Energy and Economical Study of Different Renewable Energy Technologies for Domestic Hot Water Production Under the Climatic Conditions of the Main Cities in Ecuador

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1 Introduction

It is known that approximately 40% of energy consumption in the world comes from the building sector. Thus, one of the Sustainable Development Goals worldwide is to mitigate the effects of global warming through renewable energy sources and efficient technologies to reduce CO_2 emissions from the building sector [1].

In recent decades, this sector has focused its efforts on reducing energy consumption on heating, ventilation, air conditioning (HVAC) systems, and lighting [2]. This has generated that the energy used to produce domestic hot water (DHW) increases in buildings, reaching up to 32% of the annual energy balance consumption [3].

The goal is to replace conventional systems for DHW production (gas boilers, electric boilers, tanks with electric heating, electric showers, etc.) [4] for more efficient technologies and the use of renewable energy resources [5]. Thus, the proper selection of DHW systems can significantly help reduce energy consumption, CO_2 emissions, and operating costs.

At a global level, different, more efficient, and environmentally friendly technologies have been developed for DHW production; for example, heat pumps that are optimal for their high operating coefficient (COP), on average, has values close to

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3. Hence, for each unit of electricity consumption, there are three units of heat production [6]. This type of system has been developed in the last decade and has a lot of potential for hot water production at low operating costs.

Other technologies use a renewable energy source like the sun. Solar thermal systems (ST) transform solar radiation into heat using solar collectors like flat plates, vacuum tubes, or concentration collectors [7]. Solar photovoltaic (PV) technologies transform solar energy into electrical energy, which is used for water heating [8]. While this system is not exergetically efficient, the production costs of PV panels make it very economically competitive. There is also thermophotovoltaic (PV/T) technology, which combines the two systems mentioned above, and heat can be used directly to produce DHW. In contrast, electricity can be used for direct water heating with a heat pump or the immediate electricity consumption of the building [9].

In recent years in Ecuador, greater importance has been given to reducing energy consumption since it represents a high public cost due to the subsidies. The Organic Law of Energy Efficiency regulates the rational use of energy and favors research and technological development in this field [10]. In the building sector, the primary energy demand is due to the lighting, office equipment, and in the residential sector to produce DHW [11]. As far as the production of DHW is concerned, the most used systems are electric (electric shower or boiler) and gas boilers. Considering that both energy sources are subsidized, there is a potential for economic savings if the country changes to more efficient systems. It is essential to mention that Ecuador has a high and constant solar potential throughout the year and the territory [12], making it necessary to investigate technologies such as solar thermal and photovoltaic for application in DHW production.

In this context, this article shows energy and economic research on using different systems for DHW production in the residential sector in different cities of Ecuador. This is done to identify which technologies are more efficient according to the weather and the electricity consumption rate in different country cities.

2 Methods

To reach the objective of this study, a methodology divided mainly into an energy analysis, and an economic analysis is proposed. The energy analysis will estimate the electricity demand of the different DHW production systems at a monthly and annual level. The economic analysis will use the system yearly energy consumption data to evaluate, in the long term, which of the alternatives is more economically feasible in the different cities. The following section describes the details of the case study and the methodology used for energy and economic analysis.

2.1 Case Study

In this field, the use of different systems to prepare DHW in a typical house in Ecuador located in different places with markedly different climates has been analyzed. The house is inhabited by four people and has a consumption of DHW of 120 L/day. The consumption profile presents a peak of 60 L from 7 to 9 h, 30 L at 14 h, and 30 L at 19 h.

2.2 Weather Data

To consider different climatic conditions, the study has been carried out in the following cities of Ecuador: Quito, Guayaquil, Esmeraldas, Tena, Santo Domingo de los Tsáchilas, and Puerto Baquerizo Moreno. Table 1 shows the annual values of global irradiation, diffuse irradiation, and annual ambient temperature mean for each location. This data has been obtained from the NSRDB database managed by the *Systema Advisor Model* (SAM) simulation software.

2.3 Systems Description

In the present study, six different ACS production systems are evaluated:

- *Heating system with electrical resistance:* This system is considered as the reference system or conventional system. It consists of a water storage tank of 150 liters of water volume that is heated by a 700 W electrical resistance. This resistance is powered by energy from the entire electrical network (Fig. 1a).
- *Heating system with heat pump:* This system consists of a heat pump of 750 W thermal power and a nominal COP of 3 that is connected to the storage tank (150 liters) through a heat exchanger. The heat pump is powered by energy from the entire power grid (Fig. 1b).

Table 1 Locations annual global and diffuse solar irradiation and ambient temperature mean

City	Temperature	Solar radiation	Diffuse solar radiation
	°C	kWh/m^2	kWh/m^2
Quito	11.1	1908	863
Guayaquil	25.7	1767	870
Emeralds	25.4	1804	920
Tena	23.2	1569	897
Santo Domingo	22.7	1307	912
Puerto B. Moreno	23.7	2100	731

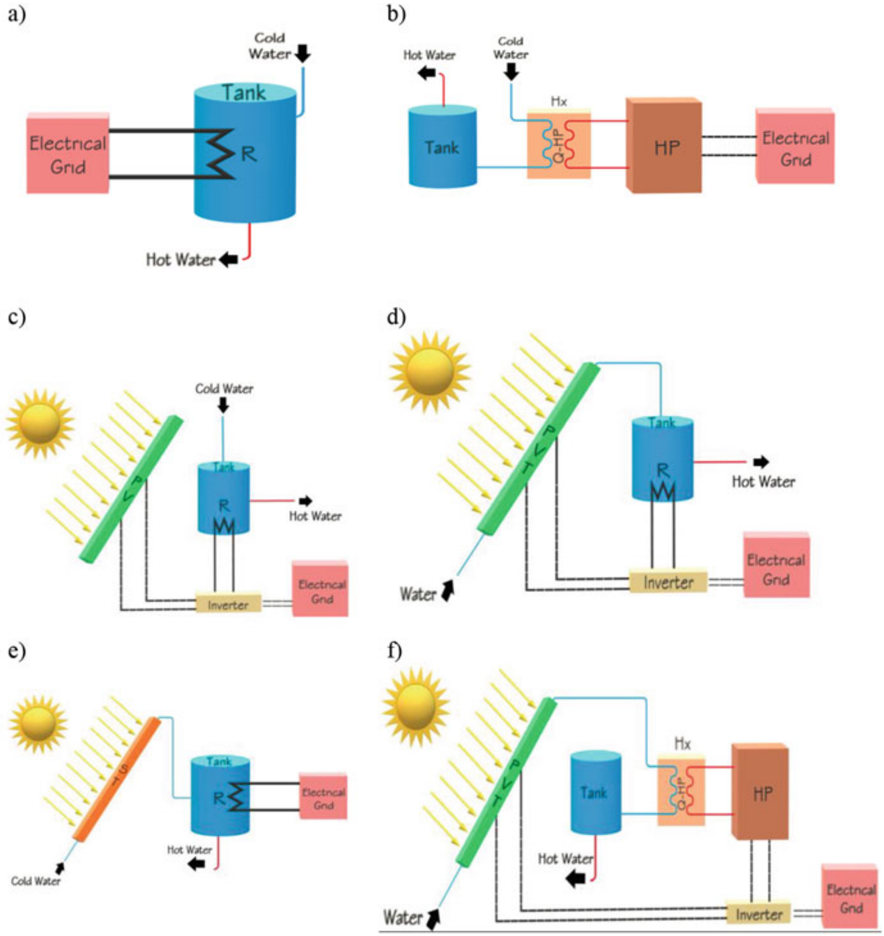

Fig. 1 Systems analyzed for DHW production: (**a**) electrical resistance, (**b**) heat pump, (**c**) electrical resistance + PV, (**d**) electrical resistance plus PV/T, (**e**) electrical + solar thermal resistance, and (**f**) PV/T + heat pump

- *Water heating system with electrical resistance assisted by a photovoltaic panel (PV):* The difference with the reference system is that the electrical resistance is assisted by the energy produced in a 2 m^2, 330 Wp photovoltaic panel, which is connected to the electricity grid to inject the surplus energy (when it exists). Likewise, the resistor is connected to the electrical network in case the energy produced in the PV panel is not enough or null (Fig. 1c).
- *Water heating system with electrical resistance assisted by a thermophotovoltaic* panel *(PV/T):* In this system, the water heating is assisted by solar thermal energy from the thermal side of the PV/T panel that serves to heat or preheat the water. If the thermal energy is not enough to reach the desired temperature, an electrical resistance (700 W) is used as an auxiliary system. The electrical resistance uses

the electrical energy produced by the PV/T. The PV/T is connected to the grid to inject any energy (if needed). Likewise, the resistance can use 100% of the electrical network energy in case the solar resource is null (Fig. 1d). The PV/T panel has a peak electrical power of 300 W, a maximum optical performance of 90%, and a surface area of 2 m^2.

- *Water heating system by solar thermal collector:* This is a heating system assisted by solar thermal energy from flat plate solar collectors with maximum optimal performance of 80% and a surface area of 2 m^2. If the solar resource is not sufficient to reach the desired temperature in the storage tank, an electrical resistance (700 W) connected to the grid heats the water (Fig. 1e).
- *Water heating system with heat pump assisted by a thermophotovoltaic* panel *(PV/T):* This system has a water storage tank (150 liters), and the water heating is assisted by solar thermal energy from the PV/T panel. When the solar thermal energy is not enough to reach the desired temperature in the tank, a heat pump is activated that is assisted by the electrical energy coming from the PV/T. The PV/T is connected to the mains for the injection of any surplus energy. Likewise, the heat pump is connected to the electrical network to be fed in case the electrical energy of the PV/T is not enough or is null (Fig. 1f).

2.4 Energy Analysis

To perform the energy analysis, TRNSYS dynamic simulation tool for energy systems will be used. This tool has different libraries of systems such as solar thermal collectors, photovoltaics, water tanks, solar irradiation processors, pumps, etc. Fig. 2 shows the Graphical Programming Environment Simulation Studio of TRNSYS for the system in Fig. 1f. It is important to mention that TRNSYS simulates the performance of the different thermal systems considering the dynamic behavior. TRNSYS performs a yearly simulation in 1-hour timestep. That is, it performs 8760 simulations considering the weather variations from a typical meteorological year (TMY) file.

2.5 Economic Analysis

The public electricity service in Ecuador is characterized by being highly subsidized, with a complex tariff schedule, which divides consumers into different types and categories according to the range of consumption [13]. The residential consumers' categorization implies that a different rate may apply depending on the region of Ecuador, given the geographical location.

Likewise, the economic development of a province determines the demand for electricity in each household. Hence to establish the rate applicable to each city, the per capita consumption according to the province is taken as a reference [14], and a

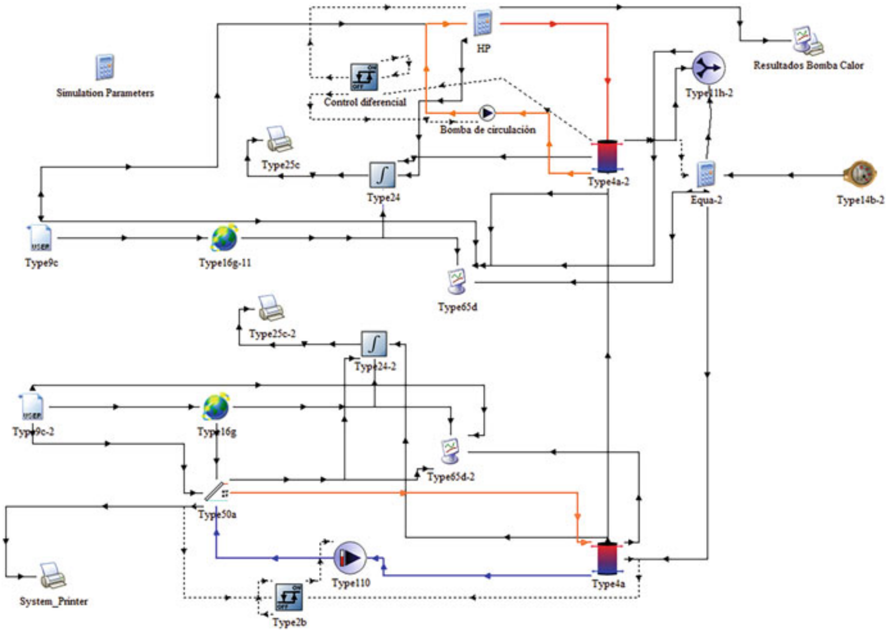

Fig. 2 Schematic of TRNSYS Simulation Studio for the system in shown in Fig. 1f

Table 2 Electricity rate according to the city

City	Per capita consumption kWh/year	Category consumption	Fare USD/kWh
Quito	1261	351–500	0. 105
Emeralds	822	351–500	0. 105
Puerto Baquerizo Moreno	1729	501–700	0. 1285
Guayaquil	1681	501–700	0,1285
Loja	562	151–200	0. 097
Tena	655	201–250	0. 099
Santo Domingo	974	301–350	0. 103
Zamora	1234	351–500	0. 105
Macas	562	151–200	0. 097

family nucleus of four people is considered. The average kWh consumed monthly is being set and as a result of the tariff range in which this consumption falls. Table 2 shows the electricity tariff data for the cities under study.

The rate per kWh is used to determine the operating cost of each of the systems under study and to calculate the savings produced by replacing the heating of water with electrical resistance with other alternatives.

The calculation of the annual costs includes the cost of operation and maintenance of the systems, as reflected in the estimation is 1 and 2 respectively:

$$Cop = Ec \times Te \tag{1}$$

$$Com = Cop + Cm \tag{2}$$

where *Cop* is the annual operating cost in USD, *Ec* is the annual energy consumed by the system in kWh, *Te* is the electricity tariff in USD/kWh, *Cm* is the annual maintenance cost in USD, and *Com* is the annual operation and maintenance cost in USD.

The maintenance period is every ten years for the electrical resistance system and every five years for the other systems. Maintenance includes labor costs and component replacement. To establish energy savings, the difference between consumption with the use of electrical resistance and the alternative system is considered, according to Eq. 3:

$$Savings = (Ecr - Ec) \times Te \tag{3}$$

where *Saving* is in USD and *Ecr* is the energy consumed by the system with electrical resistance in kWh.

It is important to mention that being a service that uses a residence, water heating becomes an expense. Therefore, the analysis is oriented to determine which of the systems represents a lower cost throughout the useful life of the equipment. A time of 20 years is used for the analysis, which refers to the duration of the photovoltaic panel.

In this way, the energy savings represent economic risk or absence of expense, which could compensate for the initial investment in the installation of the system.

In this context, a cash flow, with the discount rate equal to the reference passive rate of the Central Bank of Ecuador, is used to calculate the net present value of the total expenditure over the life of the equipment. A lower cost will be beneficial for the user since it represents a saving in the expense from the use of solar energy instead of the electrical energy coming from the distribution network. If the result gives a positive value, this will imply that there is a recovery of the capital initially invested in the installation of the system caused by the savings in operation.

3 Results

This section shows the relevant and summarized results of the energy and economic analysis carried out for the six heating systems studied in the nine defined cities.

3.1 Energy Analysis: Electricity Demand

Figure 3 shows the results obtained from the energy analysis for the city of Quito with the monthly electricity demand of each of the systems studied. The reference system (electrical resistance) is the one with the highest electricity consumption followed by the photovoltaic (PV) panel-assisted electrical resistance system.

The latter has a high electricity consumption due to the photovoltaic panels having a low efficiency (less than 15%), so the electrical resistance would work constantly. On the other hand, it can be seen in Fig. 3 that the PV/T system assisted by heat pump presents a negative electricity consumption in all months. This is because the heat pump can provide hot water without having a high electricity consumption. In this way, the electricity demand of the heat pump is assisted in total (at a monthly level) by the electrical energy gained in the PV/T panel. The negative value indicates that a surplus of electricity is injected into the electricity grid, thus generating an electricity credit on the monthly payroll that can be compensated with the electricity consumption of the house (for lighting and equipment).

A more favorable case is that of the Puerto Baquerizo Moreno city, shown in Fig. 4, with better values of extra energy injected to the grid.

Table 3 shows the summary of the results of the energy analysis for all the cities part of this study. As can be seen in the table, for all the cities of study, the PV/T system with heat pump is the one that energetically has a better behavior. This was to be expected since the heat pump has a low energy consumption (compared to an electrical resistance) that is supplied entirely by the electrical energy generated in the PV/T panels.

It can also be observed that although the demand for electricity for water heating is similar in all cities, electricity consumption varies in each system. In the case of the heat pump system, it is expected that warmer cities will have lower energy consumption compared to colder cities. This is because the performance (COP) of the

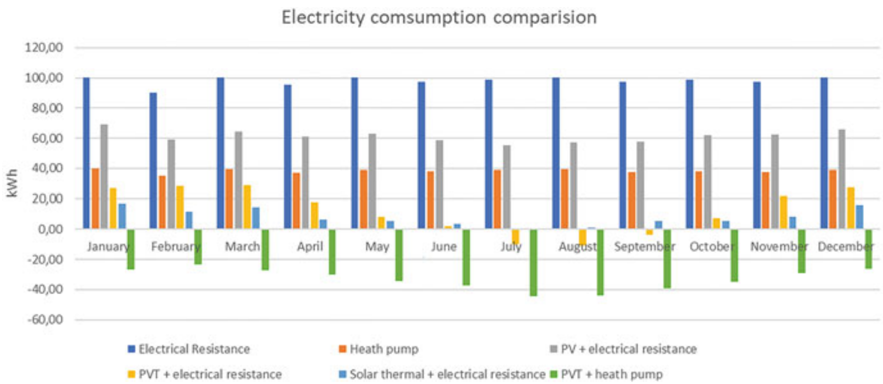

Fig. 3 Comparison of electricity consumption for the different systems studied for the city of Quito

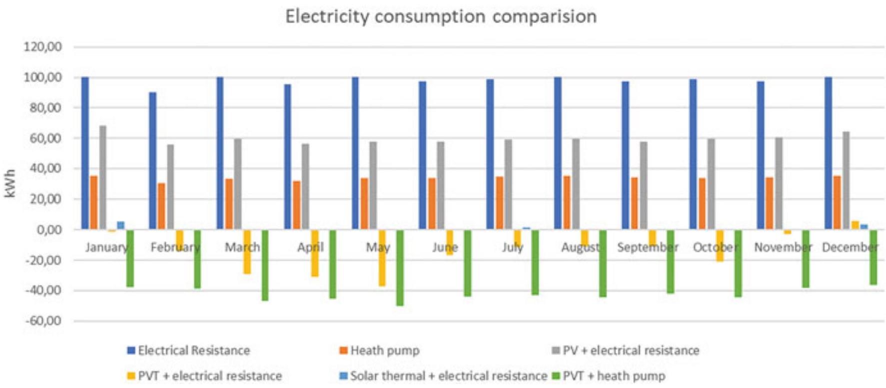

Fig. 4 Comparison of electricity consumption for the different systems studied for the Puerto Baquerizo Moreno City

heat pump is influenced by the environmental conditions of the heat source (ambient temperature). Thus, where the ambient temperature is higher, a heat pump for heating will operate with a higher COP.

3.2 Economic Analysis

The energy analysis is combined with the costs established in the electricity tariff for each city and is used for the calculation of the net present value that allows to compare the cost of the systems for the user, considering a useful lifetime of 20 years. The heating system with electrical resistance, used as the reference case, produces the installation, operation, and maintenance costs, for the studied places indicated in Table 4.

By performing the same analysis for the rest of the cities and systems, the least expensive system for each city can be determined. These results are shown in Table 5.

It is evident that the cost of installation, operation, and maintenance depend on both the electricity tariff and the solar resource present in the place. All cases have in common that the alternatives to the reference system are less expensive, and even in the case of Puerto Baquerizo Moreno, it is possible to recover the investment during the analysis period.

Table 3 Annual electricity consumption for all the systems studied for each city

City	Electrical resistance	Heat pump	PV + resistance	PV/T + resistance	ST + resistance	PV/T + heat pump
Quito	1176.36	458.31	735.5	144.78	95.32	−395.94
Emeralds	1176.36	397.80	779.74	−27.16	51.96	−424.36
P.B. Moreno	1176.36	404.25	715.49	−179.23	13.16	−510.00
Guayaquil	1176.36	395.78	790.74	−89.18	43.62	−426.18
Loja	1176.36	432.06	795.66	219.35	144.57	−144.57
Tena	1176.36	438.63	814.64	361.64	229.35	−274.84
Sto. Domingo	1176.36	417.41	884.89	497.9	367.72	−197.68
Zamora	1176.36	428.07	845.77	396.21	317.38	−240.82
Macas	1176.36	427.26	818.1	300.01	190.86	−296.62

Table 4 VAN of the total cost of the electrically resisted system

City	VAN USD
Quito	−2115. 28
Emeralds	−2115. 28
Fr.B. Moreno	−2466. 78
Guayaq uil	−2466. 78
Loja	−1995. 62
Tena	−2025. 53
Sto. Sunday	−2085. 36
Zamora	−2115. 28
Macas	−1995. 62

Table 5 NPV results for the least expensive system by the city

City	Major VAN system	VAN USD
Quito	Solar thermal with electrical resistance	−1003. 22
Emeralds	PV/T with electrical resistance	−846. 87
Fr.B. Moreno	PV/T with electrical resistance	17. 80
Guayaquil	PV/T with electrical resistance	−276. 47
Loja	Solar thermal with electrical resistance	−1224. 98
Tena	Solar thermal with electrical resistance	−1415. 86
Sto. Sunday	PV/T with heat pump	−1678. 17
Zamora	PV/T with heat pump	−1523. 02
Macas	Solar thermal with electrical resistance	−1339. 16

4 Conclusions

The present study aimed to analyze energetically and economically different systems of production of domestic hot water (DHW). Through the results it was possible to show that for all the cities studied there is a more efficient DHW production system than the reference system (heating with electrical resistance). However, it was shown that, depending on the electricity tariff and the solar radiation potential of each city, not always the same DHW production system is the most feasible.

For example, for the cities of Quito, Loja, Tena, and Macas, due to their relatively high solar radiation and no lower electricity cost than in other cities, the most economically feasible system is the solar thermal system with flat plate solar collectors and an electrical resistance as an auxiliary system. On the other hand, for cities with high solar radiation and high cost of electrical energy such as Esmeraldas, Puerto Baquerizo Moreno, and Guayaquil, the DHW production system with PV/T and electrical resistance as an auxiliary system is the most profitable. This is due to the electricity savings that are produced by the electrical production of PV/T panels.

Finally, for the cities of Santo Domingo and Zamora, due to their lower solar radiation and high electricity cost, it was evident that the DHW production system with PV/T-assisted heat pump is the most profitable in the 20-year horizon. Although this system is the one with the highest initial investment cost, the electricity savings from the use of a heat pump justify this investment in the long term.

This work opens the door for future research on the technical feasibility of local development of technologies such as solar panels, PV/T, and heat pumps in the country. Due to the unique weather conditions in Ecuador, a low-power heat pump would work efficiently and without representing a high investment. Likewise, different electric energy cost scenarios can be studied to determine minimum electric energy costs so that each of these systems are profitable throughout their useful life. Finally, it is worth mentioning that nowadays the use of artificial intelligence tools such as machine learning could be used to predict the performance of DHW systems considering the variability of the weather conditions in a place like Ecuador. This could open the door for further interdisciplinary investigation in this field.

References

1. International Energy Agency (IEA). (2019). *World Energy Outlook 2019 – Analysis - IEA*. World Energy Outlook.
2. Pomianowski, M. Z., Johra, H., Marszal-Pomianowska, A., & Zhang, C. (2020). Sustainable and energy-efficient domestic hot water systems: A review. *Renewable and Sustainable Energy Reviews, 128*, 109900. Elsevier Ltd. https://doi.org/10.1016/j.rser.2020.109900
3. O. Ibrahim, F. Fardoun, R. Younes, and H. Louahlia-Gualous, "Review of water-heating systems: General selection approach based on energy and environmental aspects," Building and Environment, vol. 72. pp. 259–286, Feb. 2014, https://doi.org/10.1016/j.buildenv.2013.09.006.
4. Li, X., Wu, W., & Yu, C. W. F. (2015). Energy demand for hot water supply for indoor environments: Problems and perspectives. *Indoor and Built Environment, 24*(1), 5–10. SAGE Publications Ltd. https://doi.org/10.1177/1420326X14564285
5. Fuentes, E., Arce, L., & Salom, J. (2018). A review of domestic hot water consumption profiles for application in systems and buildings energy performance analysis. *Renewable and Sustainable Energy Reviews, 81*, 1530–1547. https://doi.org/10.1016/j.rser.2017.05.229
6. F. J. Aguilar, S. Aledo, and P. V. Quiles, "Experimental study of the solar photovoltaic contribution for the domestic hot water production with heat pumps in dwellings," Applied Thermal Engineering, vol. 101, pp. 379–389, May 2016, https://doi.org/10.1016/j.applthermaleng.2016.01.127.
7. British Standards Institution. (2006). *Thermal solar systems and components: Solar collectors. Part 2, Test methods*. BSI British Standards Institution.
8. Aguilar, F. J., Crespí, D., & Quiles, P. V. (2019). Experimental and numerical study of the domestic hot water production with PV panels and a heat pump. *E3S Web of Conferences, 111*, 01066. https://doi.org/10.1051/e3sconf/201911101066
9. Chow, T. T. (2010). A review on photovoltaic/thermal hybrid solar technology. *Applied Energy, 87*(2), 365–379. https://doi.org/10.1016/j.apenergy.2009.06.037
10. ASAMBLEA NACIONAL. (2019). Ley Orgánica de Eficiencia Energética. *Registro Oficial, 449*.
11. Ministerio Coordinador de Sectores Estratégicos, Balance Energético Nacional. 2015.
12. Ordóñez, F., Morales, C., López-Villada, J., & Vaca, S. (2018). Assessment of the energy gain of photovoltaic systems by using solar tracking in equatorial regions. *Journal of Solar Energy Engineering, 140*(3). https://doi.org/10.1115/1.4039095
13. ARCONEL. (2019). Pliego Tarifario para las Empresas Eléctricas de Distribución.
14. ARCONEL. (2019). Estadística Anual y Multianual del Sector Eléctrico Ecuatoriano.