
iv	LPG	162	0.79	127.98
v	Petrol	86	0.82	70.52
vi	Diesel	40	0.72	28.80
vii	Kerosene	50	0.46	23.00
viii	Sawdust	1	3.07	3.07
	Total			2663.06

4. Discussion

The sociodemographic responses of the respondents' gender, marital status, age, educational level of household heads, and the number of household members (household size) show that most of the household heads are male, with the highest frequency of 338 (83.9%). This relates to the findings of [42–44], which show that household heads are mainly male, a pattern attributed to the cultural background of the people, where males are usually the heads of the family. According to [12], households are more likely to adopt cleaner energy sources when the head of the household is male; therefore, the lower the energy consumption.

The marital status of the respective household heads showed that most of the household heads were married, with the highest frequency of 309 (76.7%), which agrees with the finding by [45], with less expenditure on energy consumption [46].

The results of the age ranges of the household heads reveal that the age of the household heads falls mostly within the age category of 18–44 years, 199 (49.4%), which relates to the age category of young adults [47]. This is the converse of the finding that older household heads are less likely to switch to cleaner energy sources [36,48], which implies that young adults are more adaptable to cleaner energy sources; therefore, energy consumption is lower.

The results showed that most household heads have a tertiary education, with the highest frequency being 247 (61.3%). This relates to the findings by [45], where the household heads majorly have Diploma/NCE, followed by B.Sc./HND qualifications, with a substantial number having postgraduate qualifications, which implies that the majority of the household heads are literate. According to [12,36], the educational attainment of household heads influences energy choices, with higher levels of education associated with a greater likelihood of adopting cleaner energy, therefore expecting lower energy consumption.

The results of the household size show that most of the households have 6–10 household members, with the highest frequency of 146 (36.2%). However, the finding is in little contrast to the findings by [49], where the household size is mainly less than 5, followed by the range of 6–10 household members. According to [12,36], household size impacts energy consumption decisions, as larger households are less likely to switch to or use modern energy sources, possibly due to higher costs, resource constraints, or differing energy needs compared to smaller households.

The high energy consumption of firewood corroborates the findings by [50], where, in Nigeria, the high consumption of firewood was attributed to poverty and availability. Nevertheless, the high consumption of these energy sources results in deforestation, contributing to the effects of global warming. However, few studies have tried to estimate a collective aggregate of energy consumption by households, and these are usually for a specific task. For instance, Ref. [44] estimated the quantity of energy consumption for cooking, where the estimated consumption of firewood was 31.05 kg, ranked higher, followed by charcoal at 24.97 kg, kerosene at 11.31 kg (13.80 L), and LPG at 8.33 kg, the least per month. Therefore, this study provides a more holistic estimate of energy equivalent consumption by households in the Bauchi metropolis for various purposes.

However, on average, the carbon footprint of households in Bauchi metropolis was estimated to be 6.61 tCO_2 per household. This shows that some of these households emit less or greater than this average. The result also shows the need for targeted mitigation measures to curb these emissions, especially from the use of firewood and charcoal, in order to prevent further emissions and negative environmental impacts. In a rare similar study recently conducted in Nigeria (Benin City), it was revealed the carbon footprint range between 0.1 to 57.2 tCO_2 per household with most of the households' carbon footprint ranging 2.72 to 7.26 tCO_2, except for a few (1%) households that exceeded this range [19].

International studies demonstrate that household carbon emissions vary considerably according to energy use patterns, socioeconomic conditions, and local energy systems. In Guangzhou, China [20], based on 1097 households, reported average household carbon emissions of 15.31 kg CO_2/day, equivalent to approximately 5.59 tCO_2/year, with water heating, kitchen equipment, and refrigeration being the major energy consuming activities. In the United States, Ref. [21] estimated residential energy-related emissions at 2.83 ± 1.0 tCO_2e per capita/year from the use of electricity and heating fuels. In India, Ref. [23] reported an average annual household carbon footprint of 2.33 tCO_2e for urban households, compared with 1.13 tCO_2e for rural households, with electricity accounting for the largest share of urban emissions. Compared with these studies, the present study estimated 6.61 tCO_2 per household/year, based specifically on CO_2

emissions from household energy consumption. These values provide a useful contextual basis for comparison; however, they are not directly equivalent because the studies differ in functional units, emission metrics, emission boundaries, energy sources assessed, and household characteristics. Specifically, the present study reports CO_2 emissions per household/year, whereas the cited studies [21,23] report CO_2-equivalent emissions per capita/year. Therefore, the reported values should not be interpreted as directly comparable measures of the same emission metric or functional unit. Nevertheless, the comparison demonstrates that household carbon emissions are strongly context dependent and reflect differences in energy systems, living conditions, and patterns of household energy use.

5. Conclusions

5.1. Main Findings and Contribution

The study established the average annual carbon footprint of 6.61 tCO_2 per household from the use of firewood, charcoal, grid electricity, LPG, petrol, diesel, kerosene, and sawdust. However, high emissions were attributed to the use of firewood and charcoal by the households, which implies a serious negative impact on the environment due to deforestation, the high potential for global warming, and climate change.

The study contributes empirical evidence on household energy-related CO_2 emissions in Bauchi metropolis, identifying firewood and charcoal as major contributors and providing a basis for cleaner energy transitions and emission-reduction strategies.

5.2. Policy Recommendation

The baseline data from 403 households are highly actionable for the Bauchi State Ministry of Housing and Environment. They provide immediate evidence to inform policy formulation, targeted interventions, and emission reduction planning, and to promote sustainable energy alternatives in direct support of the Ministry's climate mitigation goals. Therefore, this data prioritizes the transition from firewood and charcoal to LPG, electricity, and feasible renewable-energy alternatives. In addition, affordable financing, targeted subsidies, reliable LPG supply, safety education, improved biomass cookstoves, and sustainable biomass-management programmes should support this transition.

5.3. Limitations

The study adopted the 2006 IPCC carbon emission factors due to a lack of Nigeria country specific emission factors, except for electricity. The study does not account for emissions from torchlight batteries due to the unavailability of applicable emission factors. Non carbon dioxide GHGs produced from fuel combustion, such as methane (CH_4) and nitrous oxide (N_2O), were not included in the analysis due to the lack of applicable emission factors for electricity related CH_4 and N_2O emissions. However, emissions associated with these are not significant.

The data collected encompass the energy sources used, the quantity consumed per month, and relevant household characteristics. Meanwhile, data collection excludes fuel consumption by household vehicles, as they are used outside the buildings. The study excluded the estimation of energy consumption from the use of solar home systems due to their zero emission ability. Data were collected during the dry season from November 2024 to January 2025. The respondents were requested to provide their average monthly household energy consumption for a typical month, regardless of the month in which they provided the information. However, recall bias and the seasonal context during the dry/harmattan period may have influenced responses.

Additionally, the study was confined to functional residential buildings within Bauchi metropolis, including Hardo, Dan'iya, Da'amar, Dawaki, Dankade, and Makama wards, specifically targeting conventional flats and apartments, given that larger households consume more energy, which may not accurately represent the energy consumption profiles of alternative housing types within the metropolis.

5.4. Future Research

Future research includes:

Future work 1: While the current study identified firewood and charcoal as priority areas for reducing household carbon emissions, future research should investigate the feasibility and spatial constraints of scaling up cleaner energy alternatives, particularly renewable energy, to support the transition from traditional biomass fuels in Bauchi metropolis. For example, Ref. [51] highlights that while solar and wind energy drastically reduce CO_2 emissions, they require significantly more land than conventional power plants. Future studies could therefore assess land use limitations and the availability of suitable spaces for deploying renewable energy infrastructure to support the replacement of biomass energy use among households in Bauchi metropolis.

Future work 2: To successfully reduce greenhouse gas emissions associated with household electricity consumption and backup generators, future research should investigate the integration of energy storage systems with renewable energy infrastructure. Future studies should reference [52], which notes that grid scale battery energy storage systems (BESS) are essential for storing variable renewable energy. Evaluating the feasibility, regulatory requirements, and market frameworks for BESS could provide a roadmap for improving reliable, low carbon electricity supply to households in Bauchi metropolis and reducing dependence on emission intensive energy sources.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

In this work, the author(s) utilized artificial intelligence (AI) tools (Grammarly and ChatGPT) to refine writing, reduce errors, and improve clarity. After using this tool/service, the author(s) evaluated and revised the content as necessary and take full responsibility for the published content."

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Author Contributions

Conceptualization, P.P.I., B.M.M. and A.M.S.; Investigation, P.P.I.; Data Curation, P.P.I.; Formal Analysis, P.P.I. and E.C.I.; Validation, P.P.I.; Resources, P.P.I.; Writing—Original Draft Preparation, P.P.I.; Writing—Review & Editing, P.P.I., B.M.M., A.M.S., E.C.I. and E.C.E.; Supervision, B.M.M. and A.M.S.

Ethics Statement

Ethical review and approval were not required for this study because it involved only a voluntary questionnaire survey, and informed consent was obtained from all participants.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study. These include: the Department of Building, Ahmadu Bello University Zaria; Bauchi Town District Head Office; National Population Commission Bauchi state branch head office, and household heads/representatives.

Data Availability Statement

Data will be made available by the corresponding author on request.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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