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Energy Efficiency Assessment: A Path to Sustainability in Housing, Santa Elena Canton, Ecuador

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ABSTRACT

Energy efficiency helps mitigate climate change, while energy efficiency assessment promotes sustainability in the building sector. Santa Elena, a province of Ecuador, is a region facing climate challenges due to high temperatures and scarce energy resources. Therefore, energy efficiency assessment is a crucial factor in promoting conservation strategies aligned with the Sustainable Development Goals (SDGs). The objective of this research is to evaluate the energy efficiency of homes in the Santa Elena province of Ecuador through energy modelling, considering energy consumption and material types to propose sustainability measures. This study adopted a three-phase approach: the first phase consisted of establishing a baseline through surveys of homes in the area; the second phase evaluated housing types based on their materials, aligning with international standards, using Open Studio energy modelling software. The third phase involved a technical comparison of energy consumption and thermal comfort to propose sustainability strategies that focus on reducing carbon dioxide emissions (CO_2). Based on the results obtained, the most common housing types in Santa Elena were evaluated: brick (52.74%), concrete (13.58%), and bamboo (12.27%). When modelling these housing types without HVAC systems, an annual energy consumption of 1639 kWh was obtained for the brick and concrete home and 1556 kWh for the bamboo. However, with the implementation of HVAC systems, particularly in brick and concrete homes with thermal conductivities of 1.13 W/m² and 0.72 W/m², respectively, consumption rose to 5392.09 kWh for the brick home and 5686.56 kWh for the concrete home. These results prove that materials with greater thermal insulation capacity contribute to energy conservation strategies in homes. In conclusion, this research highlights the significance of evaluating energy efficiency in various housing types to promote sustainable strategies that prioritise the use of natural resources, efficient thermal insulation, and reduced energy consumption and CO_2 emissions. It is worth noting that this line of research aligns with the SDGs (7, 11, and 13), promoting education and culture to ensure a sustainable future for generations.

1. INTRODUCTION

Energy efficiency is important in human development, ensuring a balance between progress, equity, and natural resources [1]. The energy efficiency assessment allows for countering vulnerabilities to energy crises and improving resilience to geopolitical fluctuations [2]. Thus, the energy transition lies in reducing energy consumption and carbon dioxide (CO_2) emissions [3].

CO_2 is considered the leading cause of climate change, generated in significant quantities by thermoelectric plants due to the combustion of fuel [4]. These emissions vary depending on the productive sector, for example, in the energy industry (24.2%), agriculture (18.4%), transportation (16.2%), and residential use (17.5%) [5]. In response to this problem, strategies such as CO_2 capture and storage [6] and the use of technologies to take advantage of renewable energy and energy efficiency [7, 8].

Regarding CO_2 emissions in the residential sector, their impact is accentuated by the high energy consumption due to the implementation of Heating, Ventilation and Air Conditioning (HVAC) systems [9], considering 10.9% for residential buildings and 6.6% for commercial buildings [5]. Therefore, addressing energy efficiency in homes implies improving energy performance by promoting a lower ecological impact [10], due to the relationship between the energy the system uses and the resources employed [11]. Furthermore, it is considered an energy resource due to its capacity to produce energy by saving the system's demand [12].

Evaluating energy efficiency in homes allows addressing factors such as design orientation, thermal envelope, construction materials, energy consumption, and HVAC systems [13]. For the thermal envelope, examples include thermal coating paints, which can reduce up to 7% of a building's thermal load [14]. These textile membranes enable sunlight control by providing efficient thermal insulation [15] and vacuum insulation panels reduce heat transfer by conduction and convention. However, the latter is not recommended for long-life homes [16].

In the case of construction materials, 55% of buildings in the Andean countries (e.g., Argentina, Bolivia, Chile, Colombia, Ecuador, Peru, and Venezuela) are predominantly made of masonry [17], where energy consumption in these types of constructions is approximately 567.5 GJ [18]. It has led to strategies to reduce energy consumption, such as the use of cellular concrete bricks due to their compressive strength of 35-17.4% in thermal insulation [19], and gypsum boards made from natural waste, including Oceanic Posidonia, used in ceilings and walls, improving energy efficiency by 8 and 17%, respectively [20]. Conversely, wood has efficient thermal performance due to its natural insulating material, which results in energy savings [21]. In this context, the thermal properties of materials directly influence energy performance in homes, measured based on their thermal conductivity expressed in (W/m.K), specific heat (J/kg.K), and density (kg/m^3) [22].

The correct use of the thermal properties of materials not only guarantees thermal comfort but also contributes to sustainability and a reduction in energy consumption demand [23]. Energy efficiency assessment allows for the approach of criteria focused on energy sustainability [24], becoming a fundamental part of sustainability, as it allows for the quantification of its results and the subsequent optimisation of the use of energy resources, reducing the carbon footprint and aligning with a circular economy [25].

Sustainability conserves productive and ecological systems through practices that optimize resources and integrate economic, social, and environmental criteria [26]. However, speaking of sustainable development is orienting toward a favourable future for humanity, satisfying needs without compromising environmental stability [27]. The nexus of natural resources and climate change is notably intensified in the scientific field, thus, addressing energy sustainability is fundamental to the Water-Energy-Food (WEF) Nexus criterion [28].

Energy sustainability entails efficiently using resources, balancing renewable energy, affordability, and energy efficiency to ensure their availability for future generation [29]. Addressing energy efficiency in homes allows progress towards achieving the SDGs due to its direct relationship with some of them [30]. The challenges address SDG 7, affordable and clean energy; SDG 11, sustainable cities and communities; and SDG 13, climate action [31]. In this context, it is essential to remember that the energy crisis, which has been intensifying since the 1970s, has been fundamental to the development of global energy strategies [32]. Since that decade, energy challenges have been exacerbated by concerns about sustainability, intensifying notably after the signing of the Kyoto Protocol [33], which consists of an international agreement of the United Nations Framework Convention (UNFCCC), whose main objective is to reduce greenhouse gases in developed countries [34].

A sustainable home brings countless paradoxes, such as type of materials, costs and energy efficiencies [35]. Sustainable homes are designed to minimize environmental impact, and are built with eco-friendly materials and efficient water and energy systems [36]. One of these materials is coconut fibre, used as thermal insulation due to its physical and mechanical properties [37]. Wood is also a versatile material due to its strength, durability and thermal properties [38] such as k=0.13 W/m.K, cp=1381 J/(kg K) y ρ=840 kg/m^3 [39]. These types of buildings promote the benefit of the environment and society, promoting the improvement of the quality of life of their inhabitants [40].

In Europe, passive and zero-emission housing construction is promoted based on the adverse effects of climate change [41]. Thailand encourages sustainable buildings through eco-technological housing concepts focused on renewable energy and thermal insulation [42]. In Brazil, the integration of green design into construction is aligned based on the types of materials that adapt to the local climate [43].

Buildings in Ecuador require high consumption of natural resources and energy, contributing significantly to climate change [44]. Electricity consumption is 13% and the residential sector represents a third of this consumption [45]. Therefore, the evaluation of energy efficiency in homes must be governed by the Ecuadorian Building Standard-Habitability and Sustainability-Energy Efficiency (NEC-HS-EE, acronym in Spanish) [39].

In Ecuador, 73% of buildings are predominantly made of construction materials (block and brick), followed by 13.5% by concrete [46]. However, the demand for these materials differs according to the area's climatic conditions, making passive strategies viable to counteract high energy consumption [47].

Energy consumption in Ecuador's coastal regions plays a key role in its development, as it depends on its climate. Therefore, the demand for HVAC systems represents 14.3% of total energy demand [48], due to the temperature in these areas, which varies between 23°C and 26°C, where the need to apply ecological materials in construction is imminent [49].

In Santa Elena province, addressing meteorological factors is key due to its semi-arid climate, which places greater demands on home HVAC systems [50, 51]. Housing conditions in the province vary by location and socioeconomic level. According to data from the National Institute of Statistics and Census (INEC, an acronym in Spanish) for 2022, the housing stock is as follows: 76.04% of homes are made of brick and block, 12.09% are uncoated cane, 7.02% are concrete, 1.99% are coated cane, 1.54% are prefabricated panels, 1.01% are wood, 0.27% are other materials, and 0.04% are adobe or rammed earth [46].

The lack of adequate infrastructure and limited access to efficient technologies exacerbate the problem, increasing household energy costs [52]. Furthermore, the reliance on conventional energy sources contributes to environmental impact, which calls for adopting sustainable and affordable solutions to improve the use of energy resources in the region [53]. Therefore, the following research questions arise: How does energy consumption vary between homes made of different materials, and what energy efficiency opportunities can be identified from these variations? Which structural and climatic factors most influence the energy consumption of various types of homes? Which energy conservation measures are most effective in improving sustainability in different kinds of homes?

This research aims to evaluate the energy efficiency of homes in Santa Elena province, Ecuador, through energy modelling using OpenStudio software, considering energy consumption and material types to develop energy sustainability measures. For energy modelling, a baseline is established based on surveys conducted in the province of

Santa Elena, focused on obtaining relevant information on energy consumption, housing sizing, and materials.

2. MATERIALS AND METHODS

This research focused on analysing housing in a coastal area of Ecuador. It selected a representative sample to establish a general baseline for considering construction materials and stratified the study sample to subsequently collect relevant data. Furthermore, housing types were identified and evaluated based on energy variables to create a model that helps observe the factors influencing housing energy efficiency. In this context, each housing type was analysed based on energy consumption to develop a strategic approach to environmental sustainability.

The process consisted of three phases: the first phase was based on a survey to create the baseline; the second phase involved analysing housing types and their energy variables through study modelling using OpenStudio software; and the third phase involved comparing housing types to propose sustainability strategies, focusing on energy conservation. Figure 1 summarises this methodological approach.

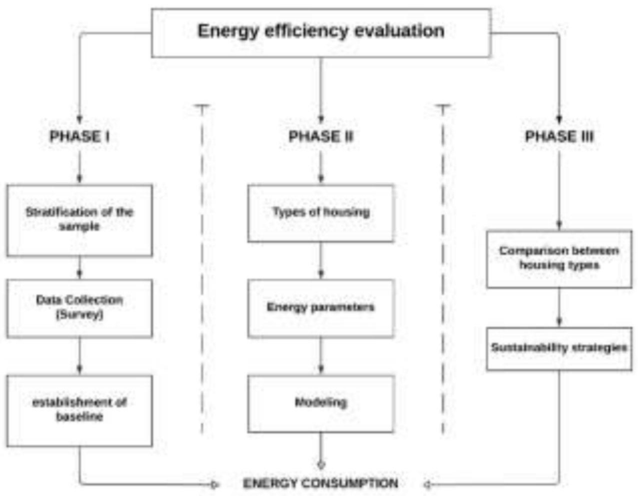

Figure 1. General methodological scheme

2.1 Phase I: Baseline

It consisted of identifying typical houses through the systematic collection of initial data, which served as a reference to evaluate the variability of the variables. In addition, a structured questionnaire with closed questions was developed to obtain precise data on energy consumption and efficiency practices in different types of housing and establish reference baseline [54].

2.1.1 Study area

The study area is located in the province of Santa Elena, in the coastal region of Ecuador (Figure 2). It is composed of three cantons, Santa Elena, La Libertad, and Salinas, covering an area of approximately 3762.8 km² [55], and having an average annual temperature of 24°C with a coefficient of variation of 2.7%. According to the National Institute of Meteorology and Hydrology (INAMHI acronym in Spanish), rainfall occurs from December to May [50, 56]. The province has a population of 385,735 inhabitants and approximately 79,178 homes in urban areas, as well as 65,158 in rural areas. Additionally, 47% of the population lives in poverty, and the economically active population stands at 150,836. However, 80.30% are employed, with 19.04% in commerce, 15.90% in the primary sector (agriculture, livestock, forestry and fishing), 9% in construction, 8.22% in manufacturing, 7.29% in food services, 5.76% in transport and 34.79% in other activities [46].

Figure 2. Study area, Santa Elena Province [57]

For sample determination, established inferential statistics guidelines were used to extract figures proportional to the target population. The data extracted for population determination were indexed from the Ecuador Census website (INEC), where the search regarding the general condition of housing predominated in the 2022 results. Table 1 shows the classification by area.

Table 1. Number of houses according to area

Area	Houses	Percentage (%)
Urban	79,178	54.86
Rural	65,158	45.14

Table 2. Housing according to the predominant material of exterior walls

Predominant Material	Housing	
	Rural	Rural
Concrete	2,309	4,586
Brick-block	34,905	39,795
Prefabricated panel	1,221	296
Wood	592	404
Coated cane	963	993
Uncoated cane	5,439	6,440
Total	45,429	52,514

A systematic stratification was conducted based on data from the INEC, revealing the types of occupied housing by canton, area, and predominant exterior wall material. In this context, the study focused on housing typology based on predominant materials: concrete, brick-block, prefabricated panels (gypsum, fibre cement), wood, coated cane, and uncoated cane. Differential distribution of housing types by areas was obtained: urban (53.62%) and rural (46.38%). The results are presented in Table 2.

2.1.2 Sample calculation

The sample calculation allowed focusing the data collection for the study, ensuring a direct relationship with the population. This process guaranteed the statistical validity of the results, reducing the margin of error and increasing precision.

$$n = \frac{NZ^2pq}{e^2(N-1)+z^2pq} \tag{1}$$

where,

n is the sample size;

N represents the size of the study population (N=97,943);

p represents the probability of occurrence or expected proportion of the response variable (p=50%);

q represents the complement of p or proportion of the population that does not represent characteristics of interest (q=50%);

e represents the acceptable margin of error (e =5%);

Z represents the critical value associated with the confidence level derived from the standard normal distribution (z=95%).

Eq. (1) was used to calculate the size of a sample from a finite population [58].

Where the following is obtained for a confidence level of 95% = 1.96. The sample calculation of a population (n = 97,943 houses) determined the need to obtain a sample of 382,329 ≈ 383 houses.

Surveying housing types involved a structured process that allowed collecting quantitative and qualitative data on the energy profile, including wall envelope, floor area, energy consumption, energy use of energy-balanced technology, energy-saving measures, and the presence of climatization systems and appliances. Including closed-ended questions in the instrument facilitated the generation of predictive models for energy performance. For the structured questionnaire (Table A1), the form of the national urban and rural household income and expenditure survey was used [59]. Thus, questions 4 (building materials), 8 (internal loads), and 9 (air conditioning) were adapted.

2.1.3 Focus group

In complement to the survey results, a focus group with four experts in energy, environment, and sustainability was held from January 28 to 30, 2025. This group analysed the data and suggested applying statistical techniques to identify modelling parameters. In this context, a cluster analysis using the K-Means algorithm was proposed to identify patterns through similarities and precision, providing a more solid basis for decision-making. For this, we used Python 3.13.5 software with the Spyder 6 development environment, which allows us to run and debug code efficiently using libraries such as Matplotlib, Pandas, and NumPy [60].

Clustering allowed classifying the dwellings into homogeneous groups according to variables such as predominant material, area, division of the dwelling, occupancy, HVAC systems, and internal loads, as shown in Figure 3. The parameterisation of the variables can be found as supplementary material (Table A2, Table A3, Table A4).

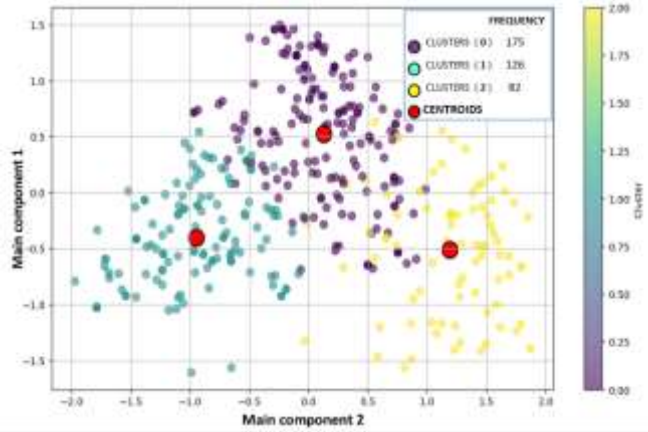

Figure 3. Clusters using K-Means algorithm

2.2 Phase II: Evaluation of housing types and modelling

The housing types were evaluated according to their construction materials; the Ecuadorian Construction Standard for Energy Efficiency (NEC-HS-EE) was considered for this purpose, which is based on international standards. During this phase, the energy simulation software OpenStudio v.1.7.2, a tool based on EnergyPlus, was used [61]. OpenStudio v.1.7.2 is open source (LGPL) (GNU Lesser General Public License) and has graphical interfaces together with the developer Software Development Kit (SDK), allowing modelling buildings based on geometries [62]. The importance of using this software lies in creating three-dimensional models to evaluate housing materials (envelope), integrating climatic and construction parameters. The climate file was downloaded from EPW Map by LadyBug Tools [63], from the meteorological station TMYx Salinas-Páez International Airport (OMM#842000), latitude -2.2, longitude -81.0. With an elevation of 18 feet and a climate zone of 3A with a time zone of -5.0 GMT. The maximum temperature is 86.18°F, with a daily range of 6.3°F and an average wind speed of 7.49 mph. The building orientation was predetermined at a north-axis angle of 0°. The internal load parameters were modelled by ASHRAE standards 90.2-2018 and 189.1-2009. Internal loads include lighting, television, washing machine, refrigerator, fan and computer. Occupancy hours were defined from 6:00 am to 11:00 pm [64]. The simulation with the HVAC system considered a temperature with the highest cooling demand in semi-arid climates, 21℃ [65], and activation in the summertime, with humidity typical of the province obtained from the weather station (WMO#842000).

2.3 Phase III: Comparative evaluation of housing typologies for sustainability

According to the above criteria, housing types were compared considering their materials, energy consumption, thermal comfort, and environmental impact and conversion systems were evaluated based on their energy efficiency and ability to adapt to different climatic conditions [66]. Based on this, strategies were proposed to help achieve energy sustainability, such as using renewable energy, optimising its resources, thermal insulation contributing to the reduction of energy consumption and CO_2 emissions [67].

3. RESULTS

3.1 Demographic-energy data

The demographic analysis of the 383 respondents in the province of Santa Elena showed a balanced sex distribution, with a slight male predominance of 51.17%. Meanwhile, in the distribution of age, there was a significant concentration of young people and adults, ranging from 18-29 years to 30-44 years. These characteristics, combined with housing typologies, are relevant for energy consumption modelling.

The results show a predominance of brick homes (52.74%), followed by concrete structures (13.58%). Although these structures are built with resistant materials, they pose thermal challenges that affect energy efficiency. Unclad reed housing accounted for 12.27%, followed by wooden homes at 11.75%. A total of 6.27% were clad reed housing, and 3.39% were prefabricated panel housing. Furthermore, the results showed a classification based on the size of the home and its internal layout, with 40.21% of respondents living in dwellings with areas between 51 and 100 m^2, followed by 34.99% living in spaces less than 50 m^2. Similarly, 35.77% of the surveyed homes had three bedrooms. However, there was a 35.25% similarity with two-bedroom dwellings. Houses with more than three bedrooms accounted for 16.19%, followed by houses with one bedroom at 12.79%.

The data obtained highlight the importance of implementing strategies based on construction materials to maximise the performance and sustainability of energy consumption. Furthermore, the results show a significant gap in the adoption of energy-efficient technology in homes, showing that 86.68% do not have technology that helps offset energy consumption, while 5.22% use green technology and only 8.09% use inverter technology.

In Ecuador, specific regulations promote the use of efficient equipment, particularly in air conditioning systems [68]. However, in Santa Elena, it is not applied due to socio-economic conditions and the initial operating cost. It should be noted that the Ecuadorian government, through Executive Decrees N° 384 and 442, promotes the "saving pays" programme, which aims to reduce electricity consumption in homes [69]. This scenario emphasises the need to implement variable-frequency technology that helps optimise the power factor and operational efficiency of equipment to reduce energy consumption and improve efficiency. Similarly, 49.09% of the results correspond to an energy consumption range of 100-200 kWh, whereas 1.31% consumed more than 500 kWh (Table 3).

Table 3. Home energy consumption

Detail	Absolute Frequency	Percentage (%)
< 100 kWh	112	31.59
100-200 kWh	188	49.09
201-500 kWh	69	18.02
> 500 kWh	5	1.31
Total	383	100

It should be noted that adopting energy-saving habits is essential for optimising energy consumption in homes. The sample data showed that 82.25% of homes used energy-saving measures. A total of 39.67% turned off lights when leaving the room, 29.96% unplugged unused appliances, and 23.12% preferred natural light over artificial light. However, 17.75% of the participants did not practice these measures. These data indicate a growing awareness of the use of responsible energy.

3.2 Energy modelling

3.2.1 Housing type parameter

For the modelling, three housing types were considered according to the survey results; each type of housing varied in its thermal envelope and interior distribution. The distribution area of the concrete and brick housing ranges from 51 to 100 m², and for the bamboo housing, an approximate area of 50 m² is chosen. These values stand out in both the survey results and the cluster analysis (Table 4).

Table 4. Criteria for modelling based on survey results

Criteria	Dwelling		
	Concrete	Concrete	Concrete
Area	75.1 m^2	75.1 m^2	50.16 m^2
Rooms	3	3	2
Air conditioning system	No	No	No

The parameters presented for the housing types represent the baseline for OpenStudio modelling, comparing them with the implementation of HVAC systems. These parameters describe the physical and operational conditions that allow the establishment of an energy model, the thermal performance, and the efficiency of the HVAC system.

Figure 4 shows the housing types based on the survey results. Geometry was used to represent the three-dimensional design for a preliminary energy simulation. This process allowed us to define the constructive and spatial characteristics of homes.

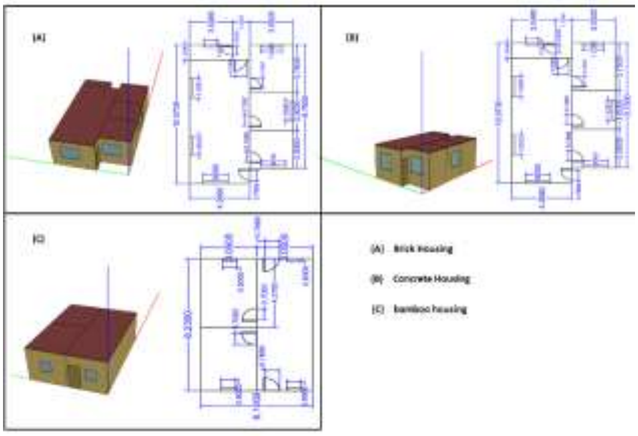

Figure 4. Housing modelling
Note: Sizing in meters

To ensure an efficient simulation, thermal zones were added to facilitate the analysis of each area's thermal behaviour. Spatial types were classified by differentiating between common areas. Construction design was carried out considering aspects such as the heat capacity, conductivity, and thermal resistance of the construction materials (Table 5).

Table 5. Properties of building materials [39]

Material Type	Density (kg/m^3)	Conductivity (W/mK)	U Factor (W/m^2 K)
Brick	1920	0.72	2.79
Concrete	2000	1.13	3.54
Bamboo	714	0.3	5.46

3.3 Energy modelling results

3.3.1 Annual energy consumption of different types of housing

Table 6 shows the annual energy consumption of the three housing types, showing similar trends with slight variations. The energy consumption of brick and concrete homes was identical across all categories, providing consistent results. It highlights that, despite the variability in the thermal conductivity of the materials, there is no heat loss or gain due to the thermal envelope because the modelling was carried out without HVAC systems. The software considers passive energy consumption due to internal loads. However, in the second case, it is attributed to the implementation of HVAC systems.

Table 6. Annual consumption in kWh

Criteria	Dwelling			% of Contribution		
	Concrete	Brick	Bamboo	Concrete	Brick	Bamboo
IL	85.46	85.46	50	5.2	5.2	3.2
OL	74.9	74.9	50	4.6	4.6	3.2
IE	1478.6	1478.6	1456	90.2	90.2	93.6
Total	1639	1639	1556	100	100	100

Notes: IL: Interior lighting; OL: Outdoor lighting; IE: Interior equipment.

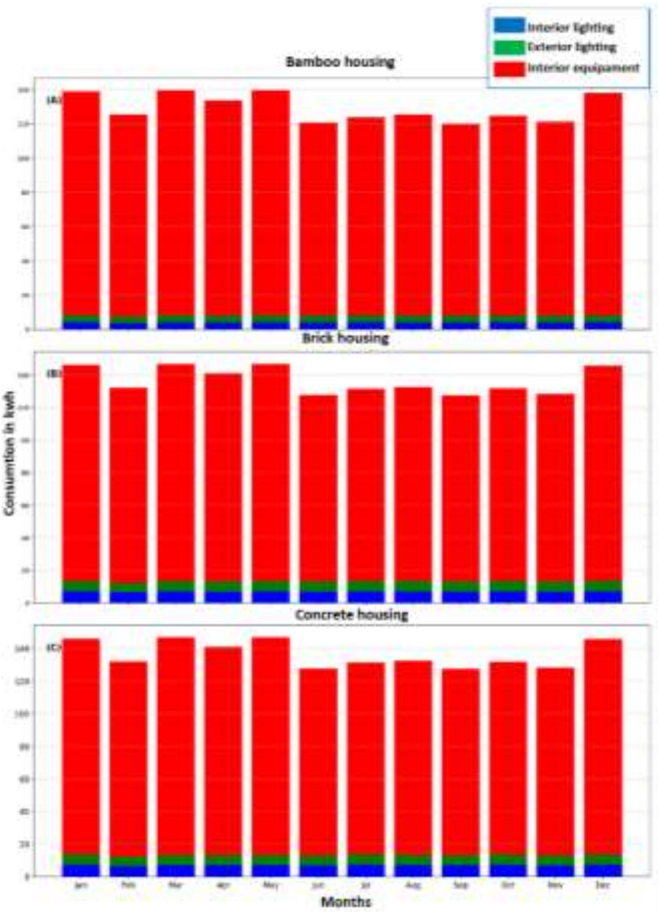

Figure 5. Monthly energy consumption in housing types

Figure 5 shows the monthly consumption of different types of dwellings, revealing a comparative analysis that indicates a slight reduction in energy consumption for brick and concrete dwellings (Figure 5a). This behaviour is associated with the demand for the use of electrical appliances, which allows for maintaining thermal comfort inside the dwelling. In addition, its energy consumption is influenced by thermal variation, suggesting that its construction system favours passive thermal regulation. Despite the increase in energy consumption, a similar trend is observed throughout the year (Figure 5b). It indicates that although the building material (brick) provides a degree of thermal insulation that favours energy demand, it may not be sufficient to reduce the use of internal equipment.

It is observed that similar monthly consumption ratios are maintained for brick dwelling (Figure 5c). It shows that the thermal properties of the two types of housing do not significantly affect the electricity consumption per equipment. However, the concordance of the thermo-physical properties of the materials is influenced by the weather conditions, as high energy consumption is evident during the wet seasons, while there is a slight decrease in the dry season. These fluctuations suggest that these building materials.

3.3.2 HVAC implementation

By implementing HVAC systems in brick and concrete dwellings, a significant increase in annual energy consumption is observed, as shown in Table 7.

Table 7. Annual consumption in kWh with HVAC system

Criteria	Dwelling		% of Contribution	
	Concrete	Brick	Concrete	Brick
Cooling	3817.56	3550.89	67.13	65.85
IL	85.46	85.46	1.50	1.58
OL	74.9	74.9	1.32	1.39
IE	1478.60	1478.60	26	27.42
Fans	230.04	202.24	4.05	3.75
Total	5686.56	5392.09	100	100

Notes: IL: Interior lighting; OL: Outdoor lighting; IE: Interior equipment.

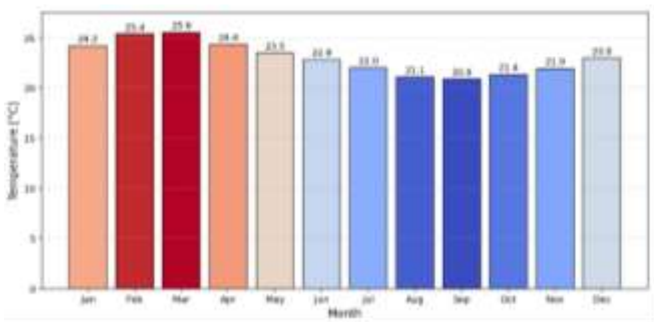

Figure 6. Average monthly temperature, Santa Elena

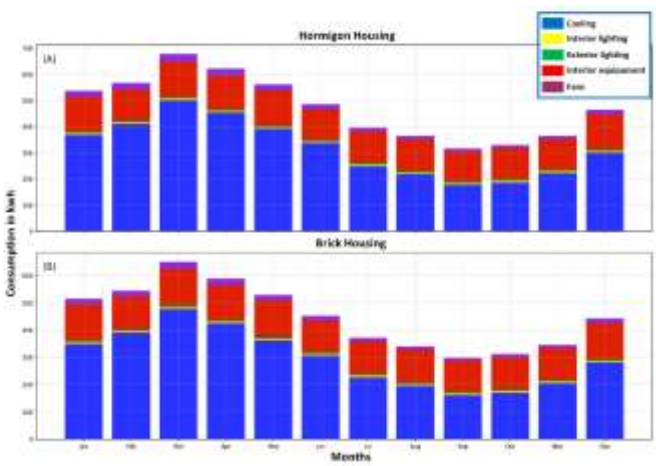

Figure 7. Monthly energy consumption in types of homes with HVAC systems

The variation in energy consumption across housing types is related to different factors, among which the implementation of HVAC systems stands out. These parameters are parameterised according to the climatic conditions and thermal inertia of the building materials. The cooling system operates more intensively in the warmer months because the thermal load of the house increases in correspondence with the seasonal climate in Santa Elena (Figure 6).

Figure 7 (A) shows a significant trend in the cooling system, with peaks in June and July, while Figure 7 (B) shows a similar trend, indicating excessive consumption associated with HVAC during periods of extreme heat.

3.3.3 Sustainability strategies

Energy sustainability in housing is relevant to reducing CO_2 emissions. This highlights the importance of implementing passive designs and thermal insulation in homes to minimise heat loss and gain, thereby reducing the need for HVAC systems and promoting thermal comfort. This study allowed for the development of energy sustainability strategies, considering the diagnosis and classification of housing, surveys conducted, and analysis using OpenStudio software.

Thermal insulation is considered the capacity of building materials to reduce heat transfer, evaluated through their thermal conductivity (λ), and its unit of measurement is W/m. k. The lower the coefficient, the better the thermal insulation. This measure can be used on ceilings, walls, and floors, and its applicability allows for a reduction in dependence on a cooling system owing to heat dissipation in the building materials. For example, when simulating with the insulating material (expanded polystyrene EPS) in the walls, with k=0.04 W/mK, cp=1450 J/(kg K) and ρ=15 kg/m^3 [39], an annual consumption for the brick and concrete house of 4600.59 kWh and 4667.3 kWh respectively was obtained, generating an energy saving of 17.20% for the brick house and 21.84% for the concrete house. Furthermore, considering the CO_2 emission factor for mainland Ecuador of 0.1200 tCO_2eq/MWh [70], the following CO_2 contribution is obtained (Table 8).

Table 8. Annual CO_2 emission with HVAC system

Annual CO_2 Emission	**Brick**	**Concrete**
Without insulation material	0.6471 t $CO_{2\,eq}$	0.6824 t $CO_{2\,eq}$
With insulation material	0.5521 t $CO_{2\,eq}$	0.5601 t $CO_{2\,eq}$
Percentage of variation	17.20	21.84

Implementing strategies such as the responsible use of electrical equipment, lighting, and HVAC systems can reduce energy wastage and optimise system efficiency. An effective way to encourage adopting energy-efficient habits is through training in workshops, social activities, and educational sessions, which can strengthen energy-saving opportunities.

4. DISCUSSION

The results highlighted the importance of addressing the thermal properties of materials due to their proportionality in energy consumption and thermal comfort. The right choice of materials reduces energy demand and optimises its operating cost. Similarly, Zhang et al. [52] emphasised the need for energy-efficient infrastructure because a 1% increase in energy efficiency leads to a price increase of 0.583%. In this way, it is crucial to consider the typology of the construction materials; however, in the houses of the province of Santa Elena, masonry materials predominate at 35.68%; these results are consistent with the data obtained by Soto-Chahua et al. [71], which indicates that 33.33% of the houses in the population centre of Cana Eden, use industrialised materials, affecting thermal comfort due to their high conductivity. The housing design in coastal areas contributes to energy crises due to high levels of humidity, lack of use of sustainable materials, bioclimatic design and thermal insulation; these findings provide an opportunity to design and build passive houses that address social and economic issues. This finding is aligned with the study of Calderon et al. [72] where strategies that help mitigate the energy impact are evidenced, for example, changing the roof for a 0.478 mm aluminium sheet with a 1.5 cm polyurethane thermal insulation, redesigning the walls with wood and distributing areas considering cross ventilation. Similarly, Echarri-Iribarren et al. [73] in their design, achieved a 14.8 cm increase in thermal insulation and optimised thermal bridge breakage, reducing energy loss from 5% to 0.5% and optimising energy demand by 5-8 kWh/m^2 per year in coastal areas of Spain.

When performing energy modelling in OpenStudio with the implementation of an HVAC system, considering the average energy consumption of the two types of housing, an increase of 238% in annual energy consumption was obtained, from 1639 kWh to 5539.33 kWh, which represents an absolute value of 3900 kWh. This variation not only drastically affects the energy demand but also the socioeconomic conditions of the user, where using the tariff range of electricity consumption from the Ecuadorian Electric Corporation Public Company (CELEC-EP acronym in Spanish) residential area [74], its monthly operating value is approximately $46.16 per month. Pérez-Lombard et al. [75] showed that the increase in energy consumption depends on air conditioning systems; for example, in Spain, due to the need to maintain thermal comfort, it has achieved a consumption growth rate of 4.2%. However, Balbis-Morejón et al. [76] indicated that the implementation of these systems requires a high initial cost, limiting the possibility of acquiring technology that helps to optimise thermal comfort in dwellings.

The operability of the HVAC systems is in the fusion of the meteorological conditions of the area; for this case, a temperature of (21℃) was used and for its complement, the information provided by EnergyPlus Weather File (EPW) and thermostat schedules was integrated. Similarly, Coma et al. [65] used temperatures of 21℃-18℃ for their study, based on ASRHAE standards, as the cooling period for the continental Mediterranean climate typically ranges from 23℃ to 26℃. Although this research implemented HVAC systems for comparative analysis, these parameters were not used for the Bamboo housing due to economic and social factors, as Bredenoord [77] indicated that sugarcane housing faces economic constraints that limit access to the implementation of these systems.

The results of this study indicate that concrete buildings with HVAC systems are one of the factors that consume a large amount of energy, at 75.72 kWh/m² per year. In addition, it allowed for the evaluation of the HVAC system's performance in terms of construction materials, ensuring the system was sized correctly to minimise energy consumption. This finding underscores the need for dialogue with decision-makers in the province to implement energy-saving measures. In this context, assessing energy efficiency presents an opportunity to promote sustainable housing, taking into account social, economic, and political factors. According to

Fontalvo et al. [44], the implementation of energy models that facilitate interaction between political factors and energy demand contrasts with the results of this research.

The integration of sustainable strategies in buildings not only contributes to environmental sustainability but also aligns with SDGs 7, 11, and 13. This research, with its data and results, reinforces the criterion that sustainable housing is synonymous with reducing environmental impact, which in turn reduces energy demand in thermoelectric plants, thereby decreasing their capacity and lowering emissions of polluting gases. Shao et al. [25] reaffirmed the criterion that the evaluation of energy efficiency and sustainability is directly proportional, and their applicability reduces the carbon footprint.

Despite the findings obtained during the research, some limitations need to be considered; for example, modelling was carried out using EnergyPlus Weather File (EPW) and DDY (Design Day file), where weather data is predetermined by collecting historical data and by the American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE). However, in a changing world where weather conditions fluctuate with climate change, this could lead to variations in the operability of HVAC systems. Conversely, the lack of simulation of the Bamboo reed house with an HVAC system, considering a wall cladding and a U-factor heat transfer coefficient of 4.61 W/m^2K, could have provided results that would have facilitated a more efficient comparative evaluation, yielding significant data for this study.

While this research yields relevant results, it highlights the need for further studies to validate these findings. Such studies could explore the nexus between energy efficiency and carbon footprint reduction, as well as investigate the applicability of new types of building materials that consider energy efficiency, operating costs, and sustainability.

5. CONCLUSIONS

This research is a proposal that contributes to the area's sustainable development, given the consistency of the data and the correlation between the INEC results, in which concrete, brick and cane houses stand out. Energy efficiency evaluation indicates that concrete is favourable for thermal insulation and energy savings of 71.8 kwh/m^2. The analysis parameters in the OpenStudio software showed that energy performance fluctuates depending on materials and energy consumption, leading to renewable energy, sustainable materials, and thermal insulation.

The Santa Elena province has a tendency towards brick houses, with 52.74%, representing 76.04% of the population. When evaluated based on their thermal conductivity of 0.72 W/m.K with respect to concrete of 1.13 W/m.K, an increasing variation of 5.46% was obtained. This is due to the capacity of the materials to release heat according to their thermal mass, reducing the operability of the HVAC system. However, the implementation of this system increased energy consumption in the range of 1639-5392.09 kWh per year.

This study showed that materials' behaviour in terms of energy consumption provides criteria to promote sustainability strategies and opportunities, break a waste cycle, and take advantage of natural resources. However, the need to conduct comparative studies opens up future research lines that consider different housing types and how they interact with various kinds of thermal insulation.

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APPENDIX

Table A1. Cuestionario estructurado utilizado en la Fase I, versión final
Energy efficiency assessment: A path to sustainability in housing, Santa Elena Canton, Ecuador

Statement of Consent

This survey is aimed at the citizens of the province of Santa Elena and aims to collect information on energy consumption. Your information will be relevant for this study to be carried out, allowing us to evaluate the level of energy efficiency and identify opportunities for improvement to reduce consumption and promote sustainable practices. By continuing with this survey, you are giving your consent for the data provided to be used and published as described above. If at any time you wish to withdraw your consent or change the way your data is used, you can contact us via the following email address: pablo.gonzalezgonzalez@upse.edu.ec

1. Do you wish to participate in the study?
Yes
No

2. Indicate your gender?
Man
Woman

3. What is your age range?
18 - 29 years
30 - 44 years
45 - 59 years
60 years or more

4. Type of housing?
Concrete
Prefabricated panel (gypsum, fiber cement, etc.)
Wood
Brick
Coated bamboo
Uncoated bamboo

5. Is the use of your home exclusively residential or does it include economic activity?
Residential
Residential and commercial

6. What is the total area of your home in m^2
Less than 50 m^2
Between 51 and 100 m^2
Between 100 y 150 m^2
More than 150 m^2
7. What is the number of rooms in your home?
1 room
2 rooms
3 rooms
3 More than 3 room
8. Does it have a climate control system (air conditioning or heating)?
Yes, air conditioning
Yes, heating
Both
I do not have an air conditioning system.
9. Which of the following equipment does your home have?
TV Refrigerator
Washing machine Air Conditioning
Water heater Electric Shower
Freezer Induction stove
Centrifugal Pumps Computer
Fan None
10. Does it have Inverter or Ecological technology to reduce energy consumption?
Ecological
None
Inverter
11. What is energy consumption in kWh in the last two months?
Less than 100 kWh
Between 100 y 200 kWh
Between 201 y 500 kWh
More than 500 kWh
12. Do you use energy saving measures?
yes
No
13. If yes, which of these measures do you use to save energy?
He usually turns off the lights when he leaves the room.
Unplug appliances that are not in use.
Performs preventive maintenance on its equipment to ensure energy efficiency.
Use natural light instead of artificial light during the day.
Other measures.

Table A2. Matrix of proportions by clusters

Variable	Cluster 0	Cluster 1	Cluster 2
Concrete	0.097143	0.063492	0.329268
Prefabricated panel	0.028571	0.031746	0.048780
Wood	0.165714	0.126984	0.000000
Brick	0.502857	0.507937	0.609756
Bamboo clad	0.085714	0.063492	0.012195
Bamboo unclad	0.120000	0.206349	0.000000
Less than 50 m^2	0.171429	0.714286	0.170732
Between 51 and 100 m^2	0.531429	0.190476	0.451220
Between 101 and 150 m^2	0.251429	0.063492	0.280488
More than 150 m^2	0.045714	0.031746	0.097561
One bedroom	0.005714	0.365079	0.024390
Two bedrooms	0.445714	0.277778	0.268293
Three bedrooms	0.400000	0.246032	0.439024
More than three bedrooms	0.148571	0.111111	0.268293
Residential	0.902857	0.936508	0.914634
Commercial	0.097143	0.063492	0.085366
Air conditioning	0.000000	0.007937	0.524390
Heating	0.000000	0.000000	0.256098
Both	0.000000	0.007937	0.219512
None	1.000.000	0.984127	0.000000
Less than 100 kwh	0.017143	0.849206	0.134146
Between 101 and 200 kWh	0.765714	0.111111	0.487805
Between 201 and 500 kWh	0.217143	0.031746	0.329268

More than 500 kwh	0.000000	0.007937	0.048780
Tv	0.954286	0.706349	0.975610
Refrigerator	0.902857	0.698413	0.975610
Washing machine	0.617143	0.309524	0.853659
Air conditioning 2	0.000000	0.015873	0.975610
Water heater	0.000000	0.000000	0.268293
Electric shower	0.017143	0.015873	0.536585
Freezer	0.131429	0.031746	0.256098
Induction stove	0.108571	0.079365	0.146341
Centrifugalpump	0.000000	0.000000	0.036585
Computer	0.497143	0.230159	0.768293
Fan	0.702857	0.333333	0.731707
None	0.000000	0.103175	0.000000

Table A3. Parameters for modeling

Clusters 0		Clusters 1		Cluster 2	
Concrete	0.097143	Brick	0.507937	Concrete	0.329268
Brick	0.502857	Bamboo unclad	0.206349	Brick	0.609756
Wood	0.165714	Wood	0.126984	Prefabricated_panel	0.048780
Between 51 and 100 m^2	0.531429	Less than 50 m^2	0.714286	Between 51 and 100 m^2	0.451220
Two bedrooms	0.445714	One bedroom	0.365079	Three bedrooms	0.439024
Residential	0.902857	Residential	0.936508	Residential	0.914634
-	-	Air conditioning	0.007937	Air conditioning	0.524390
Between 101 and 200 kwh	0.765714	Less than 100 kwh	0.849206	Between 101 and 200 kwh	0.487805

Table A4. Internal loads

Clusters 1		Clusters 2		Cluster 3	
Tv	0.954286	Tv	0.706349	Tv	0.975610
Refrigerator	0.902857	Refrigerator	0.698413	Refrigerator	0.975610
Fan	0.702857	Fan	0.333333	Air conditioning 2	0.975610
Washing machine	0.617143	Washing machine	0.309524	Computer	0.768293
Computer	0.497143	Computer	0.230159	Fan	0.731707