Design and implementation of a web-based residential energy assessment platform: A case study in Cuenca-Ecuador

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Abstract. Population confinement caused by the COVID-19 pandemic has led to an increase in household energy consumption. Electricity consumption in the residential sector in Latin America and the Caribbean increased by 20% during 2020 in comparison to 2019. An upsurge in electricity consumption at the residential level was observed between March and August of 2020 due to the emergency sanitary declaration in Ecuador. Viewed in this context, the residential customers of Cuenca have increased their consumption by around 13% during May 2020 in comparison to the same month of the previous year. Adopting energy efficiency and sufficiency measures could counteract this increase in energy and contribute to managing the demand in the residential sector. The present work aims to evaluate energy savings and emissions reduction in the residential sector in Cuenca through the design and implementation of a web-based platform for estimating electricity power savings. To develop the platform, information was gathered, through surveys, on the energy consumption of the average household. Power consumption of appliances was obtained from various sources, mainly from a database provided by a local appliance retailer. Energy-saving strategies for electrical and electronic appliances were taken from technical guidelines and academic sources. The functional and visual specifications of the platform were designed with specialized tools. The platform allows for calculating household electrical energy consumption and potential savings in energy, economic, and environmental terms in a simple and visually attractive manner. The study shows that 4 members of a family household consumes an average of 182 kWh/month, which is equivalent to 17.1 USD and an annual environmental footprint of 1068.9 kg of CO_2. From this energy consumption, 57% is consumed by household appliances, 31% corresponds to technology and entertainment, and 12% represents lighting. Nevertheless, it is possible to reduce monthly energy consumption by 45% if energy sufficiency and efficiency measures are applied by consumers. This reduction will produce a monthly saving of 7.9 USD and an annual reduction of 485 kg of emissions. By implementing this web-based tool non-specialized users can analyze and decide the best way to reduce energy consumption, creating an appropriate energy culture with a positive impact on the household economy and promoting environmental sustainability.

Keywords: COVID-19, energy consumption, residential sector, energy efficiency, savings potential, CO_2 emissions.

1 Introduction

COVID-19 pandemic had a significant impact on energy consumption dynamics. Population confinement and the application of restrictive measures adopted by the government to control virus spread generated changes in electricity power consuming patterns. Globally the was a 38% decrease in the short-term consumption trend during confinement and a 14.5% decrease during the reopening period; mainly caused by the shutdown and cessation of industrial and economic sectors [1], [2]. Nevertheless, in residential installations energy demand increased by up to 30% during the isolation period [3]. The main factor is the increased use of energy-intensive systems during daylight hours, such as heating, air conditioning, lighting, and appliances. The household electricity consumption, in times of confinement, has increased by up to 30% in hours close to noon and 23% during typical working hours [4]. A study in New York City showed that total energy consumption in the industrial and commercial sectors decreased by approximately 7% during the pandemic. However, household consumption increased by around 23% in March and by 10% in April 2020 [5]. Meanwhile, in Canada, the average daily electricity consumption in a residential household sample increased by 12% in 2020 compared to 2019 [6]. Similarly, research carried out in Huelva, Spain showed that energy consumption from residential customers increased by around 15% during the full shutdown and by 7.5% during the reopening period [1]. In Latin America and the Caribbean, final energy consumption decreased by approximately 9% due to containment measures between 2019 and 2020; however, energy consumption in the residential sector increased by 20% [7]. Ecuador also experienced an increase in electricity consumption in the residential area between March and August of 2020; therefore, the consumption trend in this economic sector was the same for the city of Cuenca [8]. According to data provided by the Empresa Eléctrica Regional Centro Sur C.A., for the year 2019, the consumption of electricity in residential sector in Cuenca was 265.9 GWh, from which 71.3% of energy consumption is represented by urban area. In 2020, energy consumption in Cuenca urban residential sector increased up to 193.8 GWh, unlike 2019 consumption, which was 189.4 GWh. In this context, in March 16th there was a notable increase in average energy consumption per customer, where the maximum value throughout the year is recorded in May with 152 kWh; this is due to during the first three months of the sanitary emergency the confinement measures were more restrictive [9] (Figure 1). In May 2020, residential customers increased their electricity power consumption by 13% taking as a reference the same month of the previous year [10]. Nevertheless, the 25th of May, the city of Cuenca planned a flexible policy, going from red to yellow epidemiological traffic light, and in turn, the economy in the industrial and commercial sector begins to reactivate, which implies an increment in mobility and a reduction in household electricity consumption [11], in such a way that average consumption per customer in August was 121 kWh. In September 13, the state of emergency ended, and in the urban area of Cuenca electricity power consumption for the last 4 months of 2020 had a similar trend like in 2019 [12].

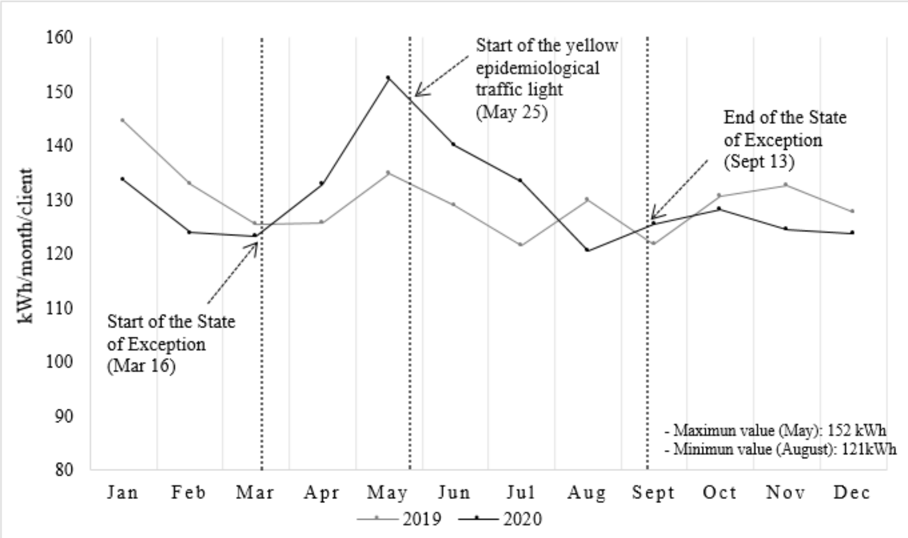

Figure 1. Average monthly electricity consumption per customer in Cuenca.

It is notable that during the time of confinement the household electricity consumption profile had increased throughout the day. Nevertheless, no measures have been taken to ensure a sustainable energy supply to meet the required demand. Furthermore, the poor dissemination of energy-saving information and the high level of electricity subsidies are generally the main causes of indifferent behavior towards the culture of reduction [13], [14]. To reduce energy intensity and absolute energy consumption, not only is it necessary to impose taxes or subsidize investment in more efficient technologies but also to propose incentives or even develop tools that contribute to generating changes in consumption habits [15]. Energy consumption in residential buildings can be reduced with energy-saving strategies such as energy sufficiency and efficiency. The first refers to the consumption of energy services at a level consistent with equity, welfare, and environmental limits [16], [17]. On the other hand, energy efficiency is a strategy consisting of using energy-efficient equipment without considering wether such equipment is used under sustainable consumption patterns [18]. Models, have shown that 48% savings in electricity consumption can be achieved in the residential sector when efficient technology is implemented and consumption habits are improved [19]. Other research, such as Tonn's and Peretz's, study, reports that energy efficiency practices in households reduce energy consumption by 20% [20]; while potential savings of 10-25% can be achieved when people adopt responsible consumption habits [21].

In this context, changes in energy consumption patterns in the residential sector resulting from the impact of the COVID-19 pandemic, are a tipping point for accelerating environmental concern towards sustainable habits and behaviors in post-pandemic [22]. Therefore, energy assessment tools are alternatives that provide information, stimulate energy rationalization, and, with simplified language, allow quantifying electricity consumption in the residential sector. In Ecuador, there are no easy-to-use, easy-to-understand tools developed locally that enable consumers to counteract their lack of knowledge about electricity consumption as it pertains to household appliances, which is one of the most important factors in total household consumption. The present work aims to evaluate energy savings and emissions reduction in the residential sector of the city of Cuenca, Ecuador, through the design and implementation of an online platform to estimate electricity consumption and identify reduction opportunities. This tool can be further be expanded to cover other cities inside Ecuador and other countries within the region.

2 Methods

The scope of the study covers urban residential areas of the city of Cuenca, which is located in the highlands at 2530 m.a.s.l. [23]. Cuenca is organized into 15 urban parishes with 99.64% electricity service coverage [24]. In Cuenca, single-family households represent 73.31% of residential construction with an average of 4.08 people per home [23], [25].

To design the online energy consumption calculation platform, information related to main household appliances used in the residential sector of Cuenca, average electricity consumption, local cost of electricity, CO_2 emission factor, and electricity consumption reduction percentage with both energy sufficiency and efficiency measures were collected. Based on these data, calculation algorithms, functional design of the prototype, and version 1.0 of the platform were developed. Figure 2 shows a general outline of the methodology applied in this research project.

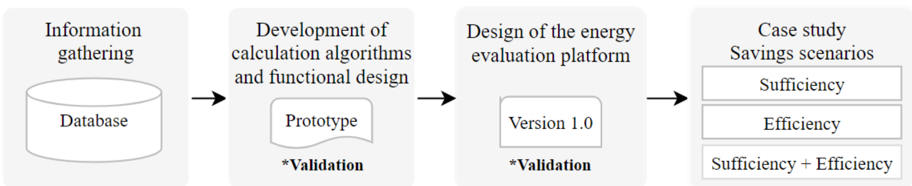

Figure 2. Methodology scheme.

2.1 Data collection

Electricity power savings and emissions reduction assessment of Cuenca's residential sector began with a gathering of information on energy demand and technical specifications of commonly used household appliances. Different types of electronics and electric appliances that can be viewed and selected by users of the platform were obtained from digital surveys applied to 451 households in Cuenca. In this sense, the structured surveys based on semi-closed questions allowed access to quantitative data per household on electricity consumption, quantity and time of daily use of household appliances. The specific sampling design applied is of the non-probabilistic opportunity sampling type, a sampling method considered due to the mobility difficulties and confinement measures generated by the COVID-19 pandemic. On the other hand, the model, power, and energy efficiency of each type of appliance were obtained from a local household appliance retailer's database and also from different catalogs. In addition, the Technical Regulations of the Ecuadorian Institute of Standardization were reviewed to gain legal support and to know which appliances comply with energy efficiency and labeling regulations.

To assess energy reduction potential in housing, energy sufficiency and efficiency strategies were investigated. Savings percentages of these measures were extracted from academic sources and energy-saving and efficiency technical guides from certain organizations and countries. Savings strategies were organized according to household energy needs, taking six categories into account: heating, cooling, household appliances, lighting, sanitary water heating, and technology and entertainment. The application of energy sufficiency measures will depend largely on individual users' degree of interest, knowledge, and commitment to energy saving. Table 1 shows that sufficiency measures found have application in household appliances, water heating, and technology and entertainment categories.

Table 1. Energy sufficiency measures.

Categories	Energy sufficiency measures	Savings (%)	Sources
Water heating	Take regular showers for short periods (maximum 5 min).	20	[26]
Household appliances	Increase the freezer temperature by one degree Celsius.	7.8	[27]
	Increase the temperature by one degree Celsius in the refrigeration compartment.	2	
	Clean the back of the refrigerator.	2	
	Place the refrigerator in a cool and ventilated place, away from possible heat sources: solar radiation, ovens, microwaves, stove, etc.	0.9	
	Do not open the refrigerator door unnecessarily.	7	[28]
	Place the refrigerator at a distance of 15 cm between the back of the refrigerator and the wall.	15	[29]
	Air dry clothes and do not tumble dry.	100	
	Cook in containers with lids.	25	

	Using the microwave instead of the conventional oven saves energy and time.	60	[30]
Technology and entertainment	Disconnect technological and entertainment equipment (TV, computers, consoles, etc.) when not in use.	10	[31]

In terms of energy efficiency, 14 strategies were considered, distributed in all categories. The application of these strategies has an investment cost that is dependent on the type of technology to be implemented and, in general, the return on investment is only recognized after some time. Table 2 presents each of the considered energy efficiency measures and their respective savings percentages.

Table 2. Energy efficiency measures.

Categories	Energy efficiency measures	Saving (%)	Sources
Space heating	Switch to an efficient portable electric heater.	10	[29]
	If possible, install double-glazed windows	15	[32]
Water heating	Change the electric shower to a more efficient one (Save water and energy).	15	[29]
Household appliances	Replace with a low energy consumption refrigerator (class A).	60	[27]
	Replace with a low energy consumption washing machine (class A).	30	[33]
	Buy cookers with induction plates because they consume less electricity than conventional glass-ceramics.	20	[30]
	Replace the electric oven with one with low energy consumption (class A).	30	[29]
	Replace the microwave with a low-energy one (class A).	54	[34]
Space cooling	Switch to an air conditioner with inverter technology.	60	[33]
	Install awnings on the windows where the sun shines the most, avoiding the entry of hot air into the interior of the house and adequately insulating walls and ceilings.	30	[30]
Lighting	Replace incandescent lamps with LEDs.	85	[35]
	Replace fluorescent lamps with LEDs.	60	[36]
	Incorporate lighting controllers (timers, occupancy sensors, dimmers).	20	[37]
Technology and entertainment	Replace the LCD TV with LED technology.	40	[38]

2.2 Calculation algorithms

Before developing the platform, it was initially considered to integrate and test the calculation algorithms in a prototype developed in an Excel spreadsheet to test method functionality and effectiveness. Electricity consumption in homes is generated by lights, washing machines, refrigerators, showers, electric heaters, televisions, and computers, among others. Calculation of monthly energy consumption derived from each appliance, *E*, is defined by Equation 1.

$$E = P \bullet Q \bullet t \bullet f_1 \bullet f_2 \tag{1}$$

where *P* is the power for each appliance (Watt), *Q* is quantity per appliance type (units), *t* is daily usage time (hours), f_1 is an energy conversion factor (1kW/1000W) and f_2 is a time conversion factor (30 days/1 month). However, to determine a household's total energy consumption, E_T, equation 2 is used, where *i* is a type of appliance, *n* indicates the total number of appliance types, *j* is one of the rooms, *m* is the total number of rooms, and E_{i1}+ E_{i2} + E_{i3} +...+ E_{nm} represent the set of electrical consumption values of the appliances in each room (kWh/month). Equation 2 provides more accurate consumption values since the total consumption of a home is calculated based on the energy consumption per room, and it is easier for the user to remember what equipments they have in their home.

$$E_T = \sum_{i=1}^{n} \sum_{j=1}^{m} E_{ij} = E_{i1} + E_{i2} + E_{i3} \cdots + E_{nm} \tag{2}$$

The monthly value to be paid for electricity consumption, V_p, is determined with equation 3, where *c* is the tariff in USD per kWh that is applied according to the level of consumption and as established in the current tariff schedule [39]. The annual CO_2 emissions generated by electricity consumption, G_e, are calculated with equation 4 where f_3 is the time conversion factor (12 months/year) and F_e is the emission factor (0.4897 $kgCO_2/kWh$) used [40].

$$V_p = E_T \bullet c \tag{3}$$

$$G_e = E_T \bullet F_e \bullet f_3 \tag{4}$$

Once electricity consumption has been estimated, saving strategies can be applied to improve energy consumption in the household. Equations 5 and 6 establish the improved consumption with energy sufficiency, E_{se}, and the improved consumption with energy efficiency, E_{ee}, for each appliance respectively. In the equations shown below, *se* denotes savings percentage with sufficiency and *ee* represents savings percentage with energy efficiency for each appliance.

$$E_{se} = E \bullet \left(1 - \frac{se}{100}\right) \tag{5}$$

$$E_{ee} = E \bullet \left(1 - \frac{ee}{100}\right) \tag{6}$$

However, equation 7 shows improved consumption in a household when energy sufficiency and efficiency, E_{see}, are simultaneously applied.

$$E_{see} = E_{ee}\left(1 - \frac{se}{100}\right) \tag{7}$$

The prototype's calculation structure was validated by performing different calculation exercises to verify that the energy consumption reported in the electricity consumption plan of a household is similar to the value provided by the prototype.

2.3 Energy assessment platform design

Once the calculation methodology was validated in the base prototype, a visual design of the web platform (https://redies.com.ec/calculadora/) was developed. This tool has interactive features that ensure easy understanding by non-specialized users to guide them towards an energy-saving culture. Residential energy assessment platform functionality is divided into three sequential stages (Figure 3). The first one consists of collecting input data such as the type, quantity, power, and hours of daily use of the appliances according to the number of rooms in the house, to make it easier for the user to identify the appliances in each room. In this first step, users have the option of using default appliance power values or they can modify these values according to the power specified on the label of each appliance in their home. With this input data, the platform will show the monthly estimate of the home's total energy consumption, consumption distributed by rooms and categories, the estimated cost for the electric service, and CO_2 emissions expressed as the annual equivalent that a vehicle can exhaust.

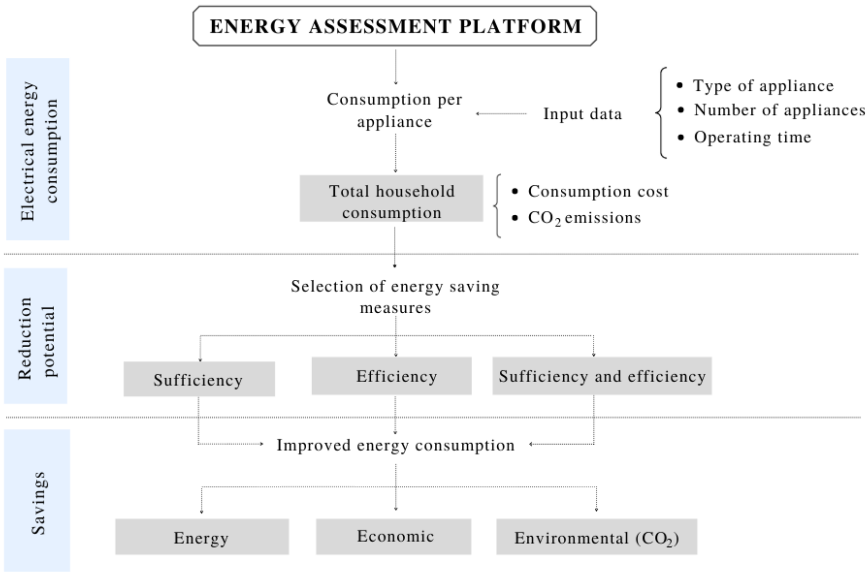

Figure 3. Energy assessment platform functional diagram.

The second phase corresponds to the savings potential; here the platform provides a series of energy efficiency and sufficiency measures for the user to select and see the energy consumption reduction reflected. In the last stage, a detailed summary of the savings achieved in energy, economic and environmental terms is presented on the platform. It also displays improved electricity consumption, percentage energy savings generated by the selected energy sufficiency and efficiency measures, and a pie chart showing improved consumption distribution by category (Figure 4). Finally, to inform about the existence of the platform and encourage a culture of energy saving in the population, in this last section the user is given the option to share the findings of his or her energy evaluation experience through social networks.

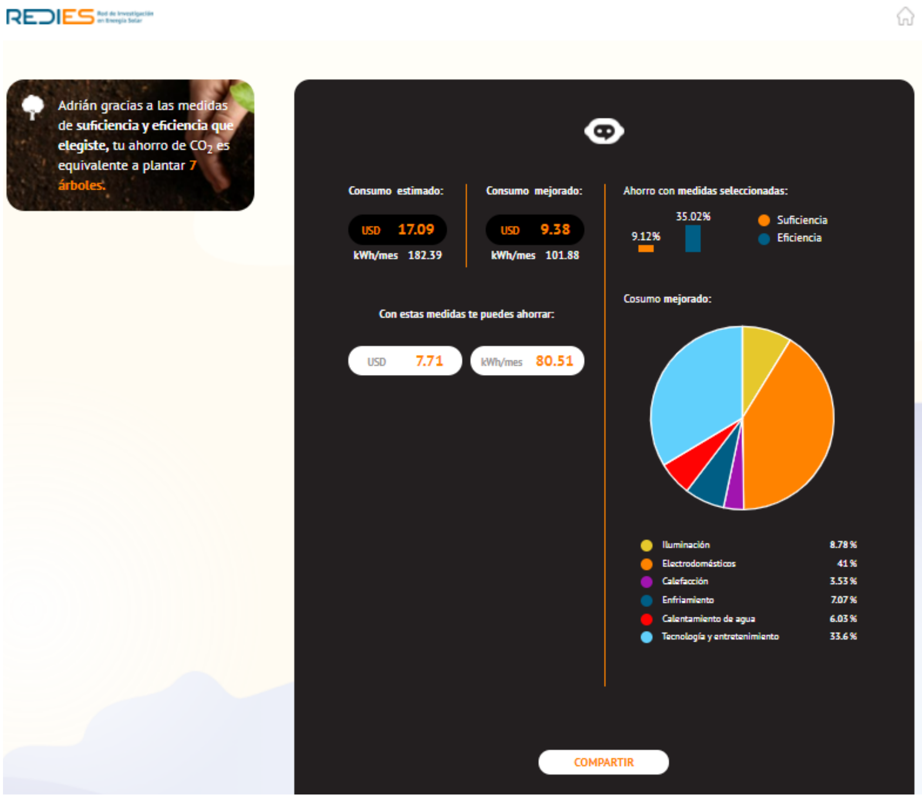

Figure 4. Screenshot of platform results section (results in Spanish).

To ensure the proper functioning of the platform, several test exercises were carried out until the results were congruent with the Excel prototype.

2.4 Case study

The following is a case of study based on data obtained from surveys conducted through digital media, so it should be noted that the results could be biased towards the upper-middle class stratum. The data shows that 139 of the 451 respondents belong to families with 4 members, which represents the average number of people in a household in the city of Cuenca. Thus, the aim is to quantify the average consumption of a home and the reduction that can be achieved by applying the saving strategies available in the residential energy assessment platform.

In order to determine energy-saving potential through the platform, it is necessary to know each appliance's power and the daily number of usage hours. Most common equipment and time of use were obtained based on the surveys; while, to avoid using low or high power values in the appliances to be considered for this study, an average power level was determined for each type of appliance using as reference the power of the efficient and non-efficient equipment available on the platform. Table 3 shows the power, quantity, and time of daily use of the appliances used to calculate the base consumption of a household in Cuenca.

Table 3. Appliances used for the case study.

Categories	Appliances	Power (Watt)	Quantity	Time of daily use
Household appliances	Refrigerator	339	1	8 h *
	Clothes washer	743	1	15 min **
	Vacuum cleaner	1800	1	15 min
	Microwave	1300	1	5 min
Technology and entertainment	LED TV	93	1	1 h
	Plasma TV	170	1	1 h
	Desktop PC	75	2	8 h
	Home audio system	135	1	3 h
Lighting	Luminaire	31	6	4h

* Daily refrigerator run time is based on the proposal estimated by the United States Department of the Energy (USDOE) [41].
** Daily usage time is based on washing machine usage twice a week with a 50-60 min wash cycle duration.

With the appliances' technical information and using the energy platform, a typical or baseline consumption of a house in Cuenca was estimated. Once the average consumption of a household was estimated, sufficiency and efficiency scenarios and the integration of energy sufficiency and efficiency were evaluated to determine the reduction potential in energy, economic and environmental terms.

3 Results

Based on the information gathered, the results of this study show that the average electricity consumption in a typical upper middle class home in Cuenca is 182 kWh/month which is equivalent to a cost for the service of 17.1 USD and an annual emission of 1068.9 kgCO_2. Figure 5 shows that of the base consumption, the household appliances category represents 56.9% (103.55 kWh/month) of total electricity consumption, including the refrigerator, washing machine, microwave, and vacuum cleaner within this category. Technology and entertainment (televisions, computers, and sound systems) occupies second place in the level of consumption with 30.8% (56.04 kWh/month), while luminaires contribute 12.3% of total energy consumption in the home. In addition, there is evidence of a gradual reduction in energy consumption as energy strategies are applied, while the household appliances category shows the highest percentage of savings in all scenarios comparatively, because these appliances have the highest energy consumption, as is the case of refrigerators.

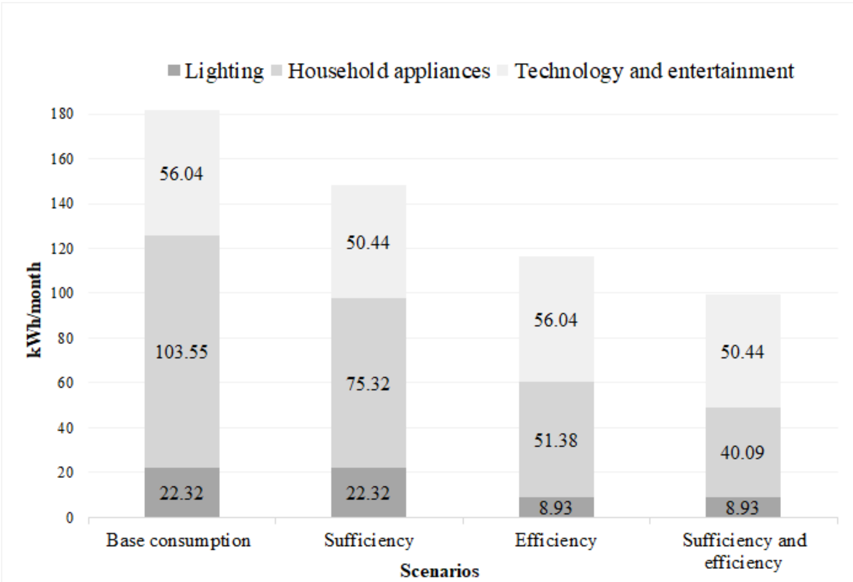

Figure 5. Base consumption and energy consumption reduction scenarios.

According to the above, applying energy sufficiency measures in a household in the city of Cuenca will have an improved consumption of 148 kWh/month, 116 kWh/month with energy efficiency measures, and 99 kWh/month applying the two measures; which in turn represent 19%, 36% and 45% energy savings in the household, respectively (Table 4). In addition, with energy sufficiency, efficiency, and energy sufficiency-efficiency measures the family can achieve monthly economic savings of about 3.3, 6.3, and 7.9 USD, respectively; and an annual reduction in emissions of up to 484.6 kg CO_2/year could be achieved with energy sufficiency-efficiency measures.

Table 4. Reduction potential analysis on base energy consumption in energy, economic and environmental terms.

Scenarios	Cost (USD)	CO_2 emissions (kg/year)	Energy-saving (%)	Monetary savings (USD)	CO_2 savings (kg/year)
Base consumption (BC)	17.1	1068.9	n.d	n.d	n.d
BC+sufficiency	13.8	870.2	19	3.3	198.8
BC+efficiency	10.8	683.7	36	6.3	385.3

BC+sufficiency and efficiency	9.2	584.4	45	7.9	484.6

Note: The monetary values correspond only to the charge for the consumption of electrical energy and are based on the tariff schedule.

In household appliances, energy sufficiency measures were targeted at the refrigerator as the appliance with the highest consumption, and these strategies included: increasing by one degree Celsius in the freezer and refrigeration compartment, cleaning the back, avoiding opening the door unnecessarily, placing the refrigerator away from potential heat sources and placing it at a 15-centimeter distance from the wall. As for the Technology and entertainment category, the measure applied was to disconnect these appliances when they are on standby. On the other hand, to evaluate savings with energy efficiency measures, it was proposed to replace high-consumption appliances and devices with Class A labeling.

4 Discussion

The platform is a dynamic and easy-to-use web tool designed to be used by residential users in Cuenca's urban area to evaluate the electricity consumption in their homes. The particularity of this tool is that it orients the user towards a saving culture based not only on efficiency measures but also on energy sufficiency; in such a way that it allows evaluating electricity consumption reduction according to family solvency. In addition, it reflects the results of energy savings in monetary and environmental terms, which can be very useful for users to understand the economic benefits and generate awareness within the family environment about the importance of reducing greenhouse gas emissions. These innovative features and advantages extend and improve the functionalities provided by other web tools such as "Planillita" developed by the Electricity Regulation and Control Agency in Ecuador [42], the "Edenor Simulator" of Argentina [43] and the "Energy Calculator" of the Ministry of Energy and Mines of Peru [44], which only have functions that integrate the calculation of the monthly electricity consumption and the cost of the service, without providing concrete information to the user on the energy, economic and environmental savings that can be achieved if consumption reduction strategies are applied.

Based on the proposed case study, the results of the energy evaluation show that the average consumption of a house in Cuenca is 182 kWh/month and that by using the platform to determine the potential for reduction according to energy sufficiency, efficiency, and sufficiency-efficiency scenarios, a reduction of 19%, 36% and 45% in electricity consumption can be achieved. These results are consistent with those reported by Baquero and Quesada [23], who determined that by applying basic strategies such as replacing electrical appliances with efficient equipment, taking advantage of natural lighting, and replacing conventional lighting fixtures with LEDs, a 46% maximum electricity saving of total consumption is achieved. However, the average consumption for a home in Cuenca determined from this work is 10.66% higher than the value reflected in our study. Another research conducted in Bogotá, Colombia showed that, by applying a model of demand management strategies, consumption reductions from7% to 19% are achieved when residential users change their consumption habits; from 6% to 26% when replacing devices; and from 17% to 45% of total savings when energy sufficiency and efficiency strategies are combined [45].

However, it should be noted that the platform calculates consumption reduction potential based on energy efficiency and sufficiency savings percentages extracted from academic sources. Although the values may be determined in different conditions and contexts, it can be considered that the first version of the electricity consumption calculator generates useful insights to encourage electricity savings in residential customers. As for the source of the appliances list displayed on the platform, the database of a local retailer and various equipment catalogs were included. The advantage of having a first complete local inventory of electrical and electronic equipment is that, with relatively little specific information, it is possible to show the user appropriate data according to the study area. However, this data can be modified as new information becomes available until a sufficiently nourished database is consolidated.

Finally, the accuracy of electricity consumption calculation and the potential savings that the user will be able to observe after using the residential energy assessment platform will depend on the accuracy level concerning the appliances usage time, the power according to the efficiency level, and the number of strategies that the user considers to apply to the equipment present in the household.

5 Conclusions

In this paper, we have presented the development of the first version of a residential energy assessment platform that allows a dynamic and simple way to estimate the electricity consumption of households in Cuenca. This tool has 11 sufficiency measures and 14 energy efficiency measures that are distributed in 6 consumption categories; so that the user can evaluate the potential energy, economic, and environmental savings. Concerning this case of study, which determined that the average consumption in a typical upper middle class house in Cuenca is 182 kWh/month, and when evaluating the reduction potential for this consumption with the scenario that integrates energy sufficiency and efficiency, it is possible to achieve 45% energy savings, which represents a monthly saving of 7.9 USD in the payment of the electricity bill and a reduction in emissions of 484.6 kg CO_2/year. However, when evaluating the energy sufficiency scenario where no investment is required, a 19% reduction in energy consumption can be achieved, a monetary saving of 3.3 USD and the annual emission of 198.8 kg CO_2 into the atmosphere can be avoided. These results demonstrate how energy sufficiency and efficiency contribute to the management of electricity demand in the residential sector. Finally, as future work, it is planned to carry out acceptance tests of the platform; and a statistical analysis on the estimates of electricity consumption, electricity savings and CO_2 emissions using the record of information provided by the users through the platform.

In addition, we intend to conduct pilot tests with distribution and commercialization agents (electricity companies) to extend the application to other cities in Ecuador.

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