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Impact of Solar Thermal Energy on the Energy Matrix under Equatorial Andean Context

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Abstract: Low-temperature solar thermal energy is a viable and mature alternative to reduce the use of fossil fuels for domestic hot water heating. The impact of the inclusion of this technology in the energy matrix in the Andean city of Cuenca, Ecuador, is analyzed. In Ecuador, liquefied petroleum gas (LPG) is currently used to heat water due to the high state subsidy, with a cost of 0, 11 USD for an LPG kg compared to the international price of 1.18 USD a Kg of LPG in 2021. Sustainability indicators show that the urban energy matrix would be minimally affected by a high penetration of solar thermal systems. The indicators that are positively affected are related to energy self-sufficiency, emissions, and employment at the expense of an increase in the cost of energy. Moreover, the analysis of the impact on consumption exclusively in the residential sector shows that liquefied petroleum gas consumption would drop from 73 to 64%, mainly because the liquefied gas is used in cooking. However, the change in technology is limited by the subsidized cost of liquefied petroleum gas, which makes the adoption of this technology difficult in the current state

Keywords: solar thermal; sanitary hot water; LEAP; energy matrix

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1. Introduction

Solar thermal (ST) technology is useful for increasing the temperature of a gaseous or liquid fluid, usually air, water, or coolant. In ST systems, a solar collector surface transfers the energy in the form of heat to the fluid. Then, the fluid is conducted through an aerial or hydraulic circuit until its final application, sometimes deferring the use of energy through storage. The most widespread technologies for buildings are flat plate collectors (FPCs) or evacuated tube collectors (ETCs). Despite the emergence of collectors designed for architectural integration [1], given their costs, complexity, and lack of standardization, these collectors do not prevail in the market. ST systems are typically used to satisfy demands for domestic hot water (DHW), industrial applications, and even cooling [2,3].

Previous studies have analyzed the use of FPCs and ETCs comparatively. The market share of these two technologies varies in each country. For example, in Turkey, the United States, Mexico, and China, FPCs account for 99, 86, 36, and 5% of the market share, and ETCs account for the remainder [4–6]. ETCs are more efficient than FPCs in cold climates and climates with a substantial presence of diffuse irradiation; however, their cost exceeds the cost of FPCs by 20% [7]. FPCs have a greater absorption area than ETCs with a similar footprint, which allows them to compensate for their energy generation when direct irradiation predominates, and there are no losses due to the external cold [8].

Due to solar intermittency, solar thermal systems require backup equipment fed from conventional sources (electricity or fossil fuels), guaranteeing the user the required temperature and amount of energy. Residential solar thermal systems require storage, which may or may not be integrated, and if not, require pumping of the fluid [4]. The incident fluid in the solar panels can be directly used in the applications, or there can be a cooling fluid in a separate circuit that delivers the energy through a heat exchanger, heating the water for use [9]. This variability in designs and equipment causes investment costs to vary by up to an order of magnitude [9].

The technology is available for applications in single-family households, buildings, and urban districts. In Mexico, it has been estimated that, in urban housing, 45.60% of the LPG used for water heating can be replaced by thermal collectors. Despite the existence of a potential market for the technology as an economical alternative, if it is compared with LPG, adequate incentives are needed to support the adoption of ST technology [5]. In the Chinese cities of Haining, Huzhou, and Ningbo, where solar water heaters are manufactured, the use of this equipment exceeds 90% in urban areas. The success of the social adoption of this technology depends not only on the lack of fossil resources but also on production infrastructure, economic incentives, and municipal policies. In addition, a positive image of the use of this technology has been built, which has allowed wide acceptance among the public [6]. Izquierdo et al. [10] conclude that 68.40% of hot water requirements can be supplied using ST in 8005 Spanish municipalities. To achieve this, less than 20% of the roof surface is needed, with the rest being available for photovoltaic panels.

The influence of shadows in ST technology is less important than in photovoltaic technologies. Marique et al. [11] showed that urban density affects thermal energy production due to the area available for the placement of thermal panels. Lower energy production is obtained in areas with lower housing density per surface area. In the case of the floor space index (FSI), or the ratio of the total surface of the building to the total area in which it is built) with values lower than 1.5, the thermal demand can be fully supplied [12].

Due to the maturity of the ST technology, it is used in different countries with different degrees of penetration. The availability of space for its placement can be a limitation, as can the requirement of auxiliary energy; nevertheless, this technology has clear advantages for efforts to reduce energy demand. Table 1 shows the potential of the technology in different places.

Table 1. Technical energy potential for different cities.

City	Potential	Demand	Use	Reference	Objective of the Study
Mexico (urban residential areas)	45.60%	29,088 GWh/year	Thermal	[5]	Evaluates the solar potential for water heating.
Spain (8005 municipalities)	68.40%	28,249.00 GWh/year	Thermal	[10]	Determines the roof surface available for the placement of thermal solar panels.
Concepción, Chile (3233 dwellings)	75.00%	19,788.70 MWh	Thermal	[13]	Determines the hip-end with the best suitability per dwelling according to orientation and inclination; compares joint feasible production in the area of study against typical demands.

The present study investigates the technical, economic, and environmental implications of the inclusion of ST technology for water heating in a market (Ecuador) where liquefied petroleum gas (LPG) is mostly used as fuel due to the strong subsidy. In Ecuador, it is essential to provide alternatives to LPG to reduce or eliminate current public spending on this fuel, which is mostly imported. However, the possible elimination of the subsidy without promoting any alternative would entail an important social impact [14]. This work establishes different scenarios of ST penetration and the possible impact on energy consumption in the residential sector of the city of Cuenca in Ecuador.

1.1. Characteristics of Low-Temperature ST Systems

The efficiencies in the case of ST systems vary according to the technology and system, as observed in studies reflected in Table 2, depending on the characteristics and efficiency, which are correlated with the climatic conditions and demand.

Table 2. Technical energy potential for different cities.

Efficiency (%)	Source
70	[15]
80	[10]
35	[8]
65 to 70 Flat plate collector	[7]
70 to 75 Evacuated tube collector	[7]

In the case of ST energy for applications in households, a direct thermosiphon system may be needed. This system is less expensive than indirect systems with electronic controllers or systems that require pumps; however, with the integrated collector, the equipment involved in thermosiphon systems has greater dimensions and weight, affecting architectural and structural requirements. The wide availability of technologies means that costs also vary widely [9]. Low-power applications require between 1.4 kW and 3.4 kW and mean power requirements are between 14 kW and 140 kW. Systems considered large scale for district heating require between 0.5 and 2 MW [16]. For single-family households, the power requirements can be between 1.5 kW and 15 kW; however, the systems requiring high power include DHW and solar heating [17]. The costs of the facilities are shown in Table 3.

Simple ST systems with integrated thermosiphon storage do not require operating costs related to electricity consumption, unlike those that use pumps and electronic systems. The maintenance of this equipment is necessary to increase its useful life. A system subjected to adequate and periodic maintenance can exceed 30 years of useful life [9]. Table 4 shows the operation and maintenance values related to equipment investment. Operation and maintenance costs related to the investment are established in %.

Table 3. Investment costs (DHW production).

System	Investment Costs	Reference
Solar water heaters	546 USD/kW Thermosiphon flat plate collector 1.4 kW *–2 m^2)	[4]
	502 USD/kW Direct without pump 1.3 kW–1.85 m^2	[4]
	440 USD/kW Direct thermosiphon 2.48 kW–3.55 m^2	[5]
	671 USD/kW Thermosiphon flat plate collector 1.4 kW–2 m^2	[16]
	300 USD/kW ** Thermosiphon evacuated tube collectors 1.05 kW–1.05 m^2	[9]
	786 USD/kW Direct thermosiphon evacuated tube collector 1.4 kW–2 m^2	[18]

Table 3. *Cont.*

System	Investment Costs	Reference
Solar water heaters	2309 USD/kW Indirect with pump 3.24 kW *	[19]
	2150 USD/kW Indirect with pump 3.85 kW	[18]
	790 USD/kW Direct with pump 2.3 kW	[16]
	1120 USD/kW Flat plate collector 10 kW	[9]
	854 USD/kW Flat plate collector less than 20 kW ****	[9]
	649 Flat plate collector less than 40 kW ****	[7]
	1322 USD/kW Evacuated tube collector 10 kW	[20]
	960 USD/kW Evacuated tube collector less than 20 kW ***	[20]
	887.5 USD Flat plate collector	Local suppliers Ecuador (2021)
	1425 USD Evacuated tube collector	Local suppliers Ecuador (2021)

* Calculated considering that 1 m^2 of solar collector is equivalent to 0.7 kW/m^2 [9]. ** 1 CNY (Chinese Yuan) = 0.14 USD. *** 1 € = 1.12 USD. **** Mean values of those presented in the S classification of the Solar Heat for Industrial Processes database [20].

Table 4. Investment costs (DHW production).

System	Inv. (%)	Source	USD/kW
Solar water heaters	1 4.25 Parallel plate collectors	[19]	17.95
	5.45 Evacuated tube collectors	[18]	

Renewable energies (RE) are characterized by their low or zero emission of gases into the atmosphere in their operational phase; however, manufacturing the components requires inputs and energy valued through the life cycle analysis. Therefore, this analysis is considered depending on the manufacturing or operation phases. In this same sense, the life cycle analysis provides an assessment from manufacturing to waste that includes the associated impacts from extraction to final disposal [21]. Although life cycle analysis is a powerful tool for identifying environmental impacts, the studies' results are different. This difference is due to the regional context in which the analyses are applied (energy demand, resource), the configuration of the system [8], or the tools used for the evaluation. Tables 5–7 show the results of CO_2, SOx, and NOx emissions associated with global warming, acid rain, and eutrophication, respectively.

Table 5. CO_2 emissions (DHW production).

kg CO_2/GWh	Reference
33,998.5 Flat plate collectors	[8]
29,340.0 *	[22]
13,998.0 * Flat plate collectors	[23]
24,480.0 Evacuated tube collectors	[23]
38,998.8 Evacuated tube collectors	[8]

* The mean value of that presented in the reference study.

Table 6. SO_2 emissions (DHW production).

kg SO_2/GWh	Reference	Mean kg SO_2/GWh
205.0 Flat plate collectors	[8]	185.6
209.9	[22]	
162.6	[23]	
151.6 Evacuated tube collectors	[23]	
207.0 Evacuated tube collectors	[8]	
205.0 Flat plate collectors	[8]	

Table 7. NO_x emissions (DHW production).

kg NOx/GWh *	Reference
292.3 Flat plate collectors	[8]
72.0 **	[22]
857.5 ** Flat plate collectors	[23]
886.3.15 Evacuated tube collectors	[23]
315.4 Evacuated tube collectors	[8]
292.3 Flat plate collectors	[8]

* The original values are in phosphate (PO4). The conversion1 g NOx = 0.13 g PO4 is used [24]. ** It is the average value of what was presented in the reference study.

1.2. The Intermediate City of Cuenca

Intermediate cities are considered those that do not exceed one million inhabitants; from an administrative point of view. They are more governable cities with greater administrative management capacity [25]. They are particularly suitable cities to implement policies, and experiences in these cities can be extrapolated to other cities with similar characteristics. Cuenca in Ecuador is located in the Andes mountain range, near the equatorial line. The city is located between the geographical coordinates 2°30′ to 3°10′ south latitude and 78°51′ to 79°40′ west longitude, with a mean elevation of close to 2600 m asl [26]. Figure 1 shows the spatial location of the city of Cuenca. The proximity to the Equator and the altitude produce a temperate climate with little variability during the year. The minimal seasonal variation implies minimal variability of irradiation demands and levels.

Approximately 2.28% (73 km^2) of the territory of Cuenca (3,190 km^2) is urbanized. By 2010, Cuenca had a population of 505,585 inhabitants, 329,928 living in the urban area (65%) and the remaining 35% in the headwaters of rural parishes and populations scattered within the cantonal territory. In the last census period (2001–2010), the urban population presented a 2.75% annual growth. Currently, the urban population is approximately 400,000 inhabitants, according to projections.

The Cuenca diagnosis prepared by the Inter-American Development Bank [27] establishes that the city has ideal coverage in terms of providing basic services of water, sanitation, solid waste management, and electrical energy coverage (greater than 80%). However, urban growth, and the corresponding increase in the number of vehicles, have increased air pollution. The problem is complicated by the considerable horizontal expansion of the city, which hinders the provision of services [27].

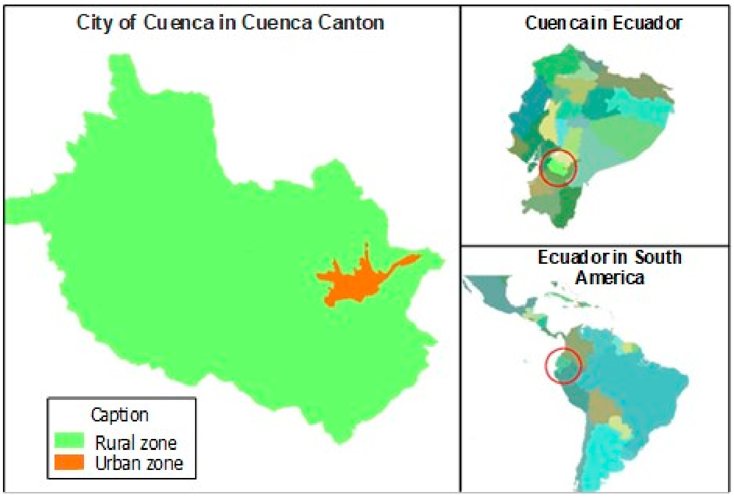

Figure 1. Spatial location of the Cuenca canton, urban area.

In the urban area of Cuenca, 59% of the population uses LPG for sanitary water heating, and 35% uses electricity (showers and heaters) [28]. The use of ST heaters is negligible. The LPG is distributed to users through 15 kg cylinders. The gas must first be liquefied and stored and then transported to the consumption centers, where it must undergo a regasification process before household use [29].

2. Materials and Methods

To assess the impact of ST energy in the city of Cuenca, the energy balance of the baseline situation was determined. Three possible scenarios of ST adoption are defined. Each scenario establishes how the energy demand in the residential sector would be modified with the adoption of ST technology. A perspective is established that allows comparisons of each proposal with the base case.

To estimate how the intensive adoption of ST systems would affect the urban energy model, sustainability indicators are used to determine how the social, environmental, and energy dimensions would be altered with the adoption of this technology.

2.1. Scenarios

The scenarios proposed are based on experiences in other countries, and particularities of the study site are incorporated. The scenarios will allow comparisons with the base case based on energy balances in the residential sector and based on sustainability indicators in the urban energy matrix. In the latter case, the first scenario is analyzed (intensive use of ST panels).

Scenario 0. The use of LPG for DHW heating is maintained.

Scenario 1: An extreme case based on experiences in Chinese cities is considered (Han et al., 2010). In the case of a consolidated market, 95% of the demand covered by this technology could be reached. If, in addition, it is considered that in Cuenca, the solar fraction would not exceed 78% [30], a contribution from other sources, such as electricity or LPG, would be needed. With this assumption, 74% of LPG could be substituted by ST technologies.

Scenario 2. This scenario is proposed based on a study by Calle-Seguncia in an area where he proposes that ST technology could account for 44% of domestic hot water heating by 2030 [31].

Scenario 3. This scenario is based on the suggestion of the Energy Research Institute of Ecuador (Instituto de Investigación de Energía–INER) [32], which proposes the adoption of ST technology in 90% of electrical systems for households.

For the assessment of scenarios, the LEAP model (Long Range Energy Alternatives Planning System) (https://leap.sei.org/ (accessed on 1 June 2022)) was used to characterize and disaggregate the energy demand required by the residential sector. The choice of the LEAP model as a tool to assess urban metabolism is novel since it also allows the inclusion of the estimated potential of RE in the city. The degree of disaggregation makes it possible to incorporate other efficiency measures or policies aimed at reducing energy imports.

To establish the urban energy baseline of the city of Cuenca, available information was gathered from national, institutional, and academic reports. Specific information was requested from several entities that do not necessarily handle the issue of energy but were essential to disaggregating energy demand. Since the local government does not plan in terms of energy and the entities that manage energy (fuels and electricity) do not focus on the urban situation of Cuenca, it was necessary to gather and consolidate the energy information of the city in a previous study. It was determined that the city of Cuenca has a high dependence on fossil resources. Sixty percent of the energy is used for transportation, while that consumed by productive activities and commerce does not exceed 25%, and the residential sector requires 13.7%. In the same sense, the consumption of fossil fuels accounts for 90% of energy use, while electrical energy accounts for 10% [33]. With the level of disaggregation, particularly in industry and transportation, which account for approximately 80% of energy requirements, it is possible to identify where it is appropriate to make technological changes or undertake energy efficiency campaigns.

The thermal energy demand required to provide DHW was used to develop scenarios. The value used in the LEAP model of useful energy corresponds to 878.49 kWh/year per dwelling. Of the households that use DHW, 89.00% use a water heater that uses LPG, with an efficiency of 45%. Since 94% of the total households have DHW, there is an energy requirement of 1633.22 kWh/year per household for this service.

2.2. Sustainability Indicators Used to Measure the Impact of the Use of ST Heaters for DHW in the City of Cuenca

Previously defined sustainability indicators are used to analyze the incidence of ST systems in the city of Cuenca [34]. These indicators are intended to holistically measure how the environmental, social, or economic vertices are affected by implementing public policies promoting ST collectors' use.

The indicators are used or constructed based on what is intended to be measured. In this case, it is proposed to use the same indicators used at the national or regional level [35–37].

Through these indicators, the impact of an energy model that encourages the intensive use of ST systems can be evaluated. This information would support the construction, for example, of public policies aimed at promoting RE in the city.

The indicators used should also be formulated based on the available information [38]. Likewise, indicators that use variables that do not overlap with others are preferred; that is, indicators whose variables are not modified if the variables that compose them are modified are preferred. The indicators used to measure the energy structure of the countries and, in this case, are applied to estimate the incidence of technology in an urban area. Table 8 shows the indicators that measure sustainability and that are applicable in cities. In addition, the references on which the indicators are based are included.

Table 8. Energy sustainability indicators.

Dimension	Indicator	Unit	Source
Economic	Autarchy	%	[39]
	Energy price	USD/BOE *	[40]
	Mean energy price	USD/BOE	[40]
Environmental	Use of RE in energy supply	%	[39]
	Use of RE in electricity supply	%	[40]
	Purity of energy	CO_2/BOE	[39]
Society	Employment	Jobs-year	[38]

* Barrels of oil equivalent (BOE). 1 BOE ≈ 1628.2 KWh.

2.2.1. Energy Autarchy

Energy autarchy is an indicator that measures the share of imports in the energy supply [39], as shown in Equation (1):

$$EA = \frac{\sum_i^m IE_p + \sum_i^n IE_s}{ES} \quad (1)$$

where,

EA is the autarky [%],
IE_p indicates primary energy imports (BOE),
IE_s indicates secondary energy imports (BOE), n is the number of primary energy forms, and m is the number of secondary energy forms.
ES is the gross domestic energy supply (endogenous energy + primary energy imports + primary energy imports-primary energy exports-secondary energy exports) (BOE).

2.2.2. Energy Price

The energy price is obtained from production costs plus profits (Ut) and taxes (Tx) [40], expressed in Equation (2).

$$PE_j = C_e \times (1 + Pr) \times (1 + Tx) \quad (2)$$

where,

PE_j is the energy price j [USD \$/BOE],
C_e is the cost of energy production during its useful life [USD \$/BOE],
Pr is the business profit [%], and
Tx indicates taxes [%].

2.2.3. Cost of Energy Production

The cost is calculated according to Equation (3):

$$Ce = \frac{\sum_t [Inv_t + O\&M_t] \cdot (1 + r)^{-t}}{\sum_t \left[Eth_t \cdot (1 + r)^{-t}\right]} \quad (3)$$

where,

Ce is energy production cost during its useful life [USD/kWh],
Inv is the investment in the year (including interest during construction and all auxiliary elements and electrical infrastructure) [USD/kW],
$O\&M$ represents operation and maintenance cost per year t [USD/kWh],
r is the discount rate,
Eth is the energy produced in year t [kWh], and
t indicates the years of operation of the plant.

2.2.4. Mean Price of Energy to the Final Consumer

The mean price of energy to the final consumer represents the mean energy prices, according to [40], expressed in Equation (4).

$$PE = \frac{\sum_{j=1}^m \sum_{k=1}^n PE_{jk} \times E_{jk}}{\sum_{j=1}^m \sum_{k=1}^m E_{jk}} \quad (4)$$

where,

PE is the mean energy price [USD \$/BOE],
PE_{jk} is the price of energy k in sector j [USD \$/BOE],
E_{jk} is the amount of energy of energy k in sector j [BOE],

m is the number of consumption sectors, and
n is the number of energy forms.

2.2.5. Use of RE in the Total Energy Supply

The use of RE in the total energy supply is the participation or contribution of RE in the urban energy matrix [39], in concordance with Equation (5).

$$UR = \frac{\sum_i^m RE_i}{ES} \tag{5}$$

where,

UR is the share of RE in the total energy supply [%],
RE_i is the supply of RE i [BOE],
ES is the gross domestic energy supply [BOE], and
m is the number of renewable energy production technologies.

2.2.6. Use of RE in the Supply of Electricity

The use of RE in the supply of electricity indicator assesses the participation of RE in the production of electrical energy [40], according to Equation (6):

$$URe = \frac{\sum_i^m REe_i}{ESe} \tag{6}$$

where,

URe is the participation of the RE in electric energy production [BOE],
REe is the production of electricity using RE with i [BOE] technology,
ESe represents the electrical energy requirements in [BOE], and
m is the number of electrical energy production technologies with RE technologies.

2.2.7. Relative Purity of Energy Use

This indicator relates CO_2 emissions to energy consumption [38], expressed in Equation (7).

$$PRe = \frac{CEC}{\sum_i^m ED_i} \tag{7}$$

where,

PRe is the energy purity [ton CO_2/BOE],
CEC represents the carbon dioxide emissions related to energy demand [ton CO_2],
ED is the total energy demand [BOE], and
m is the energy required in the city.

Emissions related to demand (CEC) [41,42] are estimated with Equation (8) with the help of the LEAP Model:

$$CEC = \sum_i \sum_j \sum_n AL_{n,j,i} \times EI_{n,j,i} \times EF_{n,j,i} \tag{8}$$

where,

$AL_{n,j,i}$ is the activity level related to fuel type n, equipment j, and sector i;
$EF_{n,j,i}$ is the emissions factor related to fuel type n, equipment j, and sector I; and
$EF_{t,m,s}$ is the emissions factor related to the primary fuel type used to produce secondary energy type t using equipment type j.

The emissions factors are those suggested by the Intergovernmental Panel on Climate Change (IPCC) [42].

2.2.8. Employment

This indicator describes the number of jobs related to the energy industry [39], calculated through Equation (9).

$$Em = \sum_{i}^{m} D_i \times fe_i \quad (9)$$

where,

Em represents the jobs per year in the energy industry,
D_i is the energy demand i [BOE], and
fe_i is the energy use Factor i [jobs-year/BE].

3. Results

The energy demand ST for a mean family is calculated by [6] with Equation (10):

$$Eth = Q \cdot \rho_a \cdot Ce \cdot (T_{use} - T_{netw}) \cdot n \quad (10)$$

where,

Eth is the heat energy demand to heat water (kJ/year),
Q is DHW consumed (L/day),
ρ_a is water density (kg/L),
Ce is the specific heat of water (4.18 kJ/kg°C),
T_{use} is the temperature at which the water is to be supplied (°C),
T_{netw} is the water network temperature (°C), and
n is the number of days per year (days).

The information in Table 9 is considered for the city of Cuenca.

Table 9. Standardization indicator parameters.

Indicator	x_{max}	x_{min}	Units
Autarchy	0	1	
Energy price	10	400	USD/BOE
Mean energy price	40	70	USD/BOE
Use of renewable energy (RE) in energy supply	0.1	0.5	t CO_2/BOE
Use of RE in electric power supply	1	0	
Purity of energy	1	0	
Employment	1000	300	Year-jobs

3.1. Scenarios and Prospects

3.1.1. Baseline

According to the Sustainable and Safe Housing survey conducted by the University of Cuenca [28], electricity and LPG are used for water heating (Table 10). With information from Martínez [43] showing that 13% of electricity is used for heating purposes, and the assumption that 40% of LPG is used for this purpose, the energy intensity EI is calculated. Table 11 shows the data used for the model.

For the base year, the city of Cuenca required 2,717.00 thousand barrels of oil equivalent (k BOE) in total urban consumption, representing a per capita consumption of 40.33 GJ/inhabitant/year (6.93 BOE/inhabitant or 11,205.49 kWh/inhabitant). This value is higher than the Ecuadorian mean of 35.44 GJ/inhabitant/year. The main sources of energy are fossil fuels (36.25% gasoline [GA], 29.05% diesel [DI], 14.81% LPG, 8.04% fuel oil [FO], and 2.19% natural gas [GN]), while electricity contributes 10%. This structure is similar to the consumption pattern nationwide (Ministry Coordinator of Strategic Sectors [37].

This model uses the calculation in Table 10 for fixed conditions, which will be affected by the habits and number of family members. Table 11 shows that the energy required for a family of four in the city of Cuenca is 2648.70 kWh/year. However, to analyze a possible technology substitution, the energy use per household used in the LEAP model is considered (Table 11).

Table 10. DHW demand for the city of Cuenca and required equipment.

Parameter	Value	Source
Q (L)	160 4 users	[30]
ρ_a (kg/L)	1.00	
C_a (kJ/C kg)	4.18	[30]
T_{use} (°C)	55.00	[30]
T_{netw} (°C)	16.00	[30] The mean temperature of Cuenca is 15 °C. The temperature of the network is considered to be 1 °C higher.
n	365	
E_{th} (MJ/year)	9534.03	
DE (kWh/year)	2648.34	
Solar fraction (%)	78.00 *	[30]
Energy contribution of the system (kWh/year)	2065.70	
Area of the collecting system (m^2)	2.40	[30]
Power of the collector system (kW)	1.68 **	
Plant factor (%)	14.04	

* The calculation of this parameter includes the performance of the solar panel. ** Calculated considering that 1 m^2 of solar collector is equivalent to 0.7 kW/m^2 [9].

Table 11. Information required for the LEAP Cuenca, residential, DHW model. Saturation: 94% [28]. AL: 107,598 households.

Type	Efficiency (%)	Reference	AL (%)	EI (kWh/Household)
LPG water heater	45	[44]	89.00	878.49
EE heater	90	[44]	1.00	
EE shower	90	[44]	10.00	

The energy balance in the city of urban Cuenca (Balance de Energía en la ciudad de Cuenca urbana-BEC) is detailed in Table 12. Since there are no energy production and processing facilities, all the energy required by the canton is imported. Electricity losses are 7% [45], and no losses are assumed due to fuel distribution [37].

In the case of the residential sector, whose energy sources are LPG and electricity, Table 13 shows the energy balance in the KBOE. In Figure 2, on the other hand, the energy demand and the final destination in the residential sector are presented in proportion.

In the particular case of energy consumption for DHW, LPG is the primary fuel, followed to a lesser extent by electrical water heaters and electric showers. According to [33], the base condition is shown in Table 14.

Table 12. Energy balance of the city of Cuenca canton (kBOE).

	EE	NG	GA	DI	FO	LPG	Total
Production	-	-	-	-	-	-	-
Import	282.13	59.47	984.85	789.35	218.49	402.46	2736.75
Export	-	-	-	-	-	-	-
Total supply	282.13	59.47	984.85	789.35	218.49	402.46	2736.75
Distribution	−19.67	0.00	0.00	0.00	0.00	0.00	−19.67
Total transformation	−19.67	-	-	-	-	-	−19.67
Residential	102.34	-	-	-	-	270.39	372.73
Industry	61.89	59.47		127.33	216.55	98.68	563.92
Transportation	-	-	984.83	642.73	-	-	1627.56
Commercial	59.62	0	0	0	0	25.89	85.51
Public lighting	18.56	0	0	0	0	0	18.56
Other		0.02	19.29	1.93	7.49	48.72	-
Total demand	262.39	59.47	984.85	789.35	218.49	402.46	2717.00

EE: Electricity; NG: Natural Gas; GA: Gasoline; DI: Diesel; FO: Fuel Oil; LPG: Liquefied Petroleum Gas.

Table 13. Energy balance of the residential sector of Cuenca base year.

	Electricity	LPG	Total
Production	-	-	-
Imports	110.04	270.39	380.43
Exports	-	-	-
Total Primary Supply	110.04	270.39	380.43
Distribution	−7.70	-	−7.70
Total Transformation	−7.70	-	−7.70
Residential	102.34	270.39	372.73
Total Demand	102.34	270.39	372.73

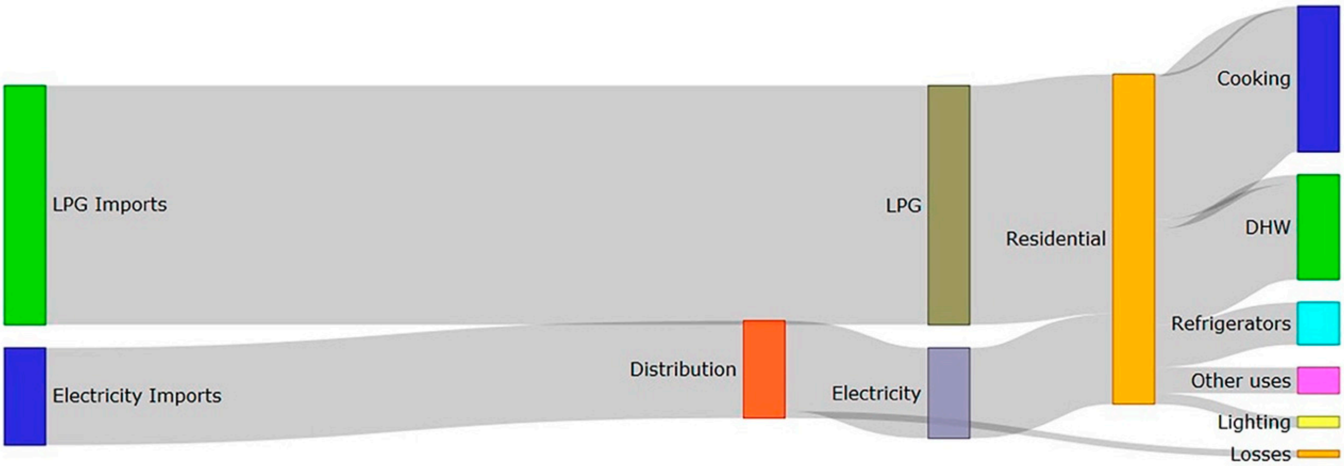

Figure 2. Sankey diagram of the residential sector of Cuenca, Ecuador, in the base year. (The figure shows the electricity losses given by the local distribution company. Losses due to marketing and distribution of LPG have not been included).

Table 14. Energy consumption for DHW in the base year.

Fuel	Base Year	Proportion
Electricity (kBOE)	9.9145	8%
LPG (kBOE)	108.3641	92%

3.1.2. Scenarios for the Adoption of ST Systems in the Urban Area of Cuenca

Four scenarios are proposed to determine the future situation if different resources and technologies are applied to the DHW. A prospective study examined the years between 2016 and 2030, with a projected population increase of 2.15% [46]. The analysis of the change in energy requirement was applied only to the residential sector. Figure 3 shows how the results vary for the three scenarios compared with the baseline trend.

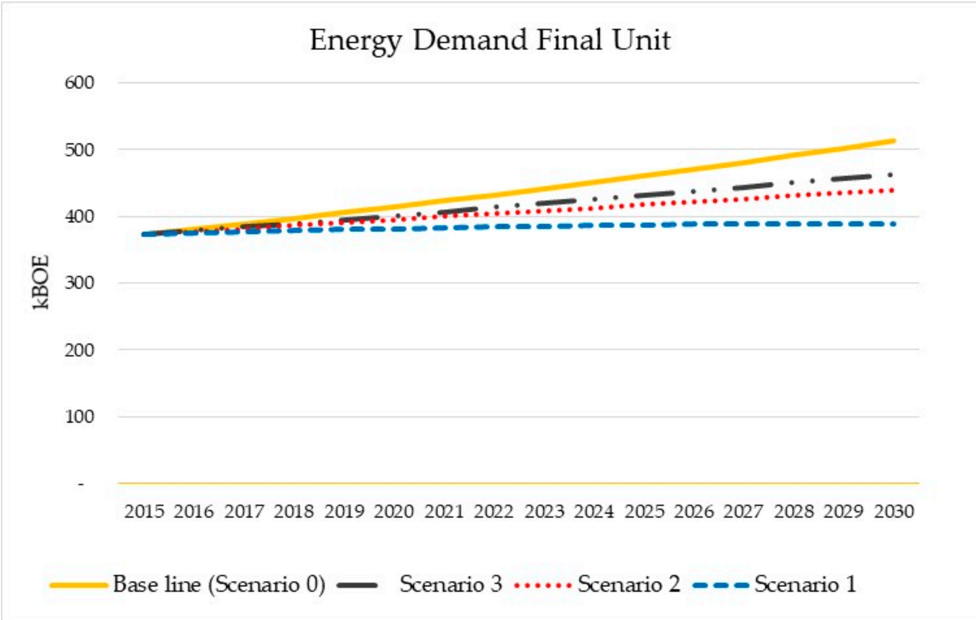

Figure 3. Prospective energy use considering three scenarios.

Scenario 0. For 2020, there is the total energy consumption of 512.82 kBOE in the residential sector, 72.59% of which corresponds to LPG, while the remaining energy consumption is electricity. Figures 4 and 5 show the results of the prospective study. Sankey diagrams are used to visualize the energy flows in the city proportionally.

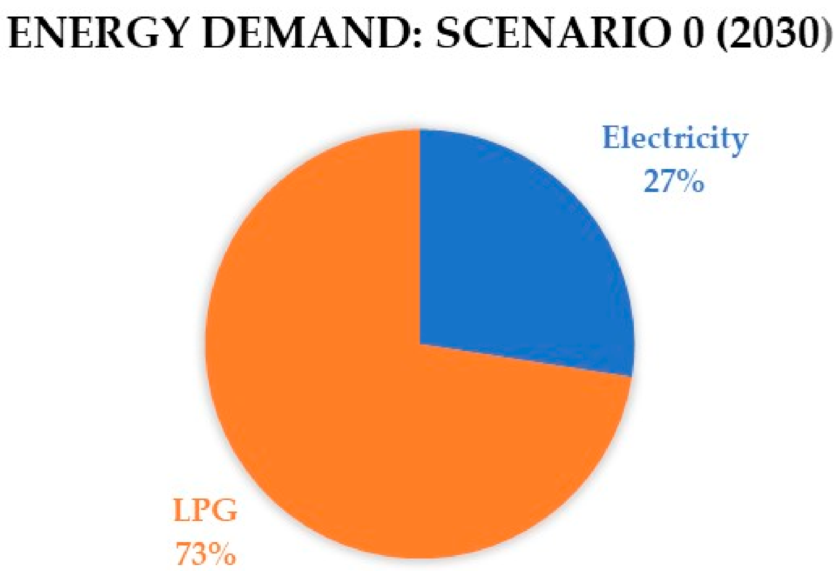

Figure 4. Scenario 0. Energy consumption in 2030, residential sector.

Scenario 2. It is proposed that introducing heaters could cover 44% of the demand for domestic hot water by 2030 [31]. Energy consumption in the residential sector is

439.74 kBOE, 14.25% less than that in Scenario 0. As in the previous case, the energy consumption from LPG decreases, accounting for 68.2% of the total energy required by the residential sector. Figures 6 and 7 show the results of the prospective scenario, including the energy from ST.

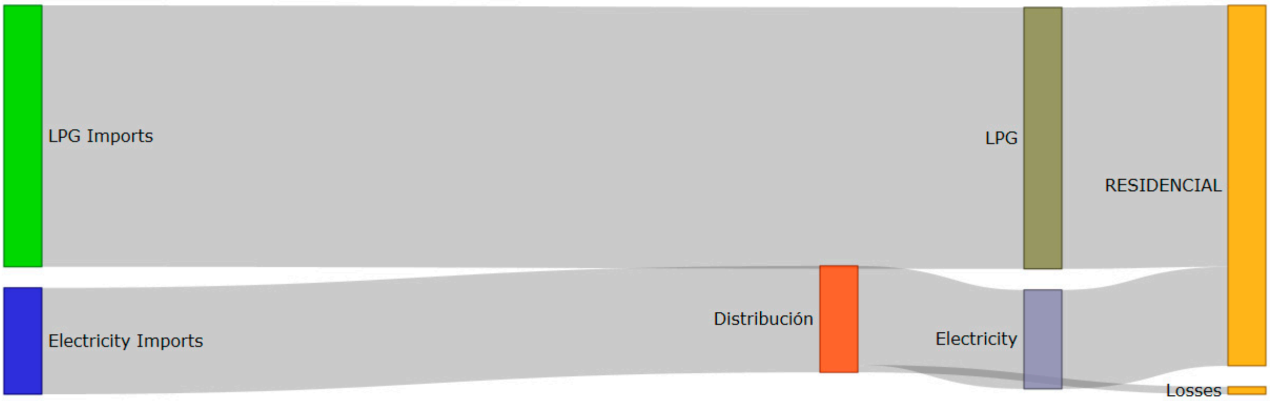

Figure 5. Scenario 0. Sankey diagram for 2030, residential sector. (The figure shows the electricity losses, given by the local distribution company. Losses due to marketing and distribution of LPG have not been included). Scenario 1: An extreme case based on experiences in Chinese cities is considered [6]. In the case of a consolidated market, 95% of the demand covered by this technology could be reached. If, in addition, it is considered that in Cuenca, the solar fraction would not exceed 78% [30], a contribution from other sources, such as electricity or LPG, would be needed. In this scenario, the electricity requirement is 389.4579 kBOE; that is, it decreases by 22.30% with respect to scenario 0. The consumption of LPG is reduced with respect to the base year and represents 64.15% of the total energy consumption. Figures 10 and 11 show the results of the prospective scenario, including the demand corresponding to heating with ST.

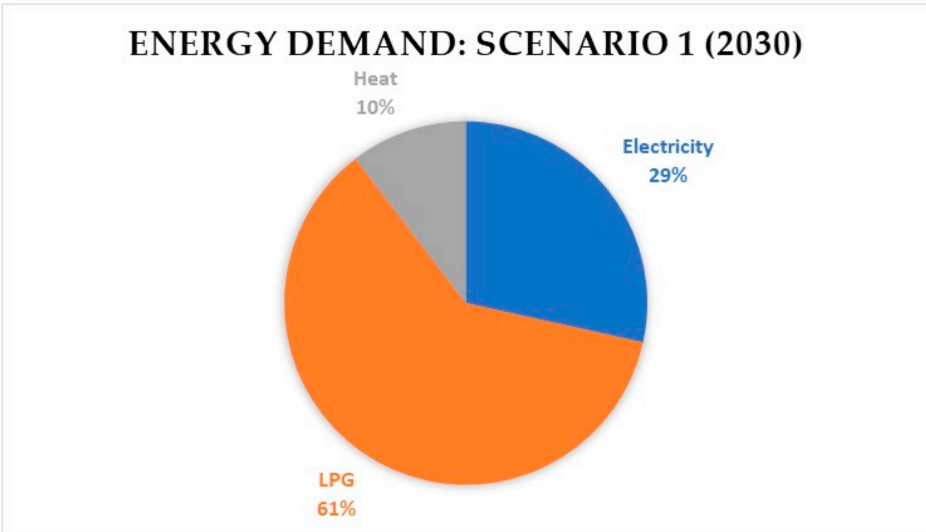

Figure 6. Scenario 2. Energy consumption in 2030, residential sector.

Scenario 3. This scenario considers the suggestion of the INER (2016), which proposes that 90% of households adopt electrical systems. The energy consumption in the residential sector is 463.76 kBOE, 5.18% lower than that in Scenario 0. In Figures 8 and 9, the results of the prospective scenario are shown. In this case, the consumption of electricity increases, and the consumption of LPG decreases but remains high due to the consumption of this fuel for cooking.

Figure 7. Scenario 2. Sankey diagram for 2030, residential sector (The figure shows the electricity losses given by the local distribution company. In addition, the losses of conversion of solar energy to heat are displayed. Losses due to the commercialization and distribution of LPG have not been included).

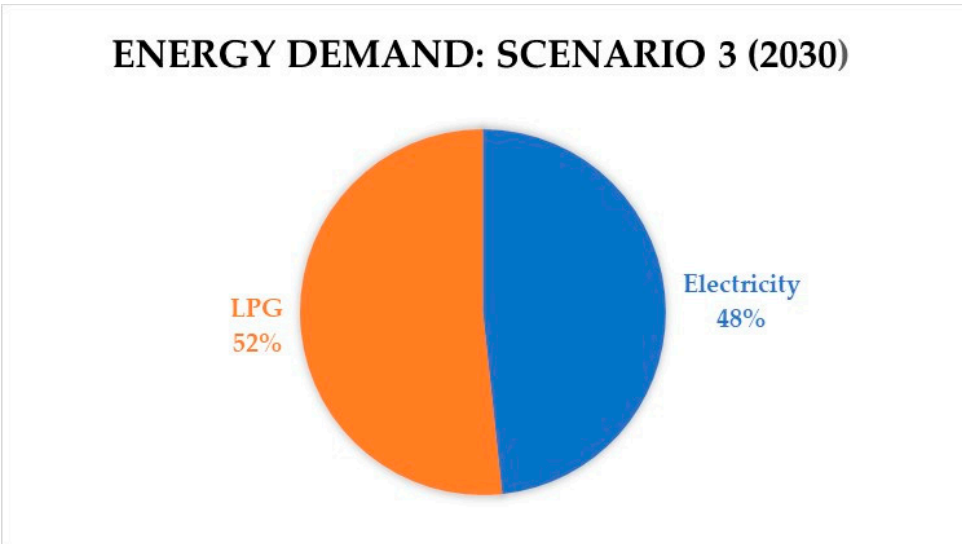

Figure 8. Scenario 3. Energy consumption in 2030, residential sector.

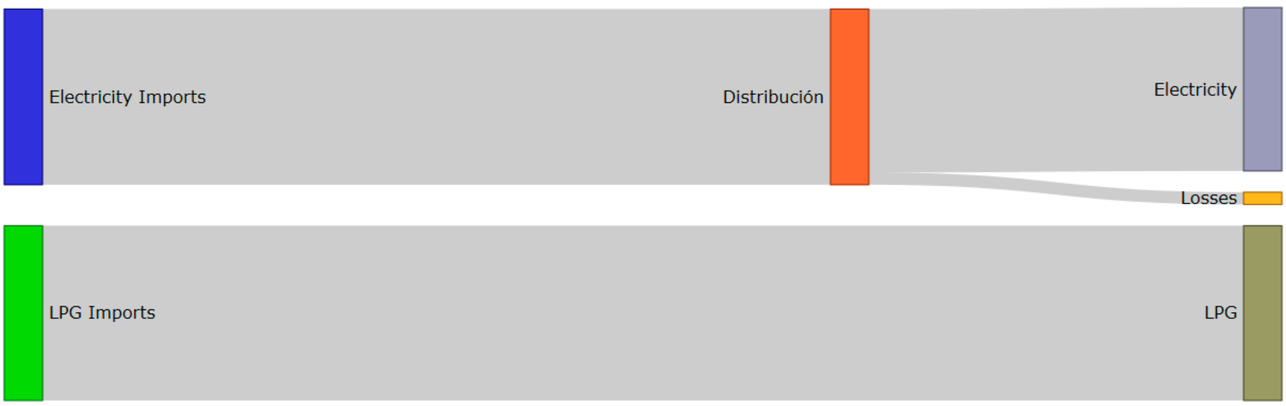

Figure 9. Scenario 3. Sankey diagram for 2030, residential sector.

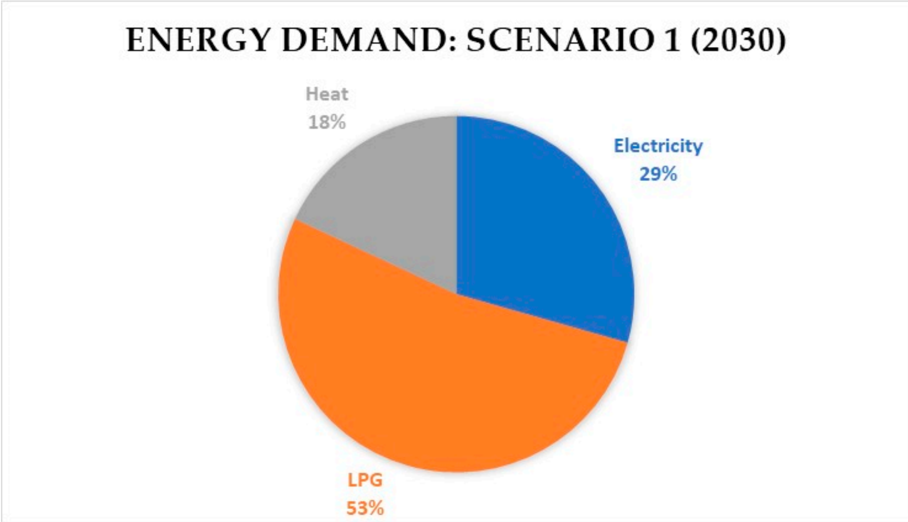

Figure 10. Scenario 1. Energy consumption in 2030, residential sector.

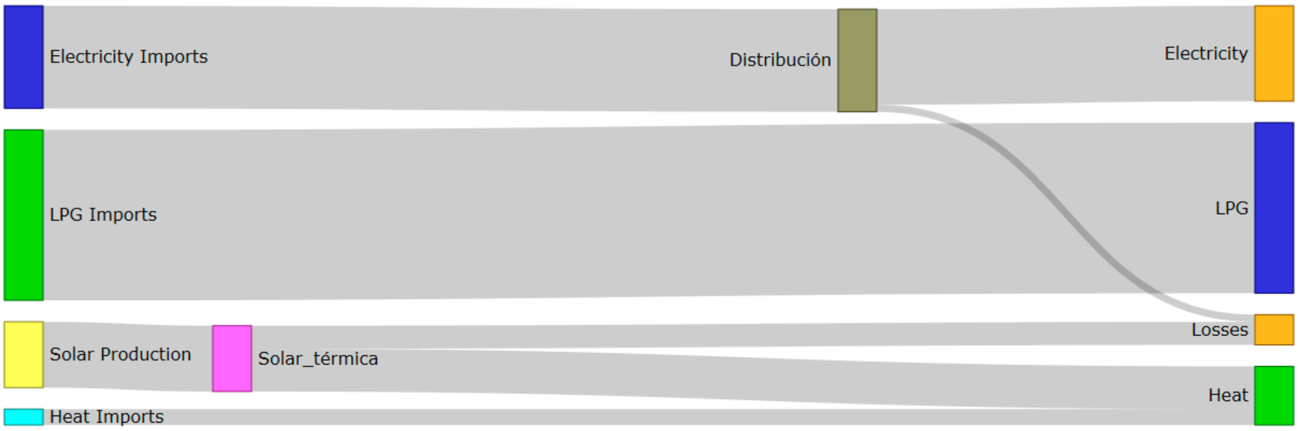

Figure 11. Scenario 1. Sankey diagram for 2030, residential sector (The figure shows the electricity losses given by the local distribution company. In addition, the losses of conversion of solar energy to heat are displayed. Losses due to the commercialization and distribution of LPG have not been included).

3.1.3. Calculation of Sustainability Indicators

To analyze the global impact of the adoption of ST systems, sustainability indicators are used to compare the base case and the extreme case of ST system adoption. The analysis is performed considering Cuenca's entire urban energy matrix (Table 12) and the energy balance if Scenario 1 were to be applied (Table 15).

Table 15. Energy balance intensive insertion of ST (kBOE).

	EE	NG	GA	DI	FO	LPG	Solar	Heat	Total
Production	0.00	0.00	0.00	0.00	0.00	0.00	95.97	0.00	95.97
Import	281.29	59.47	984.85	789.35	218.49	313.58	0.00	0.00	2647.03
Export	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total supply	281.29	59.47	984.85	789.35	218.49	313.58	89.82	0.00	2709.40
ST	0.00	0.00	0.00	0.00	0.00	0.00	−95.97	62.38	0.00
Distribution	−19.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	−19.69
Total transformation	−19.69	0.00	0.00	0.00	0.00	0.00	−95.97	62.38	−19.69

Table 15. *Cont.*

	EE	NG	GA	DI	FO	LPG	Solar	Heat	Total
Residential	101.55	0.00	0.00	0.00	0.00	181.51	0.00	62.38	345.44
Industry	61.89	59.47	0.00	127.33	216.55	98.68	0.00	0.00	563.92
Transportation	0.00	0.00	984.83	642.73	0.00	0.00	0.00	0.00	1627.56
Commercial	59.62	0.00	0.00	0.00	0.00	25.89	0.00	0.00	85.51
Public lighting	18.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.56
Other	19.98	0.00	0.02	19.29	1.93	7.49	0.00	0.00	48.72
Total demand	261.60	59.47	984.85	789.35	218.49	313.58	0.00	62.38	2689.71

EE: Electricity; NG: Natural Gas; GA: Gasoline; DI: Diesel; FO: FuelOil; LPG: Liquefied Petroleum Gas.

Autarchy

With energy autarky (EA), the city's energy dependence degree is assessed. To apply Equation (1), from the energy balances (Tables 12 and 15), the primary energy imports (IE_p), the secondary energy imports (IE_s), and the total gross energy supply (S_E) are obtained. Table 16 shows that the intensive use of solar thermal systems minimally improves this indicator, which indicates that its impact on the urban energy matrix is minimal.

Table 16. Autarky.

Scenario	IEp + IEs (MBOE)	ES (MBOE)	EA	EAn
Baseline	2.736.75	2.736.75	1.00	0.00%
ES5	2647.03	2709.40	0.97	3.28%

Energy Price

This indicator allows the price of energy to be measured individually. Table 17 indicates the useful life established in the references consulted. Since the difference is not significant, a value of 20 years is taken for each case. Using the annual operating costs (Table 3) and considering the mean values of the investment costs (Table 2), Table 18 shows the cost of energy production for water heating based on Equation (3).

Table 17. Data used for the calculation of energy cost for DHW.

System	Useful Life (Years)	Reference	Useful Life	Costs (USD kW Year)
Solar water heaters	13	[6]	20	17.95
	15	[9]		
	20	[18]		
	25	[8]		

Table 18. Energy costs (DHW production).

Scenario	Inv. (USD/kW)	O&M (USD/kW)	r (%)	Useful Life (Years)	Power (MW)	Plant Factor (%)	Ce (USD/kWh)
E_1	504.00	17.95	5	20	76.91	14.00	0.047

Investment (Inv), see Table 2. Operation and maintenance (O&M), see Table 3. Discount rate (r), 5% [47]. Useful life, see Table 16. Power and plant factor, see Table 9.

Consequently, one kW of thermal power is taken as a basis of analysis, with its corresponding operation and maintenance cost, a discount rate of 5% in accordance with [47], the useful life of each technology, and an estimated number of hours of operation. In the case of systems with integrated storage and thermosiphoning (without coolant pumping), the energy costs depend on the time of use of the installation, the size of the system, and the solar contribution. Under the established assumptions, if the collectors have an area of 2.4 m^2 (1.68 kW), there is an energy cost of 0.047 USD/kWh. If the installation has 3 m^2 of collectors, the energy cost is 0.06 USD/kWh (2.1 kW), while if the system has 1.5 m^2

collectors (1.05 kW), the cost decreases to 0.03 USD/kWh. If the collector–storage system is coupled with a pump, the costs can triple in each case. These data are in accordance with the findings reported by Islam [16]. In this case, the costs can range from 0.02 to 0.2 USD/kWh depending on the installation size.

The price of each energy form (PE) and the normalized indicator calculated (Pen) from Equations (2) and (10) are shown in Table 19. The profit increases by 15% (Pr). For fossil fuels, 12% is due to the value added tax (using the VAT in Ecuador). In the case of electricity, the VAT is 0%.

Table 19. Prices of the energy from the ST.

Scenario	Ce (USD/kWh)	Ce (USD/BOE)	VAT (%)	Profit (%)	PE (USD/BOE)	Pen (%)
E_1	0.047	77.60	0.00	0.00	77.60	82.67%

Mean Price of Energy to the Final Consumer

The prices of fossil fuels and electricity in Ecuador are identified in Table 20 (Baseline scenario E_{S0}). The Table is intended to show the situation at the time the investigation was made. It is clear that energy prices fluctuate, so the values presented in the Table could vary over time. It should be noted that the existence of subsidies in the country means that fluctuations do not depend on international energy prices.

Table 20. Energy prices in Ecuador.

Energetic *	Price	Unit	Source	Pe (USD/BOE)
E_{S0} Elec	0.0933	USD/kWh	[48,49]	150.71
Es_0 Residential LPG	0.1066	USD/kg	[49,50]	13.10
Is_0 industrial LPG	0.638	USD/kg	[50]	78.42
E_{S0} Natural gas industry	8.39	USD/MMBtu	[29]	46.29
Is_0 Residential gasoline	1.30	USD/gallon	[50]	60.24
E_{S0} Industrial gasoline	1.49	USD/gallon	[50]	69.04
E_{S0} Residential diesel	0.90	USD/gallon	[50]	36.68
E_{S0} Industrial diesel	1.32	USD/gallon	[50]	52.58
E_{S0} Fuel gas	0.80	USD/gallon	[50]	32.19

* The analysis was performed before an increase in fuel prices in 2021.

The mean price of energy is calculated with Equation (4). Table 21 shows the prices ($\Sigma Pe_j \times E_j$), the energy (E_j) of each scenario, the mean price (PME), and the normalized mean price (PMEn). The indicator shows that there would be an increase in the mean price of energy, although the substitution of energy is partial. The energy from thermal solar panels (Es_1) for water heating has a higher price than when using LPG.

Table 21. Mean price of energy.

Scenario	$\Sigma Pe_j \times E_j$ (M USD)	ΣE_j (k BEP)	PME (USD/BEP)	PMEn (%)
E_{S0}	150,846.74	2717.00	55.52	48.27%
E_{S5}	154,407.44	2689.71	57.41	41.98%

Use of RE in the Total Energy Supply

The use of RE in the energy supply is calculated with Equation (5), and the impact of including energy sources from renewable sources in the urban energy distribution is measured. Table 22 shows the use of renewable energies (RE) and the gross energy supply (ES). It is noted that 2.30% self-sufficiency is reached when applying the intensive use of solar thermal systems.

Table 22. Use of RE in energy supply.

Scenario	RE (kBOE)	ES * (kBOE)	UR	Urn (%)
E_{S0}	0.00	2736.75	0.00	0.00%
E_{S1}	62.38	2709.40	0.02	2.30%

* The supply of energy is the demand plus losses.

Use of RE in the Supply of Electricity

As is logical in the case of the use of RE in the supply of electrical energy, the indicator is not altered because a renewable technology that produces electricity is not substituted. The indicator is calculated with Equation (6). In Table 23, the production of electricity with RE (RE), the supply of electric energy (Ese), and the contribution of RE to electrical energy (Ure), as well as the normalized indicator (Uren), are shown.

Table 23. Use of RE in the supply of electricity.

Scenario	Ree (kBOE)	Ese (kBOE)	Ure	Uren (%)
Es_0	0.00	282.13	0.00	0.00%
Es_1	0.00	281.29	0.00	0.00%

Purity of Energy

The purity of the energy is calculated with Equations (7) and (8). Table 24 shows the carbon dioxide emissions (CEC) derived from Equation (8) and the energy demand (ED) obtained from the balances of each scenario. This indicator shows a slight improvement when replacing LPG.

Table 24. Purity of energy.

Scenario	CEC (kT CO_2)	ED (kBOE)	Pre (t CO_2/BOE)	Pren (%)
Es_0	987.61	2717.00	0.363	34.16%
Es_1	949.93	2689.71	0.353	36.74%

Employment

Equation (11) is used to assess the number of jobs that could be created by promoting the installation, operation, and manufacturing of these systems.

$$CIM = \frac{CIM_I \times N_I}{P_I} \quad (11)$$

where,

CIM_I is the number of people required for the construction, installation, and manufacture of a reference plant [person-years];
N_I is the number of years used for MIC of the reference facility [years];
P_I is the power size of the reference installation [MW]; and
CIM is the number of people employed in the construction of a reference infrastructure MW during N_I years [people-year/MW].

If OM is the number of jobs that were required for the operation and maintenance of a reference MW installation during one year in jobs/MW, we have Equation (12) for estimating:

$$\text{OM} = \frac{OM_I}{P_I} \quad (12)$$

where,

OM_I is the number of jobs required for the operation and maintenance of a reference facility in one year [jobs-year] an
P_I is the power production of the reference installation [MW].

With the above, we applied Equation (13):

$$Ie = \left[\frac{CIM}{t} + \text{OM}\right] \times \frac{1000}{8760 \times Fp} \quad (13)$$

where,

Ie is the employment indicator for a renewable technology [total jobs-year/GWh],
t is the lifetime of the renewable technology [years], and
Fp is the plant factor of the renewable technology.

The reference variables CIM_I, N_I, P_I, and OM_I are constant if the reference installation is known; therefore, with CIM and OM, the number of jobs per year per unit of energy can be calculated for a given installation with a determined plant factor and lifetime. For the calculation of Ie, 20 years was used as the useful life of the facilities, and the established plant factor of 14% was previously defined. Table 25 shows the total number of jobs estimated per year by energy production.

Table 25. Employment indicator (DHW production).

System	CIM (People-Year/MW)	OM (Jobs/MW)	References	Ie (Total Jobs-Year/GWh)	
Solar water heaters	8.40	*	[51]	0.34	0.52
	22.40		[52]	0.91	
	7.40		[53]	0.30	

* A global factor has been used for jobs per MW installed since it is the only data available on a large scale. This may underestimate the studies, so it does not include the OM (Renewable Energy Policy Network for the 21st Century) [54].

Likewise, Table 26 defines the employment associated with traditional energy sources.

Table 26. Use of traditional energy sources.

System	*Ie* (Total Jobs-Year/GWh)	Source	*Ie* (Total Jobs-Year/GWh)
Hydropower *	0.05	[51]	0.05
Fossil fuel electricity *	0.11	[54]	0.11
Fossil fuels **	0.05	[51]	0.07
	0.09	[54]	

* The mean number of jobs for electricity that come from outside the city is considered. ** For fossil fuels, Rutovitz et al. [51] suggest using the same factor as for natural gas.

To calculate the number of jobs produced, the employment factor Ie, from Table 26, is used. The use of conventional sources is considered according to Table 26. Table 27 shows the estimates of the number of jobs (Em) and the normalized indicator (Emn) calculated with Equations (12) and (13), respectively, for the analyzed scenarios. The use of thermal energy would slightly increase employment (E_{S1}) compared with the baseline scenario. Figure 12 presents the indicators more or less affected by introducing ST.

Table 27. Employment.

Scenario	Em (Jobs-Year)	Emn (%)
Es_0	315.00	2.14%
Es_5	356.94	8.13%

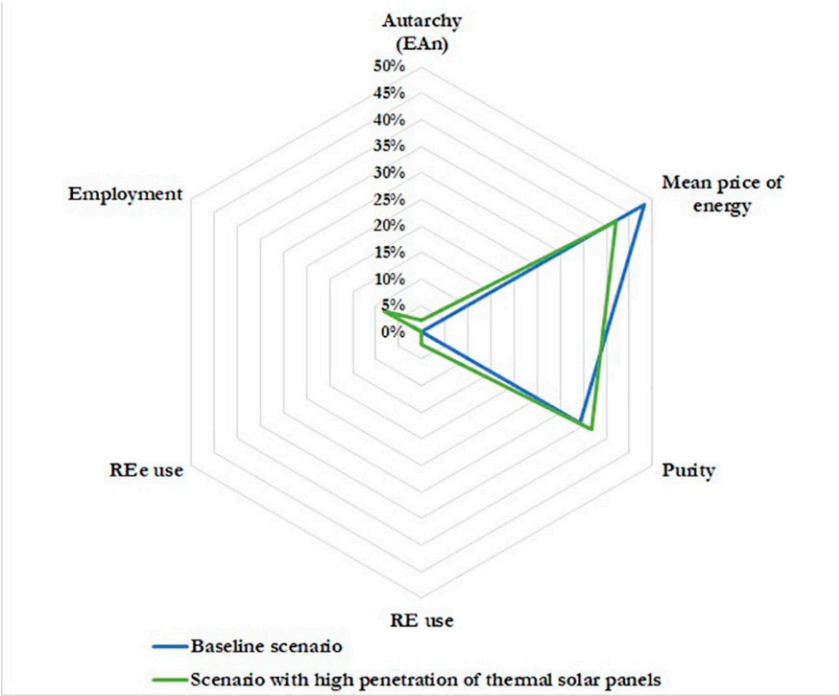

Figure 12. Behavior of the indicators regarding the use of ST energy for DHW in the city of Cuenca.

From the results of the indicators, it is established that the energy required to heat water using solar thermal collectors (E1) has a higher price than when using liquefied petroleum gas (E1). In the case of purity (CO_2 emissions), there is a slight improvement because fossil fuel is no longer used since LPG is considered a clean fuel.

3.1.4. Amortization of ST with and without Subsidy

In Ecuador, the price of LPG is subsidized, and the cost of a 15 kg tank is 1.6 USD, which contrasts with the international value of 13.65 USD (Resolution #3184, of the Internal Revenue Service of Ecuador). Based on previous values, the amortization time of the system with and without subsidy can be established (the energy associated with LPG is considered to be 13.65 kWh/kg) (Table 28):

Table 28. Amortization of solar thermal systems in Ecuador.

Denomination	Flat Plate Collectors	Evacuated Tube Collectors	Units
Energy demand	9534	9534	MJ
Solar coverage	6674.9375	6674.9375	MJ
Auxiliary coverage	2860.6875	2860.6875	MJ
Investment cost	887.5	1425	USD
15 kg tank	204.649	204.65	kWh
15 kg tank	736.73	736.74	MJ
Gas equivalent	9.06	9.06	Tanks
Subsidized tank cost	3	3.00	USD
Unsubsidized tank cost	13.60	13.60	USD
Total cost with subsidy	27.18	27.18	USD
Total cost without subsidy	123.24	123.24	USD
Amortization time with subsidy	32.65	52.43	years
Amortization time without subsidy	7.20	11.56	years

These findings suggest that the LPG subsidy must be withdrawn for the ST system to be economically reliable and attractive to the consumer.

4. Discussion

Of the appropriate technologies for water heating (ST and geothermal), the use of ST was examined in this study. The success in the application of this energy differs. In Mexico, although ST technology may be an adequate alternative to the use of LPG or natural gas [5], it has not been adopted throughout that country. In some Chinese cities, in contrast, the adoption of ST systems exceeds 90% [6].

When comparing the energy balance and the Sankey diagram under the baseline scenario with a scenario with the massive adoption of thermal solar heaters, the consumption of LPG in the residential sector would be reduced by 32.87% on average. With respect to residential consumption, the reduction in energy requirements would be on the order of 24%. However, its impact on the urban energy matrix would not exceed 1%.

The reduction of 32.87% of E_{S1} is comparable to the calculation by Rosas-Flores et al. [5], who estimated that in urban areas of Mexico, a reduction of 45.6% could be achieved, while in Spain, a reduction of 68% could be achieved [10]. In Concepción (Chile), Zalamea and García Alvarado [13] estimate a potential reduction of 75%. This variability is also attributed to the details of the estimate, the behavior of consumers, and the climatic situation of each study area.

This variability is reflected in the indicators of autarky (EAn = 3.28%, Table 15) and use of RE (URn = 2.30%, Table 20). In addition, the price of energy indicates that the cost of producing heat (Pe = 77.60 USD/BOE, according to Table 17) using ST systems is higher than if LPG is used (Pe = 13.10 USD/BOE, according to Table 18). Therefore, the mean energy price increases, manifested in the PMEn indicator's reduction by approximately 7% (Table 19). There is no significant reduction in emissions, not only because of the impact on the change in the urban energy matrix but also because LPG is considered a clean fuel (see Table 22). However, the indicator that measures employment increases compared to the base case, but this increase is minimal (see Table 25).

The impact of ST technology mainly affects the residential sector; however, three factors could prevent its widespread adoption in Ecuador, despite being an option to reduce the use of LPG: (i) the subsidized price of LPG, (ii) lack of incentives for its use, and (iii) lack of knowledge of the technology. The disadvantage of replacing LPG with ST technology may be that the initial investment costs are high and not attractive if they are incorporated with the devices currently in households. Another factor to consider is that LPG costs probably influence the high consumption of domestic hot water in Ecuador, particularly in Cuenca (40 to 50 L per person). In Europe, the mean consumption is usually approximately 30 L.

In the residential sector, 72.5% of the total energy consumed currently comes from LPG, while 27.5% comes from electricity. The substitution of LPG for water heating by thermal solar heaters is a solution that has been successful in other locations. Still, without a state and municipal strategy, the widespread adoption of this technology will not be possible. Impediments to its adoption include construction ordinances in effect in the urban areas of Cuenca as well as the incentives for LPG use among consumers, professionals, and builders, similar to the incentives provided to construction companies in Chile. It is estimated that 60% of the LPG is used for cooking, which can be replaced by electricity; hence, the degree of disaggregation of this sector would allow a medium-term prospect for the replacement of LPG-based equipment.

The analysis performed by A. Barragán-Escandón et al. (2019) [34] using the same indicators as in the present study showed that the use of photovoltaic solar energy in Cuenca would have a greater impact. Therefore, we conclude that DHW heating could be accomplished by electric heaters rather than thermal solar [34].

5. Conclusions

One of the proposals to reduce the flow of energy in the city is the use of RE; however, in city planning, RE are not considered mechanisms to reduce energy imports. Since intermediate cities will have a primary role in the future, it is in these cities that new policies and planning processes should be designed and applied to promote the use of RE in urban areas, taking advantage of endogenous urban resources. It is proposed that energy planning be expanded to the city level and not remain only at the national or regional level. The intention is for urban planning to include measures to ensure that these technologies are gradually accepted and integrated according to the available resources and local conditions.

This work analyses the hypothetical adoption of solar thermal technology as an energy source for residential use. The adoption is proposed under three scenarios; however, adopting this technology would not significantly modify the urban energy matrix. This has been demonstrated using sustainable energy indicators used at the regional and national levels. The positively affected indicators are autarky, use of renewable energies, employment, and energy purity, at the cost of an increase in energy cost.

For 2030, under the scenarios considered, the base case would require 512.82 kBOE for the residential sector (27.4% LPG and 72.5% electricity). Under a massive substitution of LPG, the energy requirement would decrease to 75.9% of the current level, with a contribution of 35.8% from LPG and 64.1% from electricity. This finding indicates that the use of LPG for cooking significantly influences the demand and type of energy requirement. However, adopting policies and, most importantly, diverting subsidies from fuel sources to clean technologies are necessary for this transition.

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