Evaluation and simulation of a neighborhood energy consumption: case study in Guayaquil, Ecuador

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Abstract

Energy consumption and air temperature tends to increase. Guayaquil city shows the highest energy consumption among Ecuadorian cities and it is located in a “very hot humid climate zone”. This study was developed in “Socio Vivienda 1” neighborhood, in Guayaquil. The case study started for 2156 standardized social-houses. In this study firstly a spatial and statistical analysis of electric consumption was developed, and consumption types were formed. Based on these results, three representative houses were selected in order to simulate, calibrate and optimized. Field surveys contributed to assess the thermal behavior and energy consumption based on site-related climate conditions. When implementing the Ecuadorian energy efficiency normative considerations on the energy simulation of the selected houses, an approximate reduction of three Celsius degrees at the interior of the house and an approximate reduction of 35% of the total energy consumption was detected.

Introduction

It is known that climate change (CC) will amplify existing risks and create new ones for natural and human systems, affecting mainly those people and disadvantaged communities in countries at all levels of development (IPCC, 2014).

CC affects directly energy consumption for air conditioning (AC) in buildings (Xian-Xiang, 2018). The effect on AC-use requires to identify the existing correlation between energy consumption and environmental temperature. For this purpose, it is necessary to determine whether a greater amount of energy consumed in buildings is bound to an equipment's base-load (regardless of the increase or not of the temperature) or if this is related to the use of AC (highly dependent on the ambient temperature).

CO₂ emissions from the energy sector (production and end use) for 2050 are estimated to increase by 60% (IPCC, 2014). In this regard, in continental Ecuador it is expected until end of century will show a temperature increase by 2°C (Republic of Ecuador, 2019), suggesting an increase in energy consumption for AC in buildings.

The analytical approach presented by (Hirano et al., 2017) allows to assess a building's energy consumption upon seasonal and climatic changes. A recent literature review on global heating and cooling energy usage trends showed

that regions dominated by a warming load will see reduced growth - or even stagnation - in energy use (Ürge-Vorsatz et al., 2015).

On the other hand, warm regions, such as Ecuador, dominated by a cooling energy load will see an exponential increase (Ürge-Vorsatz et al., 2015).

Building energy and efficiency standards (NEE) are important policies for reducing energy, emissions as well as overall costs. NEE contribute to existing buildings and new ones benefit from energy efficiency measures and strategies (Gaudry, K.H. et al., 2019; USDE, 2014, 2015), by improving inside thermal comfort and the inhabitants' quality of life.

The present study develops a methodology for tracking energy consumption evolution in time, and thus identifying determinants of energy consumption. The case study rests on a neighborhood of standardized social housing in the city of Guayaquil, Ecuador. While Guayaquil has the highest reported energy consumptions in Ecuador, results indicate that there is an increase in the total energy consumption due to several factors that are not exclusive to climate but as well as other like: home additions/home remodeling, increase of electronic equipment acquisition (base load) and the installation of AC.

In order to reduce the increase in energy consumption, the Ecuadorian building energy and efficiency standard (MIDUVI, 2019) was simulated in three of the nationhood's dwelling. Inner air temperature and electric consumption was reduced. Finally, the amount of kgCO₂ Eq. mitigation potential was estimated for the social housing neighborhood as suggested too by (Gaudry, K.H. et al., 2019).

Methods

Figure 1 shows the scheme of the developed stages in this study.

Figure 1: Scheme of study stages.

Information preparation

Guayaquil is located in a very hot humid climate zone (Palme et al., 2016). The average environmental temperature of the city oscillates between 25°C - 27°C, in a typical year.

The social housing program “Socio Vivienda 1” (SV1) was initiated in 2008 by the Ecuadorian Ministry of Urban Development and Housing (MIDUVI). Its goal was to enable access to low income housing, particularly for those with no house tenure, located on zones considered of risk, or without access to financial services (GAD-Municipal de Guayaquil, 2017; SENPLADES Zona-8, 2014).

SV1 has buildings for public purposes such as schools, security facilities, recreation spaces, roads, etc. Housing plots have an area of 90 m² and a total built area of 46.9 m². Each housing unit is intended to have a capacity of four inhabitants, it consists of two bedrooms, a shared area for kitchen, dining room and full bathroom (see Figure 2 “original household”). All neighborhood houses are paired and share the same typology.

Figure 2: “SV1” household model.

On the other hand, the electric fees identified in SV1 were Commercial, “PEC” (efficient cooking program) and Residential with no dynamic change of fee per hour. The residential fee it is for houses do not hold special equipment and not commercial activities inside.

For this study, the official Ecuadorian entity CNEL-EP Guayaquil, delivered information of the monthly electric energy consumption of the SV1 from 2013 to 2017. Therefore, information of 2156 light meters distributed per fee, was gathered.

In this study, it was decided to characterize and analyze only one type of fee and thus, were selected 915 social houses that keep the residential fee. Once the information was organized, consolidated and sorted, it was complemented with the geographic location of each house by using the on-line tool “Geoportal” developed by CNEL-EP. Afterwards, the statistical analysis was carried out.

Statistical analysis of energy consumption

Spatial analysis

The spatial analysis of energy consumption was carried out by using the stochastic interpolation method of

Kriging and Cokriging. This method states that not all variables can be interpolated, one must consider that the variable fulfills with conditions such as: normality, homogeneity, a certain quantity of available points, seasonality and correlation with other variables (Hartkamp, 1999; Hong et al., 2005).

The analysis was performed from a sample of 915 housing units that showed a homogeneous spatial distribution over an area of 417.000 m². This area corresponded to the whole housing units were built, streets and service buildings. For this matter, it was configured an experimental semi variogram for each evaluated year, considering the spatial location of the housing units and the average yearly energy consumption of the sample.

Later, a linear model was used. It was adjusted by the iterative estimation of least weighted squares. The weights were determined as function of the number of point pairs and as function of the distance. By using this method, a value of the consumption variable on non-considered locations or non-existing in the sample was obtained. As a result, the rasterized images shown on were generated. They indicate the positive correlation between the mapped variable (energy consumption) and the location of the sample points (Hengl et al., 2009; Gaona, 2013). The aim of this result was to observe consumption patterns or consumption concentration in the analysis zone. Later, the analysis of the box frequency histogram was carried out in order to determine the variables of consumption and to proceed to the selection of the houses from the sample.

Frequency histogram distribution and box plot of yearly and monthly electric consumption

The analysis of relative and accumulated frequencies (histogram) was carried out to visualize the distribution of electric consumptions.

Subsequently, these methods are presented annually to observe the evolution of the energy consumption, estimating the change percentage between 2013-2017. In addition, it is possible to identify how the houses’ electrical consumption is closer or farther from the values considered moderate.

Finally, data variability, tendency and the presence of atypical data; box diagrams were plotted. Plots show that the 50th percentile (median), the 25th percentile, the 75th percentile (upper and lower limits), the observed highest and lowest value (non-atypical) and the upper and lower limits of the atypical values (1.5 times the length of the box) (Smith & Campuzano, 2010). The box diagram aims to show the quartiles of the monthly consumption for the sample, the maximum values.

After the statistical characterization of electric consumption, several studies suggest studying those dwellings that are between the limits of consumption and the reason for their behavior. It was established that one of the reasons is the increase on the purchase power of the habitants.

Climate influence in energy consumption analysis

To describe the correlation ratio between the environmental temperature and the electric consumption of a building, a function was defined by a linear regression with the analyzed variables. It is established by the determination coefficient R^2 (Devore, 2010).

The environmental protection agency EPA states a minimum R^2 value of 0.4 for correlations of simple adjustment and a value of 0.7 more complex correlations (Energy Star, 2017).

This analysis is carried out and some buildings do show this behavior. Once performed the statistical analysis, the house selection for further analysis took place in order to characterize the energy consumption.

House selection

For this study three typical housing units of SV1 were characterized and selected: "High", "medium" and "low" consumption. The criteria were performed selecting housing units show a repeated behavior of energy consumption throughout the years according to the spatial and statistical evaluation, the final decision was the climate influence. The selected housing units' were simulated, calibrated and optimized.

Particularly for the "medium consumption" household, it was possible to visit with the owner's permission to monitor the house's behavior and carry out the study. In this context, some temperature sensors and monitoring equipment were installed in the household to determine its thermal and energetic behavior.

Energy simulation

Simulation, calibration and optimization based on AHSRAE Guideline 14-2014 and NEC-HS-EE.

In the house monitored, temperature sensors were installed, to get data about inner-outer surface of windows, walls and roofs. In parallel, the meteorological conditions and the indoor air temperature of the house were registered. The verification variable was the indoor air temperature.

Values on thermal material properties, particularly on solar absorptance, emissivity and thermal conduction were adjusted based on earlier reports Vallejo-Coral, E.C., et al. (2018); Gallardo, A. (2016); Lee, S. et al. (2017) and equipment information Gaudry, K. H. et al. (2019) were reviewed.

According to the methodology of Hong, T et al. (2016) and Westphal, F & Lamberts, R (2005), for the energy simulation and calibration, as a first step, an initial thermal and energy behavior of the monitored house is estimated with data of materials, usage, equipment, architectonic model, etc.

The energy simulation and calibration was carried out by DesignBuilder v.4.0.1 software that uses EnergyPlus as calculation engine with data correspond to the monitoring period from December 25th to December 28th of 2018.

Multiple energy simulations were performed until it is considered as calibrated model under the methodology established in ASHRAE Guideline 14-2014. The

methodology defined a modeled calibrated when the Coefficient of Variation of the Root-Mean-Square Error (CV[RMSE]) and the Normalized Mean Bias Error (NMBE) present values up to 15% and 5%, respectively, using energy real and simulated monthly values.

Once the selected method has reached the standard values, the data of thermal properties of the materials was used, for low and high energy consumption households contemplating the presence of A/C in the low and high consumption models.

For the three selected houses, data of 2016 and 2017 was simulated because some reduction on the energy consumption in the entire estate was observed.

Results and discussion

It was considered the obtained criteria from the spatial distribution, the results of the frequency diagram, the box diagram, the climate influence and other factors are explained below. The results follow the steps shown in Figure 3 in order to selected analyzed houses.

Spatial analysis

The spatial analysis permitted to show the similarity of the closest values to the sample social houses, which allowed to detect local consumption patterns from 2013 to 2017. In the Figure 3 is possible to observe that the southern zone of the estate exhibited a higher energy consumption, while the northern zone exhibited a slowly average consumption. Reflecting most probably the neighborhood building phases that the anthropic activities of the SV1 were initiated on the southern zone. In addition, the location of the selected households is shown in the figure.

Statistical analysis

Figure 3 displays the distributions of the energy consumption of the 50% of the houses of every month of the year and shows the frequency histogram and the accumulate percentage of the annual electric consumption in (kWh-year). Also shows the range of the monthly electric consumption without atypical values on a box diagram.

The frequency distribution is similar for all the years regarding the annual consumption but the accumulate percentage highlights that the atypical values of the sample have been increasing in time. This means that some of the houses have kept their levels of electric consumption. Nevertheless, there are households that have exponentially increased electric consumption. The box diagram shows that the range of monthly energy consumption has a positive tendency in time. It was calculated an 18% increase in 5 years.

The monthly electric consumption median for this type was 105 kWh in 2013 and it grew until it was 125 kWh in 2017. 2016 registered a value of 129 kWh, which is atypical. It is observed also a monthly electric consumption pattern since 2014. The highest consumption months were February, May, August and November since 2014.

Climate influence analysis

When evaluating the climate influence over the electric consumption, it was not observed a correlation with the humidity, thus the analysis focused on the ambient temperature. It was observed that in 2013, 18 houses showed an electric consumption highly influenced by weather, while in 2017, the number of houses influenced reached 313. It is estimated that nowadays, approximately 30% the analyzed housing units may be using air conditioning systems.

It was evaluated the correlation between the average monthly temperature and the electric consumption of the initial 18 houses. Figure 4 displays the monthly electric consumption normalized for the number of analyzed social houses and the average monthly ambient temperature. The results plotted show that the method used is accurate for high values of R^2 were reached for all the periods.

Figure 4: Linear regression analysis between monthly electricity consumption per dwelling and mean temperature from 2013 to 2017.

For 2017 it was obtained a temperature coefficient (T) of 16.61, being the lowest identified value. It shows a low increase of the electric consumption caused by ambient temperature. Therefore, the total electric consumption is lower, compared to 2014 ($T=25.05$). In 2016 was the year with the highest electric consumption despite its value of $T=21.69$. An increase of the base load may have occurred during this year, since the temperature influence is less than in 2014.

According to the statistical analysis, houses of high, medium and low electricity consumption were selected. In Figure 5, the results of evaluating the climate influence are displayed, for each type of house in the simulation period (2016-2017).

Also, in Figure 5 demonstrate that the “medium” house type does not show correlation with the ambient temperature, and it was also corroborated *in situ*, because the house does not have air conditioning system. For high and low consumption houses R^2 reached were higher than 0.7, it demonstrated the usage of air conditioning. The coefficient T of the high consumption house was 89.31, which indicates an energy increase on approximately 10 times compared to

the low consumption house, for each Celsius degree that the outer temperature rises.

Figure 5: Linear regression analysis for high, medium and low electricity consumption.

House selection

In Figure 3, the spatial location, values of the annual and monthly electric consumption of the selected houses are detailed.

As observed, the electric consumption of the houses keep in the limits and only in 2013, the behavior is different to the pattern registered in the following years.

For the house with the highest electric consumption, was valuated that it finds itself among the atypical range of consumption, in the frequency and box diagrams. Furthermore, the consumption behavior was observed under the influence of weather.

Since some houses showed the behavior described above, the conclusive valuation is that visual check should be done *in situ* to verify that the house has indeed an air conditioning system. For this matter, the tool Geoportal of CNEL-EP (2019) was used. It employs the Street View command from Google for visualization. By using this tool, it was possible to note that some of the houses show a high electric consumption due to commercial activities in the house that may have not been reported or updated to CNEL-EP.

For the low electric consumption household, the visual check was difficult because are several the houses in this group. For this case, the climate influence on the electric consumption was verified decisive factor. This influence occurs since 2013 and becomes even stronger in 2016 and 2017.

Out of the analyzed cases (low and high), it was verifiable that the households used A/C, by the tool Street View. In addition, it was confirmed that the A/C influenced the electricity consumption since 2015.

Finally, for the selection of the medium energy consumption household, no influence of the climate was observed. In addition, information was gathered about the use of the house, equipment, consumption, etc. A visit was carry out and during the visit, it was checked out that an expansion

from the original model of the house has been made (Figure 2 “Household with extension”). This is a common practice that owners do in SV1. The expansion consists of using the space originally designed as a patio to turn it into more bedrooms, bathrooms, washing zones or other uses the owners see fit.

Building simulation

The energy balance was obtained as product of the preliminary energy simulation of the medium consumption house. Due to, it is possible to observe that the materials that gain the highest energy from heat exchange with the environment are walls (25% total gains) and roofs (72% total gains). Hence, the heat exchange through windows is lower due to the expansion of the roof that blocks the solar charge. For this, the simulation was calibrated with the electric consumption, inner and outer temperatures of the roof and the wall and the inner air temperature.

In Table 1 are shown the values of CV(RMSE) and NMBE and it is demonstrated that these are below the considered maximums on ASHRAE 14-2014 standard for monthly electric consumption previously mentioned. In Table 2 indicates the results of analyzed calibrated hourly temperatures as performed by Gucyeter, B (2018) for the inner air temperature. In order to accept the calibration conditions.

Table1: Obtained calibrated parameters for monthly energy consumption.

Monthly energy consumption	CV (RMSE)	NMBE
High consumption household	8,4	3,2
Medium consumption household	14,87	2,2
Low consumption household	10,77	2,4

Table 2: Obtained calibrated parameters for hourly surface and air temperature.

Temperature [°C]		CV (RMSE)	NMBE	Eav (°C)	R
Roof	Interior	11,71	10,68	3,12	0,91
	Exterior	16,54	12,78	3,89	0,83
Wall	Interior	2,49	2,15	0,6	0,95
	Exterior	4,19	3,36	0,92	0,95
Air temperature	Interior	2,28	1,77	0,5	0,91

It is important to mention that, according to the NEC-HS-EE, is contemplated that for the climatic zone “very hot and humid”, according to the Ecuadorian climatic zoning, under the methodology of ASHRAE 90.1 (2016) and ASHRAE 90.2 (2007); the U-Value max for the roof does not match the established limits because it is lower than 3.5 [W/m²K]. Likewise, the windows show a U-Value max outside the limits since adequate values are lower than 3.84 [W/m²K] in addition to show lower values of SHGC than 0.77. In contrast, it is listed on bibliography review the selection of the materials with the considered improvements. Once the houses have been selected and the model has been calibrated, all the models were simulated for 2016 and 2017. One A/C system was contemplated for low and high consumption. The system was “Split” type, which is the

most used type on the houses, according to images of Street View and the study of Beltran, R.D. (2018) in Ecuador.

As observed on Table 3, it is certain that, when the contemplated properties in materials are applied to roofs and windows, a reduction of the parameters evaluated for all years occurs, except for the medium consumption house that reports the same electric consumption since the climate does not influence.

Table 3: Energy simulation results.

Year	Time	Evaluated variable	Low		Medium		High	
			Int.	Op.	Int.	Op.	Int.	Op.
2016	May-21	MExT [°C]	34.7					
		MOT [°C]	30.6	28.5	33.8	30.5	30.3	28.3
	Annual	MeExT [°C]	25.6					
		Consp. [kWh]	1197	835	2120		6026	3678
		TNCH	5486	4109	6320	5906	6420	5020
2017	Apr-12	MExT [°C]	34.7					
		MOT [°C]	30	28.1	33.3	30.8	30.5	27.9
	Annual	MeExT [°C]	25.0					
		Consp. [kWh]	1203	721	2367		4505	3185
		TNCH	4507	2944	5951	5416	5757	4065

MExT: Maximum exterior temperature

MOT: Maximum Obtained Temperature initial (int) vs optimized (op) models.

MeExT: Median Exterior temperature

Consp: Total annual consumption

TNCH: Total Non-Comfortable Hours.

For the houses with existing A/C systems, the drop of the temperature entails into a reduction of the electric consumption because the system does not need to be, power on, when the user feels a climate discomfort. It is possible to observe reductions from 30% to 41% on the annual energy consumption.

However, for the medium consumption household, must be considered complementary strategies for improvement on the base load such as: appliances, lighting, equipment, etc. This because said houses do not show a seasonal behavior but an influence from the equipment.

In all cases, the drop of the inner air temperature was around 3 °C, at the time when the highest outer temperature was registered, in the hottest day of the year. Similar results are also observed on other reports (Lee, S. et al., 2018 and Romeo, C. & Zinzi, M., 2013) when the improvements specially for the roof are applied.

Another studied parameter was the decrease of total discomfort hours inside the house. This is particularly important for houses with no air conditioning systems. In this case, the total number of hours when the inner house's temperature was above 25°C, were counted, according to the simple method of determination of thermal comfort from ASHRAE 55-2013 standards. In this context, it was estimated an average reduction of 20% of total discomfort hours, for low and high consumption houses. Similar results was reported by Lee, S. (2018) and Gallardo, A. (2016).

For the medium household, it is raised that an intervention might be made in order to naturally ventilate the roof and the space inside the house, also contemplated in NEC-HS-EE. For this study this proposal an “optimized model” with ventilation system consists of the installation of air intakes to take advantage of the predominant wind orientation that comes from the south.

The air circulates and forces the ventilation as the hot air leaves the house through a window in the rear that remains open. In addition, the system helps to increase the natural lighting without increasing the incident solar radiation.

Figure 6 show the “medium” simulated household optimized model (left) and an example of original standard model (right) that uses for “low” and “high” model. Figure 6 (a) shows the application of the parameters from NEC-HS-EE and the proposed improvement to the roof (reflective paint and roof openings). It is important to make clear that the high and medium consumption house’s orientation is the one displayed in the figure. But, for the low consumption house type, its orientation is 180° opposite.

Figure 6: (a) Optimized model according to NEC-HS-EE. (b) Original model.

As final result, it is raised the hypothetic quantity analysis of the consumption saving when implementing the optimization and the energy efficiency strategies from the Ecuadorian standards to the estate houses taking into account that only 30% of the houses experience a climate influence. With the energy savings found on the simulation of 2016 and 2017 for the houses of low and high consumption houses, was firstly estimated the number of houses that would have been energized, as well as the non-emitted Kg-eq of CO₂ if the efficiency strategies would have been applied on the estate.

Table 4: Results energy savings.

Year	Type	Consp[kWh]	QHE	TS [%]	TES [kWh]	QLHE	TNE [kg CO ₂ -eq/year]
2016	Low	787.5	247	30	17506	22	6058
	High	6283	160	39	117618	149	40701.5
2017	Low	780	229	30	16076	21	5563
	High	5911	183	41	133051	171	46042.1

Consp: Annual energy consumption in Low and High selected households.

QHE: Quantity of Households Energizer

TS: Total Saved in percentage by implementing NEC-HS-EE

TES: Total Energy Saved consider that only 30% house use A/C by the climate influence study

QLHE: Quantity of Low Households Energizer with the energy saved

TNE: Total kg-CO₂ eq/year No Emitted

Results show that, with the energy savings in 2016, 171 low consumption houses could have been provided with energy on 2016, and 192 houses in 2017 (Table 4). These important

results lead to truly contemplate the implantation of the described energy efficiency strategies on other buildings.

Conclusion

Based on the results, there is an increase in the time of the number of households which have raised energy consumption, concentrating on the south and north zone of the urbanization. Further, if this trend continues, the most households will remain at “medium” and “high” consumption. On the other hand, a high percentage of households are not benefited by Ecuador subsidy tariff reduction which is focused on residential sector and apply for households that consume less than 130 [kWh-month]. A particular phenomenon between 2016 and 2017 was looked into. Because of higher temperature registered in 2016, urbanization energy consumption increased. This result is interesting because in the last years, energy consumption raised constantly. This phenomenon indicates and confirms the statement made by the climate change intergovernmental panels. Since 2017, the situation is even more alarming because more number of households (30%) is influenced by climate, indicating an increase of air conditioner systems acquisition.

For this reason, strategies evaluated by NEC-HS-EE will decrease thermal loads through of the envelope and are an opportunity area for decreasing energy consumption. The greatest benefit in expected in households considered as high consumption.

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