The Seasonal Effects of Weather on Residential Electric-Energy Usage

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Abstract

Climate change is one of two major challenges humans face in the 21st century. At the heart of climate change is global warming which directly affects the ecology, rainfall, temperatures, and weather systems of all cities. Despite the foregoing, not much research has been conducted in Ghana to assess the effects of the changing weather conditions on residential electric energy consumption. Significant literature exists envisaging probable influence of rising temperatures on residential electric-energy usage, mainly through the use of air conditioning and other mechanical means for cooling. This is expected to be significant especially in developing countries with tropical climates. Currently, 32% of the country's electricity is consumed by the residential sector. This percentage is anticipated to increase by the end of the decade; considering the existing housing deficit, the rate of urbanization as well as the increasing demand for household appliances. This study assessed the influence of the weather on Ghanaian residential electricity consumption. Empirical enquiries published in peer-reviewed journals and related literature were reviewed. Electricity billing data for twelve calendar months of 153 purposively selected households in Ghana were collected. Weather data for the twelve calendar months were also collected and Microsoft Excel software was used to analyze the frequencies and means of the data. SPSS Spearman's correlation was also used to establish the relationships between the variables. The results suggest a rather weak correlation (r=0.311) between the weather conditions and residential electric energy usage. The lower economic capacity of occupants and minimum variations in monthly temperature could be the reasons for this. Future studies could focus on establishing the extent of these factors on energy usage. However, the highest and lowest electricity consumptions coincide with the highest and lowest temperature, sunshine and relative humidity. This is critical for adequate electric energy supply and peak load factor forecast.

Keywords
Climate Change, Electric Energy, Residential Homes, Electricity Billing Data, Effects

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1. Introduction

Climate is one of the major drivers of electric-energy usage in buildings and it is considered as the weather's statistics for a geographical area over a typical interval of 30 years and determined through the valuation of the differences in the patterns of temperature, precipitation, wind, humidity, atmospheric pressure and other elements [1, 2, 3]. In analyzing climatic impacts on countries, these research works cautioned on the need to bear in mind the unique possibility of having multiple climatic zones within most countries. For instance, Ghana has the coastal belt, forest belt and the savannah belts as the three major climatic belts with each having unique weather conditions and hence requiring distinctive design interventions. Considering the probable significant impact of the weather on occupants' comfort in buildings, the designing and construction of buildings must factor the uniqueness of the weather. For the most part of the day, the external environment is not conducive to human comfort and hence buildings are expected to provide occupants with a more comfortable indoor environment. The provision of buildings come along with demand for electric energy, for their systems and services. Anthropogenic factors, through energy-related fossil fuels burning, have been the major cause of greenhouse gases (GHGs) and consequently the changes in climate globally [4]. They further argued that from 1750, the net average activities of humans have to be blamed for the effects of climate change, which has become one of the major problems of humanity in recent times. The high concentrations of CO2 emissions, as well as other GHGs in the atmosphere, are therefore major causes of climate change globally [5], [6].

The Inter-Governmental Panel on Climate Change (IPCC)'s report during its Fourth Assessment indicated an estimated CO2 equivalent emissions volume of 8.6 million metric tons being attributable to building-related GHGs and further cautions on the deteriorating rate of GHG emissions [7]. Suffice it to indicate that a major reduction in the energy buildings consumes globally, and for that matter, Ghana will be a major step in controlling climate change. The IPCC indicated that the commercial building sector from 1971 to 2004 had 2.5% growth rate in the emissions whereas the residential building sector experienced an estimated growth of 1.7% and if efforts were not taken to curb this, it could reach a double of 15.6 billion metric tons CO2 equivalent by 2030. It is therefore worth emphasizing the important role of the residential sector towards achieving reductions in GHG emissions globally. The urgency of such reductions sterns from the fact that the change in climate has resulted in significant changes in the distribution and volume of rainfall patterns, with weather conditions that are very extreme for humanity [8]. If these situations are left uncontrolled within the immediate future, man's comfortable existence on earth may be compromised.

Building occupants are more likely to become conscious of the relationship between electric energy usage in buildings and the climate, due to the outcomes from the IPCC reports [9]. The IPCC report presented evidence to confirm the contributions of building-related energy usage to GHGs emissions and subsequently global warming. As a result of such consciousness, climate change and efficient usage of energy have become issues of global concern. [10]. These have become urgent and necessary considering the increasing rate as well as the worsening impact of our demand for energy on the environment making it imperative to use energy efficiently. In relation to the other key contributors to GHGs emissions, the building sector could ensure substantial reductions globally and further indicated that with even a potential net profit in the life of the building, reductions between about 30 and 80 percent could be achieved with the tested systems that exist worldwide [3]

In lieu of the above, it is evidently clear that reducing electricity consumption is the most rational monumental effort that could be targeted at reducing GHGs and ultimately reduce the effect of global warming. There could be substantial reductions in electricity bills as well as carbon footprints if electric energy consumption could be reduced, targeted at curbing the worsening conditions of climatic change [11]. Hence, one of the most economical means of addressing this problem is reducing the amount of energy we consume (waste) in buildings [12]. Ghana has experienced an increased demand for electric energy in the residential sector over the years and currently consumes about 32% of the electricity in the country [13]. In that regard, efforts targeted at reducing the extent of end-use consumption (and wastage) must be well embraced.

In a research conducted on climate change and the effects on rising global temperatures, the findings presented suggest that its effect in Europe on electric energy is rather positive since residential homes are reducing their expenditure on electricity for heating especially in the winter months [14]. This is an important benefit since heating loads constitute the major component of energy use profile in the temperate parts of the world. This point was also emphasized by [1] who maintained that the increasing temperatures making summers hotter as well as making winters less cool, had significant impacts on electricity demand in residential homes. However, they indicated that most developing countries, which also happen to be in the tropics, are at a higher risk of experiencing increased energy usage due to increased cooling load demand in their homes. A similar argument was posited in a research, where there was an economic analysis of climate change using weather data and climate models [15]. They maintained that as the environment worldwide gets hotter, the demand for cooling is expected to rise especially in the tropics whereas the heating demands also reduce in the temperate areas. Among the various drivers that determine end use of residential electric energy usage, the climate is one of those that are beyond the control of the occupant making it critical and requiring sustainable interventions in residential homes.

A study into how developing countries will react to energy demand with reduced prices of ACs and increases in household incomes found that there is the expectation for generations in the future to install more air conditions in their homes [16]. Studies into residential demand for electricity due to the climate in California and the demand for ACs for cooling in China respectively argued that there is significant literature to show that climate change will substantially cause more households to depend on ACs for cooling purposes especially in the tropics [17, 1]. In a study where how energy consumption is impacted by climate change was modelled, it was established that there was a linear correlation between weather and energy in the residential sector in China [18]. If these predictions occur, that may lead to a continuous cycle of worsening the global warming situation. However, it is worth mentioning that, considering the current income levels in Ghana in tandem with the depreciation of the cedis to the dollar, the effect of income elasticity as well as rising cost of the

ACs may rather not offer the expected significant increase in the demand as posited by the various research works. Notwithstanding the fact that countries like Western Europe, North America, Eastern Europe, Caucasus, and Central Asia have over the years been responsible for most of the GHGs emissions globally, it is being predicted that by 2030, that of all developing countries may exceed that of the above countries [3]. This, therefore, requires urgent strategies by all through the efficient use of energy which may contribute to reducing the rate at which GHGs are being emitted into the environment and the effects of global warming.

In April 2018, Cape Town, the second largest city in South Africa was expected to be approaching “day zero”, the day when taps in the city run dry following the effects of climate change [19]. Such occurrences reemphasize the realities of climate change and the impacts on countries if left uncontrolled. The deteriorating effects of climate change, therefore, calls for a holistic approach to assess the correlation between the weather and electric energy usage in the residential sector of Ghana. The aim of this study was, therefore, to evaluate how the changes in the weather conditions are influencing the residential sector energy consumption in Ghana throughout the year. This was done by analyzing the energy consumption data of selected homes and recommendations were proposed through the incorporation of sustainable design measures including the following; i) required solar orientation of buildings, ii) shading of windows and walls facing the East and West, iii) cross-ventilation of rooms (open architecture), for Ghanaian residential homes. Providing sustainable electric energy for Ghana is one of the fundamental factors needed for the economy to develop progressively both in the short and long run. For most governments of today, there is the urgent need to be able to predict the future demand for electric energy to ensure sustainable investments in energy generation, supply, and use.

It is also imperative for building industry professionals to design and construct buildings that respond to the changes in climatic conditions to offset the effects on indoor comfort as well as adequately prepare the energy supply sector to meet the expected demand for energy due to the weather effect and ultimately climate change.

2. Weather effect on the building envelop

The barrier between the outdoor and indoor environment for occupants, known as the building envelop, influences the effect of rising temperature on occupant comfort. The building envelop comprises of the external components of the structure in the form of the walls, roofs, windows and doors. They are the parts of the building that is in direct contact with the external environment. The building envelop is one of the major contributors to energy usage and hence as the climate of the external environment gets hotter it becomes imperative to improve the performance of the envelope in order to ensure the required thermal comfort conditions indoor for occupants. The building envelops significantly contributes to energy consumption in building and hence as the external climate gets hotter the performance of the building envelope has to be improved to facilitate the assurance of thermal comfort conditions indoors for occupants [20].

Impliedly, with such improvements in the performance of the building envelop, heat transfer indoors through conduction and convection may be reduced significantly which may ultimately reduce internal heat loads for occupants. In a research into the “Impact of climate change on residential building envelope cooling loads in subtropical climates” where they assessed the response of building envelop changes to the worsening global climate, they concluded that, the increased demand for electricity in tropical climatic zones could be mainly due to the increased demand for air condition usage due to the increased temperatures [21].

Significant benefits in the form of energy efficiency savings were achieved when occupants undertook improvements in the envelope of their buildings [22]. The study further specified that though such improvements could cost the building owner or user, the corresponding energy savings acquired could ensure a faster payback time. To encourage occupants to undertake such improvement in Ghana, government, Energy Commission and financial institutions could adopt pre-financing packages for users to pay over a period of time. This could go a long way in reducing the rate at which buildings consume electric energy. In a study using hourly energy consumption data in Pennsylvania, New Jersey, and Maryland for assessing the response of electricity usage from temperature effects across the States, they managed the effects on a time basis and considered temperature in the form of cooling and heating degree days. Their research indicated that the real consumption of energy rose by 3.8% due to a 2°C rise in temperature [23]. The situation in Ghana could be much higher considering the high rate at which daily temperature rises and hence the need to motivate occupants to embark on building envelop improvements. When buildings adopt thermal insulation systems, significant reductions from 65% to 75% could be made in solar radiation heat transfer into buildings [24]. This implies a significant reduction of indoor heat loads which occupants have to deal with.

The direct exposure of a building’s roofing to the adverse climatic conditions makes the roof the most fundamental factor for thermal distress in buildings, since most of the solar heat gain into the building form is from there. This results in increasing the cooling load energy for the air-conditioned building. ([24], [25]). Depending on the climatic conditions within which a building is located, the features of the building in question and that of the roof, there could be major energy savings with the adoption of green roofs, through the absorption and insulation of heat [11]. Architects and building industry professionals in Ghana, therefore, need to begin focusing on thermal insulation improvements of roofing for both new and existing buildings to reduce the internal heat loads transferred through the roofing.

It is worth emphasizing that, windows as critical design components play a major role in allowing in natural daylight, providing cross-ventilation and offering occupants views to the outdoor space. However, if care is not taken in positioning them on the facades of the buildings they could compromise the comfort levels of the occupants through solar heat transfer. Ventilation and indoor air quality could be enriched by increasing the window to wall ratios (WWR) [26]. However, they signalled that whiles applying that, they should be considered bearing in mind their weakness as a material with solar heat gain into buildings. In line with this point, a research into exploring the impact of different technologies and designs for building envelops cladding on urban heat gain in the built environment, argued that having large windows could considerably add to the increased indoor temperature and discomfort of buildings especially those located on the east and west facades [27]. Further to this, they recommended reduced window areas, especially in hot climatic regions. This is very important in tropical climates where for the most part of the day, the weather is beyond the required comfort zone of occupants and hence allowing extreme exposure of the weather to the indoor spaces could negate the comfort levels of occupants. As a solution to such problems and achieving thermal comfort and energy efficiency in buildings, rooms facing east or west must have minimum windows with some level of shading since these facades receive the highest level of incident radiation [26].

2.1 Climate in Ghana

Ghana's climate is tropical in nature with the dry and wet seasons being the two key seasons. The country experiences the harmattan which is characterized by dry desert winds between December and March from the North-East trade winds. It also comes along with high diurnal temperature whereas the nights come with a cool temperature. The rainfall patterns also vary throughout the country with the savanna regions experiencing the lowest rainfall. The country experiences temperatures between 21°C to 28°C with 77% relative humidity [28]. One of the effects of climate change globally is rising temperature which plays a major role in thermal stress. It is estimated that there will be 4.0°C increase in mean temperature globally, which will be within the range from 2.4–6.4°C [1]. It has also been estimated that the situation in Ghana will increase in 2020 by 0.6°C, then 2.0°C in 2050, whereas that of 2080 will be 3.9°C over the mean value between 1961 and 2000 [29]. Additionally, the situation of rainfall is also similar for the same period between 1961 and 2000, where it is expected that precipitation will reduce between 1.1% and 3.1% over the entire ecological regions by 2020 whereas by 2080 it will be between 13 and 21%. Between 1950s-1980s, there was a general reduction in sky surface solar radiation, the trend was different from the 1990s where solar radiation started increasing steadily [30]. In this line, the prediction is that by 2080, solar radiation daily will rise by an average of 0.5 MJm-2d-1 in Ghana [29]. Considering the increase in temperature, reduction in rainfall, as well as an increase in solar radiation, thermal comfort levels of building occupants, will reduce. Increasing temperature means that the air temperature will be getting hotter beyond the comfort levels of occupants. Reductions in rainfall will also come along with less cool seasons as well as reduced relative humidity which will also directly affect thermal comfort. The case of increased solar radiation will also make the atmosphere hotter which will also push occupants into thermal stress. These factors, in combination, will, therefore, cause occupants to resort to mechanical and other technological means, which are electric energy dependent, for achieving thermal comfort. There is, therefore, the need to assess the weather effect on energy consumption of residential homes in Ghana.

2.2 Residential electricity consumption in Ghana

The consumption of electric energy in Ghana has been consistently rising over the past decade. As captured in Figure 1.0 as at 2005, the residential sector was consuming about 1,956 (GWh) of the total electricity produced 5,259 (GWh). The sector's consumption increased to 3,223 (GWh) in 2014 out of the total output of 10,182 (GWh). The residential sector in Ghana therefore presently uses about a third of the country's total electric energy that is produced [13]. As global temperatures keep on rising coupled with other factors like improvement in technology with a probable economy of scale leading to reduced prices of ACs as well as the improved standard of living, the demand for electricity in the country is expected to increase. Residential homes consumption of electricity is not just by virtue of the buildings themselves but also the electricity based services and systems that have been installed in them [31, 32]. Ensuring that Ghana accomplishes an appropriate level of energy efficiency has become an inevitably urgent and important issue considering the fact that the nation has been in recurrent energy challenges since the 1990s and a continuous energy crisis from 2010 to early part of 2016.

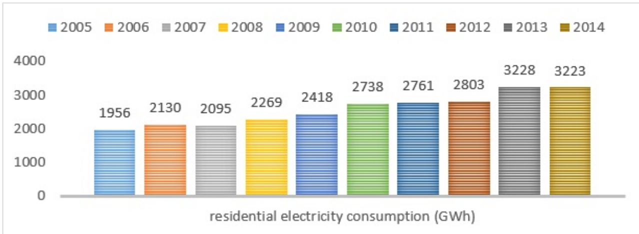

Figure 1. Residential Electricity Consumption (GWh) in Ghana. Source: Adapted from Energy Commission of Ghana (2015)

3. Methodology

This study reviewed empirical research works published in peer-reviewed journals and related literature on climate and its impact on energy usage. This enabled the researchers to appreciate what exist in the study area and also formulate a direction for the research. The study also selected 153 residential homes through purposive and snowball sampling and their electricity billing data for the year 2016 were collected. These households were located across the country in all the climatic belts of Ghana, with the coastal belt (Accra) having 57, the forest belt with 61 whereas that of the savannah belt was 35. The data were analyzed with Microsoft Excel to determine their means and frequencies. Further to that, Spearman's correlation and scatter plot in SPSS for Microsoft software was used to establish the correlation between the key weather conditions and electric energy consumption of the selected households. According to [33], the use of the billing data approach offers the opportunity to manage the variances in the various elements that are being observed in the analysis.

The main resource for this research was the electricity billing data for various residential homes in Ghana. For the purpose of this research, only electricity customers with the regular cycle of billing data were used for the analysis to be able to relate it to the daily mean temperatures. It is also worth establishing that, the cycle for the billing followed the regular calendar months in line with the temperature data. The distribution of electricity in Ghana is the final and major stage of electricity production process. Currently, the major distribution company in the country is the Electricity Company of Ghana (ECG) which is responsible for more than 70% of the supply and gives power to six administrative regions, namely Greater Accra, Ashanti, Central, Western, Eastern and Volta regions. The Volta River Authority (VRA) also established the Northern Electricity Distribution Company (NEDCo) to be responsible for the distribution of power to the Northern parts of Ghana. There is also Enclave Power Company which is the third company in Ghana that distributes power to the industrial community in the Free Zone Enclave of Ghana in Tema. Ghana Grid Company (GridCo) transmits the power to the distribution companies from 34.5kV, which they receive, into 11kV to industries whereas for commercial and residential customers, it is further stepped down to 440/230Volts [34]. From the billing data from the households, this research considered the billing cycle/duration (start date and end date), the total house consumption of electricity in kilowatt-hours (kWh), and the billing categories (whether the billing was residential or not). The study also confirmed from the households whether they have had any reason to doubt their consumption rate on the bills. This was intended to avoid issues of wrong billing that some end users in some instances complained about. Occupants were also asked whether they had undertaken any energy-related renovations as well as purchased any new appliances. This was to eliminate all possible factors that could distort the consumption rates of households. The study did not focus on the total amount of electricity used in Ghana cedis (GH ¢). This is because as the consumption of households' increase, they move into different billing rating categories which may distort the analysis of the research.

4. Result and Discusion

4.1 Relationship between air temperature and electric energy consumption

Research has shown that temperature could have a significant impact on electric energy usage of households especially those in the tropical climates. This study, therefore, analyzed the energy consumption patterns of 153 households and compared it with the air temperature over the same twelve calendar months. It was realized that the month of March was the hottest month of the year with an average temperature of 27.9°C whereas August was the coldest month of the year with an average temperature of 24.8°C. Interestingly, the month with the highest energy consumption (319.9kWh) was March which also happens to the hottest month. Between April and August, as the temperature drops, it can be seen from Figure 2 that the energy usage curve gradually falls and then after August begins to rise gradually.

To establish the correlation between temperature and energy consumption, there was the need to first undertake the scatter graph, as indicated in Figure 3, to determine whether there were any outliers in the relationship or not. The study identified that there were some outliers and hence could not use Pearson correlation but rather had to use Spearman's correlation to assess the nature of the correlation between the two variables.

The results have been shown in Figure 4 with a correlation of 0.259. Since r=0.259, it can be concluded that there is a weak positive relationship between the two variables. Hence, it is not statistically significant.

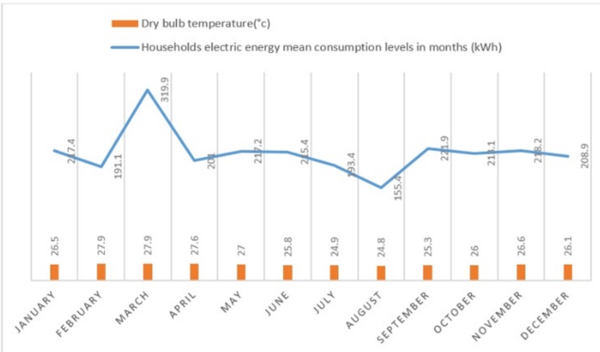

Figure 2. Air temperature and electric energy consumption monthly data

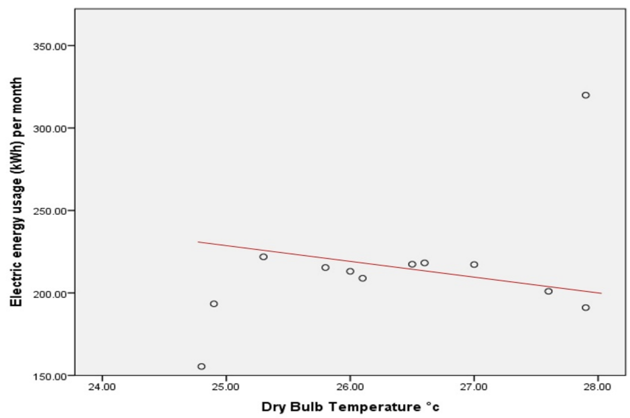

Figure 3. Scatter plots on Air temperature and electric energy consumption monthly data

Though the relationship is not strong, one cannot overemphasize the fact that the highest temperature coincided with the highest energy usage in March, whiles the lowest temperature also coincided with the lowest temperature in August. This, therefore, makes it quite critical and requires the energy providers' attention in energy supply planning purposes in Ghana.

			Energy_use	Temperature
Spearman's rho	Energy_use	Correlation Coefficient	1.000	.259
		Sig. (2-tailed)	.	.416
		N	12	12
	Temperature	Correlation Coefficient	.259	1.000
		Sig. (2-tailed)	.416	.
		N	12	12

Figure 4. Spearman's correlation between temperature and energy consumption

4.2 Relationship between air temperature, solar radiation and electric energy consumption

Spearman's correlation was also used to determine the nature of the relationship between the key weather variables including temperature, relative humidity and solar radiation. Figure 5 shows the statistical analysis of the relationship and reveals a significant negative correlation between temperature and relative humidity with (r=-0.871); a significant positive correlation between temperature and solar radiation with (r=0.890); and a strong negative correlation between relative humidity and solar radiation with (r=-0.780). The significant positive relationship between temperature and solar radiation is expected in the tropics since the sun is the major source of energy supply to the earth. With the sun on throughout the year, its effect on air temperature will always be strong in the tropics. The strong negative relationship between relative humidity and solar radiation could also be explained by the fact that, as the solar radiation increases the moisture content in the environment would reduce causing the moisture in the environment to dry up. This therefore accounted for the strong negative correlation. The same situation explains for the strong negative relationship between temperature and relative humidity. As the air temperature increases, the tendency for the moisture content in the environment to reduce is very high.

			Energy_use	Temperature	Rel_humidity	Solar_Radiatn
Spearman's rho	Energy_use	Correlation Coefficient	1.000	.259	-.393	.283
		Sig. (2-tailed)	.	.416	.206	.373
		N	12	12	12	12
	Temperature	Correlation Coefficient	.259	1.000	-.871**	.890**
		Sig. (2-tailed)	.416	.	.000	.000
		N	12	12	12	12
	Rel_humidity	Correlation Coefficient	-.393	-.871**	1.000	-.780**
		Sig. (2-tailed)	.206	.000	.	.003
		N	12	12	12	12
	Solar_Radiatn	Correlation Coefficient	.283	.890**	-.780**	1.000
		Sig. (2-tailed)	.373	.000	.003	.
		N	12	12	12	12

**. Correlation is significant at the 0.01 level (2-tailed).

Figure 5. Spearman's correlation between energy usage, temperature, relative humidity and solar radiation

4.3 Relationship between solar radiation and temperature

From the graphical analysis in Figure 6, it can be seen that as solar radiation rises so do the air temperature also rise. This, therefore, confirms the strong positive correlation as indicated in Figure 5. Thus, with the impact of solar radiation on temperature, the effects of temperature on building occupants will be thermal comfort issues which will subsequently influence occupants in adopting energy based systems and services to maintain thermal comfort within residential homes. Notwithstanding all these relationships, the finding from the study does not support earlier studies that there is a significant linear relationship between the weather and electric energy use, though a weak relationship exists. This, therefore, calls for further studies to determine on a wider scope the real situation in Ghana.

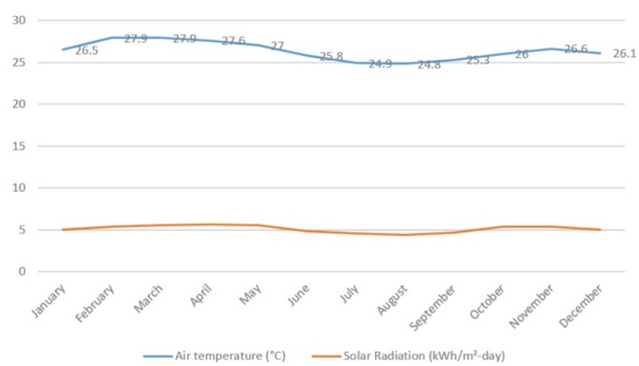

Figure 6. The relationship between solar radiation and temperature

5. Conclusion

The impact of climate change, particularly global warming has led to rising electric energy consumption across the world. With the increasing infrastructure gap in developing countries, electric energy demand is set to rise even more. Buildings consume about 40% of all energy produced. The building envelope acts as a barrier between the outdoor and indoor environment and greatly influences occupant comfort in the indoor. Electric energy consumption of 153 homes in Ghana using electricity bills for a year in Ghana across the three climatic belts was obtained and analyzed. Findings identified a rather weak correlation between electric energy usage and the elements of weather in Ghanaian residential homes. These elements had correlations of (r=0.259) for temperature; relative humidity with (r=-0.393); and solar radiation with (r=0.283). The research found this interesting, considering the predictions of existing literature, but argue that the following could be the reasons for this phenomenon:

1. Economic factors where even though the prices of ACs are getting cheaper in developed countries due to advancement in technology and economies of scale, the depreciation of the cedis against the dollar neutralizes all that benefits. This situation, therefore, makes the prices of the product relatively expensive making them not affordable for the majority of the occupants.

2. Closely related to the above is the fact that, generally income levels in Ghana are low and hence occupants are more likely to focus their expenditures on other pressing needs since ACs are considered by many as being more of a luxury.

3. Further to the above, the monthly temperature variations throughout the year in Ghana are not very significant and hence the need to resort to ACs and other mechanical means for thermal comfort throughout the year is relatively constant.

The study, however, found a high correlation between the highest and lowest electric energy consumptions and the highest and lowest temperature, solar radiation as well as relative humidity. This makes it very critical for energy providers to factor in their supply analysis and forecasts. This study, therefore, provides the base for developing comprehensive electric energy supply forecasts in Ghana. It is also very critical for peak load factor planning to ensure that, the demand for electric energy does not exceed the supply which most often leads to unplanned power cuts. The research adds to the drivers of electric energy consumption literature by indicating that each of the drivers is interdependent of each other and that the influence of one driver on the overall consumption level varies from location to location. In Ghana, even though temperature differences were identified, their influence on electric energy consumption was likely inhibited by the low economic capacity of occupants and minimum variations in temperature throughout the year. This research recommends a further study into the various probable factors causing the weak correlation between weather and electric energy consumption in developing countries, to establish the extent of their impacts. The study also recommends the involvement of all the major stakeholders including users, built environment professionals, suppliers, and policymakers in the efficient use of energy. These will ultimately lead to a residential sector with a resilient electric energy demand, supply, and use in Ghana.

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