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Strengths, Weaknesses, Opportunities, and Threats Analysis for the Strengthening of Solar Thermal Energy in Colombia

Stefania Betancur [1,2], Naghelli Ortega-Avila [3,*] and Erick César López-Vidaña [3,*]

[1] Department of Energy, Faculty of Engineering, University of America, Ak. 1 #20-53, Bogota 110111, Colombia; sbetancurm@unal.edu.co
[2] Department of Chemical and Materials Engineering, University of Alberta, 9211 116 Street NW, Edmonton, AB T6G 1H9, Canada
[3] CONAHCYT—Centro de Investigación en Materiales Avanzados, S.C., Subsede Durango, Calle CIMAV #110, Ejido Arroyo Seco, Durango 34147, Mexico
* Correspondence: naghelli.ortega@cimav.edu.mx (N.O.-A.); erick.lopez@cimav.edu.mx (E.C.L.-V.)

Abstract: Colombia has made different efforts to contribute to fulfilling its international commitments to curb climate change by reducing emissions and promoting technological development and project financing. However, the existing policies and regulatory framework primarily focus on promoting the photovoltaic industry for electricity production. Likewise, the energy sector has neglected the potential of solar thermal energy as a heat source. In this sense, it is necessary to redouble efforts through new public policies that integrate solar thermal energy in the residential and productive sectors. Using solar thermal energy for heating can contribute to the energy transition and meet its sustainable development goals. Therefore, the main objective of this work was to analyze Strengths, Weaknesses, Opportunities, and Threats to determine the potential application of thermal solar heat in Colombia while considering the local context. Factors such as their environmental conditions, policies, and regulations; the existence of international agreements; and their political status in general were analyzed. The analysis revealed Colombia's significant solar heat potential, enabling over 1.3 million cold-climate households to access hot water or reduce firewood use. Industrially, applying solar heat in 5% of the current industry could decrease fossil fuel consumption by 13 PJ. The findings highlight that Colombia's potential in thermal solar energy necessitates collaborative efforts, legislative reinforcement, climate-adaptive measures, and the resolution of political and social challenges.

Keywords: solar heat; renewable energies; policy incentives; energy transition; strategic planning

Citation: Betancur, S.; Ortega-Avila, N.; López-Vidaña, E.C. Strengths, Weaknesses, Opportunities, and Threats Analysis for the Strengthening of Solar Thermal Energy in Colombia. *Resources* **2024**, *13*, 3. https://doi.org/10.3390/resources13010003

Academic Editor: Eva Pongrácz

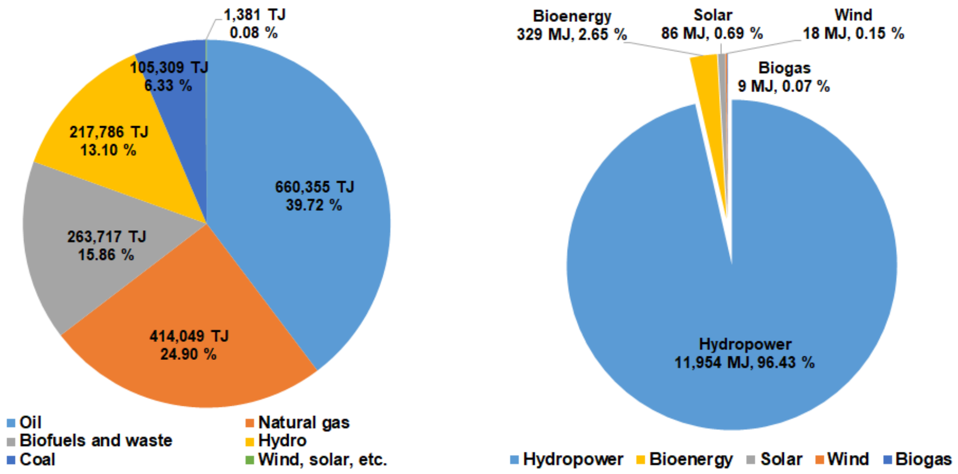
Received: 6 October 2023
Revised: 6 December 2023
Accepted: 18 December 2023
Published: 21 December 2023

1. Introduction

In recent decades, there has been increasing interest in using renewable energy to reduce greenhouse gas (GHG) emissions and carbon footprints. In 2018, 81% of the world's energy was produced from fossil sources, and it is estimated that energy consumption will increase by 48% by 2040 [1]. Furthermore, Latin America has a population of approximately 662 million people, with a clear positive trend in its growth [2]. Therefore, to satisfy the needs of a growing population, it is necessary to guarantee an affordable energy supply with a significant contribution to renewable energies.

According to the 2015 Paris Agreement, countries must develop strategies for 2050 to limit global warming and avoid global temperature increases to values above 1.5 °C [3,4]. Solutions focused on energy and transportation are emerging as crucial strategies for zero carbon emissions. In this sense, Colombia established a mitigation target to reduce 670 million tons of CO_2 between 2015 and 2030. Furthermore, the Colombian government developed the National Greenhouse Gas Inventory System (SINGEI), establishing objectives and guidelines for measuring, reporting, and verifying emissions. In addition, mitigation strategies include establishing carbon taxes (Decree 926 of 2017), developing guidelines for formulating Nationally Appropriate Mitigation Actions (NAMAs), taking advantage of international financing opportunities, promoting energy transfer, and increasing co-benefits.

As shown in Figure 1a, in Colombia, fossil energy sources represent 70.95% of the supply, and renewable energies represent 29.05%. In addition, Figure 1b shows that within the installed capacity of renewable energies, hydro-energy represents 96.43%, followed by bioenergy (2.65%) and solar energy (0.69%). Colombia's energy matrix is diverse compared to most countries in the world; however, there is a significant dependence on installed hydroelectric power capacity, which puts the energy supply at risk when there are climatic variations [5] due to various scenarios caused by natural phenomena, such as the El Niño phenomenon [6,7].



(**a**) (**b**)

Figure 1. (**a**) Total energy supply by source in Colombia; (**b**) matrix of installed renewable energy capacity in Colombia. Data from [8].

The Colombian Energy Balance [9] for 2021 showed a domestic primary energy supply of 1949 PJ, with 43.1% coming from oil, 22.6% from gas, 12.9% from hydro-energy, 10.0% from coal, and the remainder from renewable sources such as firewood, bagasse, other renewables, and waste. On the other hand, energy demand was 2788 PJ, with 50.3% allocated to final use and 49.7% to transformation inputs.

Figure 2 shows that the transportation sector accounted for 42.0% of the total final consumption, followed by industry at 21.7%, the residential sector at 18.6%, and other sectors such as public and commercial, agricultural, mines, construction, and unidentified. However, 58% of the 260.8 PJ consumed in the residential sector is used in urban areas, and the rest is used in rural areas. Meanwhile, the food industry is the largest consumer in the industrial sector at 30.0%, followed by non-metallic mineral products at 20.5%, refineries at 16.7%, and paper at 8.5%.

Moreover, due to its location, Colombia has one of the highest solar radiation rates worldwide [10], especially solar and wind potential sources in the Caribbean Region. However, the energy consumption by solar energy for 2021 was less than 1 TWh [11]. On the other hand, the implementation of solar photovoltaic systems has focused mainly on the rural sector and has allowed about 2% of the population of the non-interconnected zones (ZNI) to improve their quality of life through access to electricity to meet their most basic needs [10]. The use of renewable energies must be increased to reduce the consumption of fossil fuels and thus contribute to the fulfillment of the Sustainable Development Goals (SDGs) [12].

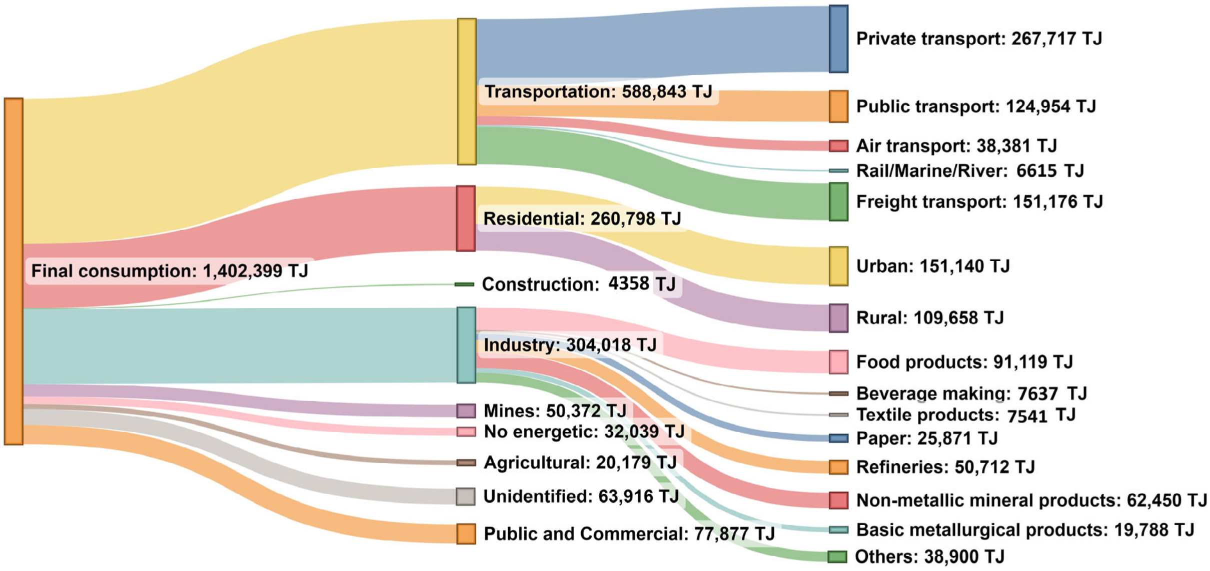


Figure 2. Final energy consumption by sectors in Colombia in 2021. Data from [9].

Literature Overview

A Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis is one of the methodologies implemented to identify such factors through internal and external evaluation criteria. In the case of renewable energies, SWOT analyses determine the impact of different scenarios or prospects that generally focus on electricity production, such as those of Rahman et al. [13] and Franco and Silva [14]. In addition, some papers analyze specific situations in certain regions or countries, such as Uhunamure and Shale [15] in South Africa, Qaisrani et al. [16] in China, and Elavarasan et al. [12] in Iceland, Sweden, the USA, India, and China. Finally, other studies analyze how renewable energy development can positively impact and decrease energy poverty; for example, in Ghana [17]. These previous studies show that using renewable sources reduces the demand for fossil fuels and the associated environmental emissions, as they are considered "green" and clean.

As for solar thermal energy, few studies have analyzed its application potential, such as Rahman et al. [13], who determined the environmental impacts on power production. They found that although the application of solar thermal energy reduces the use of fossil fuels, solar technologies have some negative ecological, environmental, and social impacts. However, solar thermal energy negatively impacts the environment less than photovoltaic energy. They consider that this SWOT analysis can be a tool for decision makers to learn about the advantages of these technologies. Qaisrani et al. [16] focused their analysis on the capacity of concentrated solar power and transition capacity in China, while Elavarasan et al. [12] emphasized that there are energy decentralization programs in India, with the direct application of solar technologies to produce heat being an important issue.

Additionally, few works analyzed solar thermal energy to produce heat, such as Schmidt et al. [18], who determined the barriers and opportunities for applying solar thermal energy in district heating networks. Meanwhile, Elmorsy et al. [19] analyzed the market potential of concentrating solar power (CSP) technologies in the Middle East and North Africa region, especially in Egypt, considering that it has high levels of direct solar radiation. They applied a SWOT analysis to determine the existing market, demand, and regulatory framework and compared the available technologies for heating, cooling, desalination, hydrogen production, and electricity production.

Regarding the application of renewable energies in Latin American countries, Horta et al. [20] developed a methodology to evaluate the possibilities of integrating bioenergy projects in Latin America, the Caribbean, and Africa through a SWOT analysis. Venegas et al. [21] researched biofuels' use and their waste management and recycling, focusing on a Colombian municipality. Finally, Diaz and Cilinskis [22] developed another study concerning Colombia using a multi-criteria analysis to define its path to decarbonization. In their work, the authors analyzed the different renewable sources in Colombia and concluded that there is great potential to exploit them. However, in the case of solar energy, they only studied the application of photovoltaic solar panels, which can have great potential at a commercial and residential level due to their cost reduction. Previous works have primarily focused on utilizing photovoltaic solar energy and other renewable energies for electricity generation, neglecting the potential of solar thermal energy as a heat source. However, some studies have been carried out to analyze the technological application of solar thermal energy in isolated cases in Colombia. Thus, Rodriguez-Toscano et al. [23] analyzed the use of solar absorption chillers in Colombian shopping centers. For their part, López et al. [24] performed an energy analysis to compare the convenience of using a parabolic trough or a linear Fresnel collector for water preheating in a sugarcane cogeneration plant, Valencia-Cañola et al. [25] determined the thermo-economic performance of a heat pump operated with a photovoltaic array and solar heat as an evaporator, and Soler et al. [26] analyzed the convenience of using a parabolic trough solar plant to produce steam in projects of enhanced recovery of extra-heavy oil. Despite these efforts, no study in the specialized literature has specifically addressed the SWOT analysis of solar thermal energy usage in Colombia.

Therefore, the objective of this work is to analyze the status of solar thermal energy use and explore its growth potential through a SWOT analysis based on the review and critical analysis of studies, research articles, laws, decrees, and institutional and governmental reports on the status of renewable energies in Colombia. The aim is to establish recommendations that strengthen the Colombian energy sector (specifically, in the solar thermal sector) for domestic, commercial, and industrial use.

2. Methodology

A SWOT analysis is based on internal and external evaluation criteria, where the internal factors are examined to highlight and interpret strengths and weaknesses. Strengths represent technical progress and resources that are available and can improve the performance of the subject in question. Weaknesses may reduce its profitability, efficiency, or utilization [15]. Opportunities are external changes such as government schemes that could contribute to further development, and threats are external factors related to the political environment that may cause problems of economic stability and profitability [27,28]. In this sense, the sustainable development of the renewable energy sector needs to work on its strengths, adjust its weaknesses, exploit the opportunities, and prevent threats [12]. Therefore, this is a helpful tool for understanding the drivers and disincentives for adopting and implementing technologies based on solar thermal energy.

The literature study of this work was based on two approaches to describe the structural sections of the article, as described below (See Figure 3):

1. The first was to collect data and other relevant content from publication databases, including scientific research articles and academic works.
2. The second source of information was obtained from the annual periodic reports of renewable energies at a global level, energy policies, and energy portfolios of Colombia.

This literature was exhaustively reviewed to generate a list of factors to consider in the SWOT matrix, and these factors were subsequently classified into four categories for analysis. The discrimination process of the consulted documents, reports, and databases was initially employed to analyze data on consumption, installed capacity, energy production, and previous projects in Colombia that incorporated renewable energy, particularly solar thermal heating. Subsequently, regulations, laws, decrees, public policies, and standards promoting Non-Conventional Energy Sources were reviewed. Finally, some relevant documents about the political and social aspects were identified to analyze their implications in harnessing solar thermal energy.

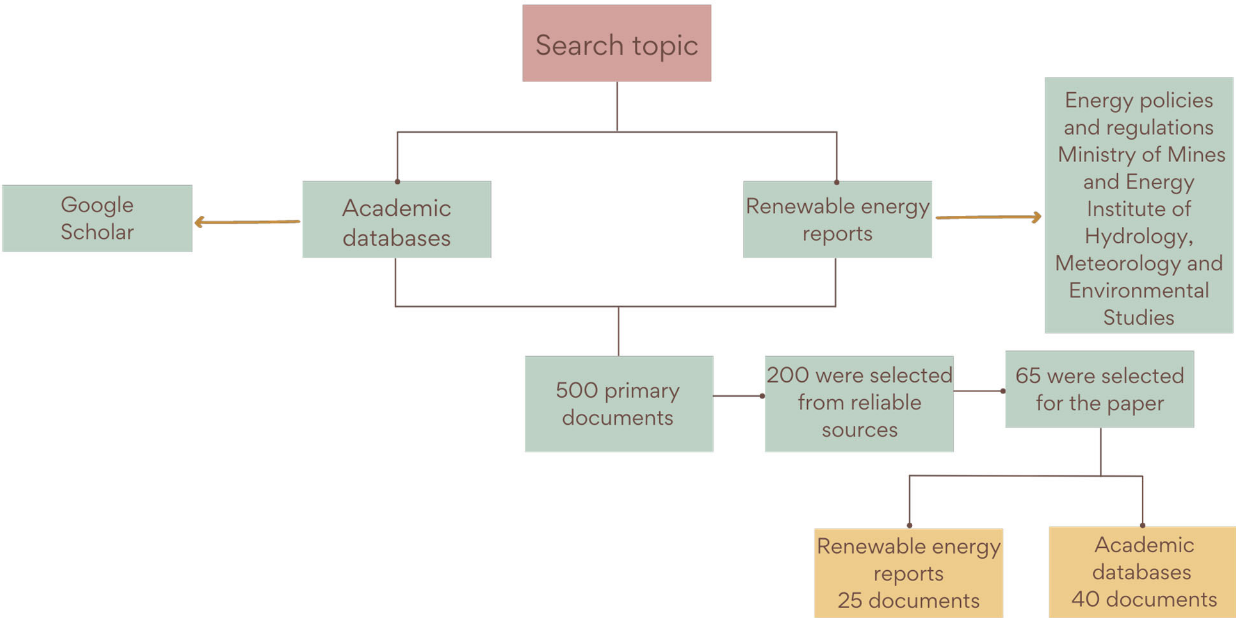


Figure 3. Methodology scheme.

As part of this review, specific keywords came up related to the aspects of the implementation, use, and promotion of renewable energies in Colombia, such as the renewable energy scenario, legal frameworks, barriers, and perspectives of renewable energies in Colombia, among others.

Mainly, the collected articles relate to renewable energy sources from Google Scholar and official documents on national energy policies and regulations in which previous researchers discussed similar implementation of renewable energy based on the resources available in Colombia.

From the Renewable Energy portfolio, data related to Colombia were compiled based on the use of renewable energy resources (reports from the Ministry of Mines and Energy as well as the Institute of Hydrology, Meteorology and Environmental Studies). On the other hand, the renewable resources available according to geographical area and the potential of solar thermal energy as the primary energy source in a wide range of processes were analyzed. Finally, the Colombian energetic balance data were analyzed to establish the heating requirements in the residential and industrial sectors and assess the potential application of solar thermal energy.

3. Results and Discussion: SWOT Analysis

Below is the analysis and discussion of the Strengths, Weaknesses, Opportunities, and Threats associated with developing solar thermal energy in Colombia.

3.1. Strengths Analysis

3.1.1. Regions with High Solar Irradiation

Despite wind and solar energy making a relatively limited contribution to Colombia's energy mix, the country relies significantly on zero-emission sources (primarily hydropower) for electricity generation. However, wind power capacity in Colombia remains comparatively low. Nonetheless, regions such as La Guajira that heavily depend on coal-fired electricity generation hold tremendous potential for harnessing solar power.

Colombia has an area of 1,141,748 km^2 divided into 32 departments comprising five regions. Its average solar irradiation is approximately 4.5 kWh/m^2/day, higher than the global average of 3.9 kWh/m^2/day. Figure 4 shows a Colombian map of the annual average daily global horizontal solar irradiation [29]. The regions with the highest global solar irradiation intensity in Colombia have values of 5.5 kWh/m^2, while the areas with the lowest have averages of less than 3.5 kWh/m^2 [30]. Thus, Colombia's solar resources are abundant (39% to 42% greater than those of Central Europe), e.g., Germany has 3.0 kWh/m^2/day and is recognized as one of the leading countries in solar utilization. This solar energy potential positions Colombia favorably for the widespread utilization of solar energy across various sectors of society.

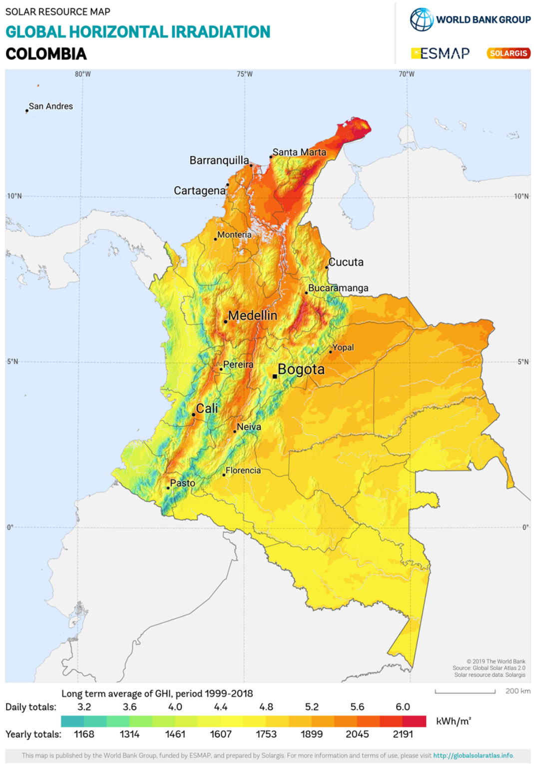


Figure 4. Mean annual global horizontal irradiation of Colombia [29], access in September 2023. "GHI Solar Map © 2017 Solargis. By downloading a free map, you acknowledge that Solargis retains all rights, titles, and interest in the information provided by the maps, including the copyright, Solargis logo and all other intellectual property rights, and that Solargis has the right to make these maps available under Creative Commons Attribution-ShareAlike 3.0 Unported License. ".

3.1.2. Availability of Solarimetric Data

Solar radiation's spatial and temporal distribution is essential to determine the strategic regions for successfully implementing solar energy technologies. The Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) and the Mining and Energy Planning Unit (UPME) developed the Solar Radiation, Ultraviolet, and Ozone Atlas of Colombia in 2015 [30]. The tool has information from radiometric stations with 230 sensors of global radiation and 497 sensors of solar brightness at the national level. Conventional and automatic meteorological stations of IDEAM were used for this atlas. The network of automatic satellite weather stations (EMAS) used 110 pyranometers, of which, after calibration and validation, 90 were selected for the atlas maps. In both cases, monthly and annual averages of global irradiation received at the surface were reported.

3.1.3. Versatility and Ease in Application of Solar Thermal Systems

Solar thermal energy involves harnessing solar energy to transform it into heat directly or indirectly in various applications of society. According to the Colombian Ministry of Commerce, Industry and Tourism [31], the main activities that sustain the country's economy are the primary sectors (coffee, bananas, flowers, sugar cane, cattle, and rice), which represent 14.1% of the gross domestic product (GDP), and the secondary sectors (textiles, chemical products, metallurgy, cement, cardboard packaging, plastic resins, and beverages), with 18% of GDP. Within these sectors, there is an excellent opportunity to integrate solar systems to supply thermal energy to the required processes. Thus, some of the primary uses that could be given to solar thermal energy in Colombia are water heating for domestic sanitary use, drying of agricultural products, air conditioning of spaces, preheating of water and air for commercial/service use, and industrial processes, among others.

Therefore, the simplest solar technologies, such as flat-plate and evacuated tube collectors, require relatively low investment and minimal maintenance, making them ideal for applications below 85 °C and 125 °C, respectively. Prior studies have highlighted the successful deployment of thermal solar collectors for water heating in a Colombian tannery industry, achieving temperatures of up to 80 °C [32]. On the other hand, imaging concentrating technologies present a broader spectrum of possibilities. Among these, the parabolic trough collector, a widely adopted design, can effectively function in the temperature range of 150 °C to 400 °C. Specific imaging concentrating technologies can even be harnessed at the apex of this range for applications demanding temperatures as high as 1200 °C [33].

Solar thermal conversion systems are mature technologies and sufficiently affordable since their components are not electronic, and their useful life is between 20 and 25 years. In addition, they have a conversion efficiency that is up to four times higher than that of photovoltaic technologies, so their yield per unit of the installed surface area is much higher. Installing these thermal systems is simple and can be done away from objects or structures that could shade the solar thermal collector [34]. Colombia's lack of distinct seasons provides a favorable environment that simplifies the construction of solar thermal systems. The absence of freezing problems in the pipes and consistent solar radiation throughout the year eliminate significant variations and the possibility of having uniform thermal performance during most of the year.

The selection of solar technology for a specific application will depend on the required temperature and mode of operation with adequate thermal efficiency at a competitive cost, ranging from USD 180/m^2 for non-concentrating collectors to between USD 270/m^2 and USD 600/m^2 for concentrating solar collectors [33]. On the other hand, water heating and space air conditioning must be covered at the domestic level, accounting for about 24% and 32% of the final energy consumption in residential buildings, respectively [35]. Both can be covered with thermal conversion systems, such as water and air heaters. Therefore, according to 2018 data, Colombia has a total installed area of solar water heaters of 100,000 m^2, with the experience of the Programa Especial de la Energía en la Costa Atlántica (PESENCA) pilot program, which was implemented in the 1980s and ended in 2016, mainly due to the displacement of solar thermal technology because of the low cost of natural gas [36].

3.1.4. Support for the Development of Renewable Energies through Government Policies

The need to migrate toward renewable energies is increasingly vital due to the adverse effects of the use of fossil fuels, so it is necessary to have solid public policies that encourage those changes that are convenient for society and the environment.

Currently, the Colombian Ministry of Mines and Energy promotes tax benefits that individuals or legal entities can access if they invest in Non-Conventional Energy Sources (FNCE) and Efficient Energy Management (GEE) projects, which consist of (1) income deduction of 50% for up to 15 years of the investment made in the project (this incentive applies to both electric power generation and non-electric uses of the FNCE); (2) exclusion of the value-added tax (VAT) on the purchase of equipment, elements or services necessary for the project; (3) tariff exemption on the import of machinery and other inputs necessary for the project; and (4) accelerated depreciation of assets applicable to equipment and civil works necessary for the project [37,38]. These tax benefits are implemented through the laws and decrees in Table 1.

Table 1. Laws and decrees granting tax benefits in Colombian projects that use Non-Conventional Energy Sources.

Law or Decrees	Article	Statutes
Law 1715 (2014)	General	Promoting the integration of non-conventional renewable energies into the national energy system through their incorporation into the electricity market, participation in non-interconnected zones, and other energy uses.
	2° subsection (e)	Stimulates investment, research, and development for producing and using energy from Non-Conventional Energy Sources (mainly renewable ones) by establishing tax, tariff, or accounting incentives.
	12	Establishes tax incentives and VAT exclusion for national or imported equipment, elements, machinery, and services for preinvestment and investment for producing and using energy from non-conventional sources.
	13	Establishes that individuals or legal entities that are holders of new investments in new FNCE projects will be exempted from the payment of import duties on machinery, equipment, materials, and supplies destined exclusively for preinvestment and investment in projects for developing renewable energy projects.
	14	Establishes an accounting incentive consisting of the accelerated depreciation of machinery, equipment, and civil works necessary for the generation's preinvestment, investment, and operation with FNCE with an annual depreciation rate of no more than twenty percent (20%).
Law 1955 (2019)	174	The National Development Plan 2018–2022 establishes the incentives for generating electric energy with non-conventional sources and the public policy objectives (called pacts).
	Pact IX (Mining energy resources for sustainable growth and expansion of opportunities)	Contemplates mining-energy development programs with environmental and social responsibility and energy security for productive development.
	296	Establishes that the commercializing agents of the Wholesale Energy Market will be obliged to ensure that between 8% and 10% of their energy purchases come from non-conventional renewable energy sources.
Resolution UPME 203 (2020)	General	Establishes "the requirements and the procedure through which the UPME will evaluate the applications and issue the certificates that allow access to the tax benefits of income deduction, VAT exclusion and exemption from customs duties to investments in research, development or production of energy from Non-Conventional Energy Sources—FNCE" [39].
Decree 829 (2020)	General	Expands the effects of the deduction article in determining income tax to include non-electric uses of FNCE [38], such as solar heating.
Law 2099 (2021)	General	Establishes modifications to Law 1715, which creates the Non-Conventional Energy and Efficient Energy Management Fund (FENOGE), which acts as a channel and catalyst of resources destined by third parties to finance plans, programs, and projects of Non-Conventional Energy Sources and Efficient Energy Management.
Decree 199 (2021)	General	Amends the Sole Regulatory Decree of the Mines and Energy Sector (1073 of 2015) regarding the policy guidelines for expanding the electric power service coverage in the SIN and ZNI. The above is based on using alternative energies to produce electric energy that can be connected to the SIN.

Although the laws and decrees analyzed generally address promoting and establishing renewable energies, the primary objective is strengthening the Colombian electricity system, expanding coverage to non-interconnected areas, or providing autonomous photovoltaic systems to communities outside the electricity service coverage network.

3.2. Weakness Analysis

3.2.1. Lack of Large-Scale Solar Thermal Projects

Colombia has no large-scale projects that use solar thermal energy for industrial and commercial use. The first applications of solar thermal energy in Colombia date from the middle of the 20th century and corresponded to the implementation of domestic solar heaters for the employees of the banana plantations in Santa Marta. Later, in the 1960s and 1970s, Colombian universities led the implementation of domestic solar heaters, mainly focused on heating water in community service centers [40]. Finally, in the 1980s, solar thermal heaters were massively implemented in residential complexes in Medellín and Bogota, and the first companies that offered the service of construction and installation of solar heaters in industrial and domestic spaces were formed. However, the growth in solar thermal energy declined with the decrease in natural gas prices, which displaced this renewable energy source from the 1990s up to now [41]. Therefore, there are no published plans for implementing projects for the massive generation of domestic, commercial, or industrial solar heaters.

3.2.2. Outdated and Geographically Limited Solarimetric Database

The spatial and temporal distribution of solar radiation is essential to determine the strategic regions where renewable energy projects can be implemented. According to the solar atlas of Colombia, it has been observed that the solar radiation measurement and data collection stations are located mainly in the Andean zone, so the Caribbean, Pacific, Orinoquía, and Amazon zones lack these stations, which makes it difficult to estimate the solar resource of these regions.

The most recent data were collected in 2014–2015, and there is no reported update of the solarimetric data collected, which implies a high uncertainty when considering the climate change that has been accentuated in recent years. Therefore, IDEAM recommends timely equipment calibration to guarantee high reliability based on the worldwide radiation reference (WRR) [42]. Likewise, the installation of global radiation stations in the automatic satellite network for the departmental capitals of Arauca, Mitú, Neiva, Puerto Carreño, Quibdó, and Tunja and the application of complementary techniques such as satellites to evaluate the solar radiation of the country are recommended [30].

3.2.3. Low Investment in Research and Development (R&D)

In Colombia, the most current value generated by the World Bank indicates that spending on research and development for 2020 was 0.29% per year, while the average in Latin America was 1%.

According to the National Development Plan (PND) of Colombia 2018–2022, in 2018, only 3.8% of companies worked with universities, and only 2.5% of Colombian researchers had a labor relationship with the industry, while the average in Latin America for 2018 was 22% [43]. This situation reflects a disarticulation of research and innovation in the Colombian public sector, which has approximately 5000 entities. The goals proposed by the government for 2018–2022 consisted of increasing investment in research and development by up to 1.5% of GDP and increasing technology transfer agreements between companies and universities supported by the Ministry of Science, Technology, and Innovation. However, promoting science, technology, and innovation and strengthening interactions between industry and academia depend mainly on the government's political guidelines.

An International Mission of Scholars (MIS) was created in 1993 to advance science, technology, and innovation and to face the country's adversities in terms of research and development [44]. According to this group of experts, between 2013 and 2017, 97 projects with a total cost of approximately 118,000 million of Colombian pesos were financed in the country, focusing on diversifying the energy basket. This indicates that in the coming years, challenges related to the efficient and rational use of energy and a reduction in environmental impact in energy terms must be faced. Therefore, the proposed research agenda focuses on topics such as smart grids, access to electricity in the ZNI, solar energy conversion, storage and complementarity between renewable and non-renewable energy sources, development of methodologies, simulation and optimization tools that support the formulation of sectoral policy guidelines, as well as decision making in terms of benefits, costs, and identification of business opportunities, among others.

3.3. Opportunities Analysis

3.3.1. Positive Impact on the Energy Transition

Currently, there is a social trend toward the adoption of renewable energies in daily activities and industry. The Program for Rational and Efficient Energy Use (PROURE) establishes some macro indicators of the impact of public policies, among which the following objectives of the National Energy Plan 2020–2050 stand out:

- Diversify the energy matrix and seek, among other things, to increase the share of non-conventional renewable energy sources in the primary energy supply from 4.1% in 2019 to 8.6% in 2030.
- Adopt new technologies for efficient use of energy resources to reduce the firewood share in the residential sector from 38% in 2019 to 26.5% in 2025 and 13% in 2030.
- Strive for an energy system with low greenhouse gas emissions.

The PROURE specifies that in the industrial sector, the most significant potential for energy efficiency is found in direct heat, which is why technological changes are sought; however, the measures established do not include Non-Conventional Energy Sources [45].

3.3.2. Economic Growth in Colombia

The projection for energy demand in Colombia made by Nieves et al. [46] suggests that by 2030, it could be between 1,597,675 TJ and 1,748,469 TJ. The largest energy consumer would be the transportation sector, followed by industry. In 2050, Colombia's energy demand is expected to be approximately 2,125,453 TJ. This increase in energy demand, together with an intensification in the effects of climate change, could encourage more significant investment in projects focused on renewable energy and a more accelerated diversification of the country's energy matrix. Experts indicate that efficiency efforts should concentrate on the most relevant types of energy use in each sector. Thus, the industrial sector should focus on heat and motive power generation systems.

3.3.3. Ideal Conditions for using Solar Heat in the Residential and Productive Sectors

Solar heat involves the thermal conversion of solar energy for applications of thermal energy supply to transformation processes. Given the levels of incident solar radiation in Colombia, solar thermal energy systems can offer a cost-effective supply of energy at the domestic and commercial level or solar heat for various industrial processes.

- *Potential for Solar Heat Application in the Residential Sector*

The residential sector's energy consumption indicates the different energy consumption patterns and sources used in urban and rural residential areas. Electricity and gas are the primary energy sources in urban areas, with 49.2% and 36.6% of the 151.14 PJ total consumption, respectively, while firewood is used much less often [9]. However, firewood accounts for three-quarters of the 109.66 PJ of energy consumption in rural areas, followed by electric energy (11.6%) and liquefied petroleum gas (9.2%). Moreover, only 21.4% of energy consumption in both residential sectors is used as useful energy [47]. As shown in Figure 5, 68.1% of final energy consumption in the residential sector was for heat (cooking and water heating), while only 31.9% was for applications that require electricity.

In addition, it should be noted that firewood was the primary heat source, followed by natural gas and liquefied petroleum gas.

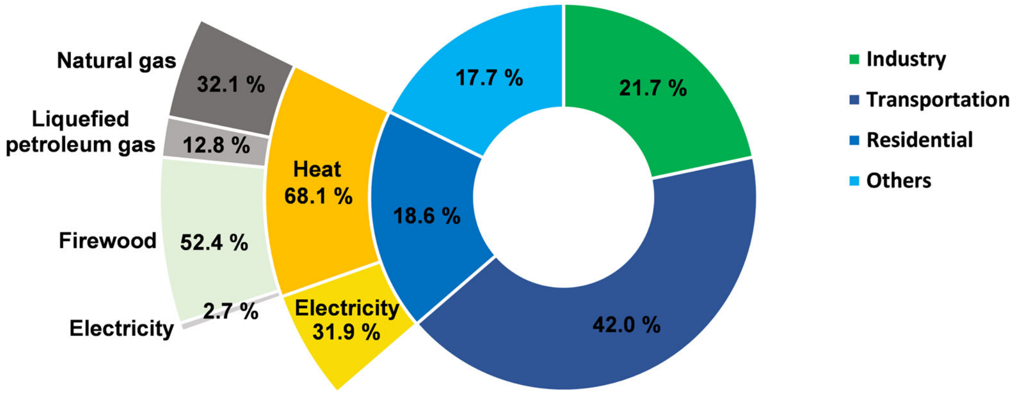


Figure 5. Final heat consumption in the Colombian residential sector in 2021. Data from [9,47].

Nevertheless, Table 2 shows that the primary energy consumption in the residential sector is required for cooking, i.e., to produce heat. Therefore, it is estimated that 1.5 million households in the rural sector use firewood for cooking food [48], with prevalence in the Departments of Cauca (11.7% of total), Córdoba (11.3%), Nariño (8.6%), and La Guajira (8.4%), among others. This situation could be addressed, but it would be necessary to establish a government program or some public policies to replace wood stoves with solar stoves, providing additional collateral benefits [49] such as reducing greenhouse gas emissions, improving public health and the local indoor environment by avoiding exposure to smoke from burning firewood, and reducing deforestation due to firewood collection, a task traditionally assigned to women and children.

Table 2. Distribution of final energy consumption according to application in the residential sector. Data from [47].

Energy Application	Energy Consumption (TJ)	Participation (%)
Cooking *	172,267.2	66.7
Water heating *	3441.7	1.3
Refrigeration	34,723.0	13.5
Television	13,300.0	5.2
Lighting	12,315.1	4.8
Air conditioning	7425.7	2.9
Fans	4706.4	1.8
Other **	9918.3	3.9

* Heat consumption; ** includes ironing, electronics, clothes washing, and other electric equipment.

On the other hand, electricity covers water heating almost entirely (93.4% of this energy consumption). Electric heaters consume up to 35% of a home's electrical energy demand [36], so replacing electric heating with solar heating represents an excellent opportunity to help meet the goals of reducing greenhouse gas emissions.

Moreover, the National Quality of Life Survey 2022 [48] shows that only 25.5% of homes in Colombia have electric showers or a water heating system with an electric or gas supply; therefore, 74.5% of homes do not have access to any water heating means. Consequently, installing flat solar water heaters could be a viable solution, as these technological options are mature, relatively inexpensive, and have more than 15 years of useful life.

The installation of solar water heaters represents an opportunity to address the lack of access to conventional heating systems, especially in areas where the main barriers to access are the cost of heaters or the lack of availability of conventional energy sources. For example, in specific cold-climate departments such as Cundinamarca, Nariño, and Boyacá, where only 50%, 29%, and 44% of households have a water heater, respectively [48], around 1.3 million households could benefit from the implementation of solar water heating systems with their respective social and environmental co-benefits.

- *Potential for Solar Heat Application in the Industrial Sector*

According to BECO 2022 [9], within the total energy consumption of 304.0 PJ in the industrial sector, the principal primary energies used were gas (30.5%), coal (25.8%), and bagasse (16.4%), while the most exploited secondary energies were electric energy (17.1%) and self-cogeneration (6.6%).

However, as shown in Figure 6, the proportion of energy consumed as heat within the industrial sector (84.8%) was higher than in the residential sector (See Figure 5). Of this portion, 66.7% was produced with natural gas or coal (92.6 PJ and 78.4 PJ, respectively), fuels that can be complemented or replaced with heat produced with solar energy, since many industries (pulp and paper, textile, food, and beverage processing, and more) use heat in at least one part of their process (sterilization, pasteurization, drying, and washing, among others). This energy can be provided more ecologically and sustainably by integrating solar thermal systems [33], since solar heat for industrial processes implies lower energy consumption from fossil fuels and consequently a reduction in operating costs due to energy efficiency.

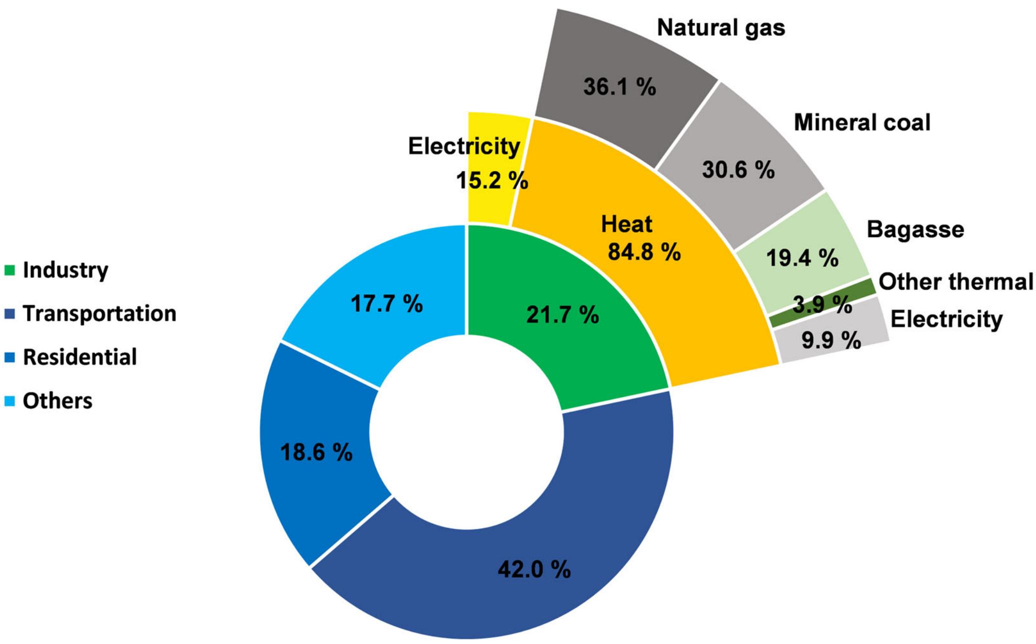


Figure 6. Final heat consumption in the Colombian industrial sector in 2021. Data from [9,50].

However, when examining the main final applications of energy in the industrial sector (see Table 3), it was highlighted that 41.1% of energy consumption is allocated to indirect heating (that is, vapor production), in which heating technologies for preheating purposes could be easily integrated using flat solar collectors, evacuated tube collectors, or heat pipes. On the other hand, in industrial processes that use direct heating—with boilers or furnaces (43.7%)—the possibility of applying solar heat will depend on the temperature requirements of each specific process.

Table 4 shows some of the most common unit operations in which solar heat can be applied in different industrial sectors classified according to their operating temperature range. Numerous industrial processes require 80 °C or less, so fixed solar technologies such as flat plate or evacuated tube collectors can be used. Solar concentrating technologies such as compound parabolic collectors and parabolic trough collectors are available for specific unit operations requiring higher temperatures (<80 °C).

Table 3. Distribution of final energy consumption according to application in the industrial sector. Data from [50].

Energy Application	Energy Consumption (TJ)	Participation (%)
Direct heating	132,498.0	43.7
Indirect heating	124,434.3	41.1
Driving force	38,618.6	12.7
Refrigeration	4295.5	1.4
Lighting	2461.1	0.8
Other electric equipment	777.5	0.3

Table 4. Required temperature ranges and recommended solar technologies for some processes of different industrial branches. Temperature range data from [51].

Unit Operation	Temperature Range (°C)	Recommended Solar Technology *				
		FPC	ETC	CPC	PTC	Fresnel
Food Industry						
Cooling/Cleaning/Drying	20–80	✔	✔			
Evaporation/Distillation/Cooking	80–140		✔	✔		
Paper Industry						
Drying/Cleaning	40–80	✔				
Calendering	80–140		✔	✔		
Metal Industry						
Cleaning/Cooling/Painting	20–80	✔	✔			
Drying/Surface treatment/Casting	80–160		✔	✔	✔	✔
Textile Industry						
Cleaning/Drying/Bleaching	20–80	✔	✔			
Other heating process/Painting	80–140		✔	✔		
Chemical Industry						
Cleaning/Drying	20–80	✔	✔			
Heating /Extraction/Evaporation	80–150		✔	✔	✔	✔
Leather Industry						
Cleaning/Bleaching/Drying	40–80	✔	✔			

* FPC = Flat plate collector; ETC = evacuated tube collector; CPC = compound parabolic collector; PTC = parabolic trough collector.

The implementation of solar heat in industrial processes depends on several factors, such as the availability of solar resources, the area available for installing solar collectors, the heat requirement profiles in the process, the fuel replacement costs, and the investment costs and financing schemes, so each integration case must be addressed individually. However, if just 5% of Colombia's current industrial thermal energy consumption could be replaced by solar heat, mineral gas and coal consumption could be reduced by approximately 13 PJ. This goal could be achieved in the medium term through a government program supported by public policies to encourage the integration of solar heat, especially in areas with radiation levels between 5 kWh/m^2 and 6 kWh/m^2, which covers around 170,000 km^2 of Colombian territory [29].

Colombia is recognized as one of the leading producers of crude oil, forest by-products, coffee, and precious minerals. These products need thermal energy at some point in their production, which can be partly or supplied by solar energy. For example, Solar Enhanced Thermal Oil Recovery (Solar TEOR) can generate the same steam quality as a conventional fuel-fired boiler, i.e., temperature and pressure ranges of 240 °C to 300 °C and 70 bar to

110 bars, respectively. Therefore, solar steam can replace up to 80% of the conventional fuel used for TEOR [33].

However, despite the great potential for solar heat application in Colombia, there is only a record of one large-scale solar heating system, which has been operating since the end of 2019 at the Mayor Méderi University Hospital in Bogotá. This system consists of 220 flat-plate solar collectors and six air-water heat pumps as backups to cover the demand for 4000 L of hot water at 55 °C for hospital rooms and other services [52]. Furthermore, the installation and operation of this type of system make it possible to publicize the benefits of its use to potential users, allowing the penetration of solar heating.

3.3.4. The Exploitation of Government Subsidies and Support

- *Extractive Industry Resources for the Energy Transition*

According to the Ecopetrol group, between 2010 and 2020, their contributions represented more than 15% of the total income of Colombia's Central National Government (GNC). For 2019, Ecopetrol's contribution to the GDP was 1.5% [53]. Under this scenario, the oil and extractive industry can implement renewable energies, and the operating companies assume the energy transition as a challenge. The Ecopetrol group plans to invest between COP 25.8 and 29.8 billion in projects for renewable energy. Around 23% of the investments will be focused on low-emission businesses, such as hydrogen production, renewable energy, carbon capture, and electric transmission.

The Ecopetrol Group has three solar photovoltaic parks to supply the energy demand of the company's operations; Castilla y San Fernando, with an installed capacity of 82 MW, registered a reduction of more than 32,000 tons of CO_2 as of December 2022 and generated savings of more than COP 22,000 million as of October 2022 [54].

- *Tax Incentives*

Section 3.1.4 explains the government policies that encourage the use of Non-Conventional Energy Sources. The UPME 045 resolution establishes the procedures and requirements to access the tax benefits of Law 1715, which, as of 2020, include projects for non-electric uses of the FNCE. Thus, in the case of solar thermal projects and systems, the equipment that can access this benefit are those required for solar resource measurement (radiometers, pyranometers, and weather stations, among others) and those needed for the development of the project (solar collectors, pumps, storage tanks, and control systems, among others). It should be noted that flat plate and evacuated tube collectors must meet quality standards. The knowledge and application of this benefit could make an investment in this type of renewable energy project attractive.

- *Standardization in Solar Energy*

To access tax incentives, flat plate and evacuated tube collectors must comply with EN 12975, EN 12976, EN 12977, ISO 9806, or SRCC OG/SD100/300 standards. However, in Colombia, there are also technical standards for national application based on the international standards EN 12975, EN 12976 [36], and ASHRAE. Table 5 presents the current Colombian standards regarding solar thermal energy.

Table 5. Current standards in Colombia related to solar thermal energy [55].

NTC 1736:2005	**Solar Energy. Definitions and Nomenclature.**
NTC 2631:2012	Solar energy. Calculation of photometric transmittance and reflectance in materials subjected to solar radiation.
NTC 2774:1990	Solar energy. Evaluation of thermal insulating materials used in solar collectors.
NTC 3322:2010	Solar energy. Used rubber seals in flat plate solar collectors.
NTC 3507:1993	Solar energy. Installation of domestic hot water systems that work with solar energy.
NTC 4368:1997	Energy efficiency. Solar water heating systems and components.
NTC 5291:2004	Domestic solar water heating systems (heat transfer from one liquid to another).

Table 5. *Cont.*

NTC 1736:2005	**Solar Energy. Definitions and Nomenclature.**
NTC 5434-1:2013	Solar thermal systems and components. Solar collectors. Part 1. General requirements.
NTC 5434-2:2011	Solar thermal systems and components. Solar collectors. Part 2: test methods.
NTC 5709:2009	Analytical expression for daily solar profiles.
GTC 108:2004	Solar energy. Specifications for solar-powered water heating systems for domestic use.

The existence of both tax incentives and standards regarding solar thermal technologies represents an opportunity to guarantee the quality of solar collectors and solar thermal installations.

3.3.5. Innovation and Generation of New Renewable Technologies

Patents have shown a positive relationship between innovation and technology transfer since they encourage research and social development of those societies that take advantage of technology transfer. According to [56], most renewable energy patents in Colombia are based on biofuels, considering that hydroelectric energy is the renewable technology with the largest installed capacity in Colombia. In 2016, of the total number of patents applied for, topics related to biofuels represented 34%, followed by hydroelectric (15%), wind (13%), hybrid solar photovoltaic (8%), solar photovoltaic (2%), solar thermal (1%), and geothermal energy (1%) [57]. Considering that solar thermal and geothermal energy presented the lowest participation in the patents applied for in Colombia, this may mean an opportunity to innovate and implement solar thermal technology in the industrial and residential sectors.

3.4. Threat Analysis

3.4.1. Uncertain Changes to Energy Regulations

According to the National Development Plan 2018–2022, the goals of the national government regarding renewable energies were focused on increasing the capacity of electricity generation with renewable energies (such as wind and solar) from 22.4 MW to 1500 MW. Similarly, the UPME projects that in 2028, about 13.75% of the 3275 MW of the country's installed capacity will correspond to solar energy. These projections agree with Law 1715 of 2014, which has been running satisfactorily. However, political uncertainty threatens the consolidation of renewable energies in the country's energy matrix. Implementing projects based on renewable energy depends on political decisions that are beyond the reach of most of the population. Furthermore, it should be noted that current policies do not show the national government's interest in implementing solar thermal energy to generate usable heat, which increases the uncertainty regarding the role of solar thermal energy in the Colombian energy matrix.

3.4.2. Corruption

According to the corruption perception index published by Transparency International, in 2012, Colombia was ranked in position 94 among 180 countries with a score of 34/100, where 0 corresponds to "highly corrupt," and 100 refers to a "spotless" country. For 2021, the perception of corruption in Colombia was almost the same, with a CPI of 39/100 [58].

One of the consequences of corruption is the loss in resources that return to citizens as goods and services, which can result in multiple violations of fundamental rights such as health, education, and life. In addition, corruption and GDP are negatively correlated. It is estimated that between 1989 and 1999, Colombia lost approximately 1% of its GDP, corresponding to COP 7.5–8.0 billion [59]. Edsand's work [60] has revealed that corruption has blocked the start of renewable energy projects. For example, some experts from the energy sector in Colombia have pointed out that some politicians require a bribe to approve a permit for a project or to start it. These kickbacks often increase the final cost of the project, ultimately making the project financially unviable. Thus, despite the appropriate economic and regulatory incentives, corruption has held back investment and progress in renewable energy projects.

3.4.3. Armed Conflict

The Colombian armed conflict is another threat to implementing renewable energy projects. Although the situation has improved after the 2016 peace agreement, armed groups and criminal gangs continue to dispute control of drug trafficking and territory. In 2019, Colombia spent approximately 3.2% of its GDP on the armed forces, ranking 25th in the world with the highest military spending [61]. The main consequence of the persistence of the armed conflict is the disinterest of investors due to the high risk they must assume due to the presence of armed groups. In addition, the construction and start-up of projects in the energy sector and others are especially vulnerable to insecurity, so private security costs must be assumed.

Despite a robust security scheme that improves the company's perception of security, the armed conflict has caused the suspension of projects in various regions of the country. In January 2023, the Canadian oil company Parex Resources Colombia received threats from the guerrilla "National Liberation Army" (ELN), for which they had to abandon their oil extraction activities in the department of Arauca. According to figures from Ecopetrol S.A., the oil infrastructure has been the target of terrorist attacks 2800 times in the last 20 years, which has caused the spill of more than 3.7 million barrels of oil into the environment [62], with Caño Limón being the deposit that has suffered the most attacks in the last 28 years worldwide [63].

3.4.4. Inequity in Education

The inequity in access to education in the country influences the population's lack of awareness regarding environmental issues and the lack of qualified personnel for the design, construction, and maintenance of projects in renewable energies. Colombia is the second most unequal country in Latin America and ranks seventh in the world out of 194 countries [64]. Likewise, there is a significant difference in the access and quality of education between rural and urban areas, where urban areas outperform rural areas. In 2013, the average years of schooling for the population aged 15 or over was 5.47 years, while that of the urban population was 9.36 years [65]. Therefore, it is necessary to train people in rural areas to operate the various energy production systems to impact rural communities positively.

3.5. Main Findings

Finally, Table 6 summarizes the results of the SWOT analysis conducted in this study.

Table 6. SWOT analysis of the development of solar thermal energy in Colombia.

Strengths	Weaknesses
• Colombia's solar resources are abundant, with an average solar irradiation of about 4.5 kWh/m^2/day, ideal for solar thermal applications. • Reliable solarimetric data are available from Colombia's Solar Radiation, Ultraviolet, and Ozone Atlas. These data are critical to developing solar thermal projects, particularly on medium and large scales. • In the household sector, Colombia currently has 100,000 m^2 of solar water heaters installed. • More than 30% of Colombia's gross domestic product is generated by the primary and secondary sectors of the country's main economic activities. Solar thermal systems could be used in a variety of different processes. • Several laws and governmental decrees in Colombia provide tax breaks to stimulate the use of renewable energy. These benefits are also applicable to solar thermal plants.	• Colombia currently lacks large-scale solar thermal installations in the industrial and commercial sectors. Moreover, despite Colombia's potential for solar heat generation, there are no government plans, either in the short or medium term, to implement projects for the massive use of solar heaters, neither at the domestic level nor at the commercial or industrial levels. • The available solar irradiation database lacks solarimetric stations in the Caribbean, Pacific, Orinoco, and Amazon regions. This restriction puts them at a disadvantage in implementing solar thermal projects. In addition, the existing data are outdated since 2015. • Lack of sufficient relevant incentives for investments in solar projects for solar thermal applications. • Law and government decrees are biased toward photovoltaic projects to produce electricity. • Lack of coordination and investment in research and innovation impede the Colombian technological development required to produce its solar thermal technologies and projects.

Table 6. *Cont.*

Opportunities	Threats
• Colombia's Rational and Efficient Energy Use Program defined several National Energy Plan 2020–2050 targets that could encourage the use of solar thermal energy. These include (1) expanding the use of non-conventional renewable energy sources in the primary energy supply, (2) reducing the proportion of firewood in the residential sector, and (3) lowering greenhouse gas emissions. • The anticipated rise in energy demand due to economic growth and enhanced climate change mitigation efforts may encourage investment in renewable energy projects. • Because 1.5 million rural Colombian households use firewood for cooking, creating a government program or public policy to replace wood-burning stoves with solar stoves would be beneficial. • Because 74.5% of Colombian houses lack a sanitary water heater, installing flat solar systems would be a great way to meet this requirement, particularly in cold-climate areas without access to alternative energy sources (more than 1.3 million households). • Furthermore, electricity accounts for 93.4% of residential water heating; however, electric water heaters consume up to 35% of a home's electricity demand. Therefore, replacing them with solar thermal technology could help reduce greenhouse gas emissions and electricity-generating requirements. • In the industrial sector, 41% of energy usage is for indirect heating; therefore, solar thermal systems could supply or supplement some of this requirement, particularly for preheating. • Furthermore, 44% of industrial processes necessitate direct heating, with much occurring at 80 °C or lower temperatures. Thus, if only 5% of Colombia's industrial thermal energy consumption was replaced by solar heat, natural gas, and mineral coal use could be decreased by nearly 13 PJ. • Beginning in 2020, the tax benefits of Law 1715 included non-electrical applications of Non-Conventional Energy Sources. In the case of solar thermal projects, similar advantages are available for solar resource monitoring equipment and all other components required to develop solar thermal projects, such as solar collectors, pumps, storage tanks, and control systems. • Several solar thermal energy standards in Colombia ensure the quality of solar thermal technologies and installations. • Only 1% of patent filings in Colombia in 2016 were dedicated to solar thermal energy challenges, indicating an outstanding opportunity to innovate in this area.	• The Colombian National Development Plan's current national targets only include the use of renewable energy for power generation. As a result, present government regulations show no interest in using solar thermal energy to generate heat. • Colombia has a high incidence of corruption, which has previously stymied the development of various renewable energy projects. This circumstance could be repeated, jeopardizing the deployment of additional solar heat projects. • Potential investors in renewable energy projects are uninterested in their development due to the substantial risk and additional costs they must bear due to the existence of armed organizations. • Environmental issues are not well known among the Colombian people. • Lack of qualified personnel for designing, constructing, and maintaining renewable energy projects.

4. Conclusions

Colombia has abundant renewable resources to cover much of its energy demand. However, by 2021, non-conventional renewable energies barely accounted for 0.08% of the total energy supply. This situation highlights the urgent need to promote the broader adoption of alternative renewable energy sources to ensure Colombia's future energy security.

In the case of solar energy applications, the efforts have primarily focused on harnessing photovoltaic energy, overlooking the potential of solar thermal systems for heat generation. Therefore, this study focused on developing a SWOT analysis to determine the Strengths, Weaknesses, Opportunities, and Threats that currently exist in Colombia to harness solar thermal energy and produce solar heat at the domestic and industrial levels. The results of this analysis show that Colombia has a high potential for harnessing solar heat. This solar energy potential could allow more than 1.3 million households in cold-climate areas to have access to hot water, or reduce the use of firewood for food preparation in part of the 1.5 million rural households that still use it by implementing a government support program with solar stoves. In addition, at the industrial level, it was determined that 13 PJ in fossil fuel consumption could be reduced by applying solar heat in 5% of current industry.

However, to achieve this level of penetration of solar thermal technologies in the Colombian market, several challenges must be met. Thus, although progress has been made in generating policies favoring subsidies and government support in developing unconventional energy projects, it is essential to strengthen legislation concerning renewable energies by enacting decrees that facilitate and motivate the integration of thermal solar energy at a massive level. Furthermore, it is necessary to develop specific financial measures for solar thermal project developers to secure the capital for investments in this type of technology.

Lastly, several threats were identified to the country's consolidation of solar thermal energy if a specific government development program for this energy source was implemented; the main one is political uncertainty. With the Colombian national government changing every four years, there is a risk of potential shifts in state guidelines, including those related to the energy sector; this uncertainty could disrupt the continuity of strategic projects with significant social impact. Moreover, the country faces high levels of corruption that hinder or even prevent the implementation of renewable energy projects. The Colombian armed conflict also negatively impacts the adoption of renewable energies. Criminal groups in various parts of the country have increased interest rates for investors, raised security costs, and, in some cases, led to the suspension of projects. If unresolved, these underlying issues could limit solar thermal project execution.

Author Contributions: Conceptualization, S.B., N.O.-A. and E.C.L.-V.; Data curation, N.O.-A. and E.C.L.-V.; Formal analysis, S.B., N.O.-A. and E.C.L.-V.; Investigation, S.B., N.O.-A. and E.C.L.-V.; Methodology, S.B., N.O.-A. and E.C.L.-V.; Project administration, S.B.; Resources, S.B., N.O.-A. and E.C.L.-V.; Supervision, S.B.; Validation, S.B. and N.O.-A.; Visualization, N.O.-A. and E.C.L.-V.; Writing—original draft, S.B. N.O.-A. and E.C.L.-V.; Writing—review and editing, S.B., N.O.-A. and E.C.L.-V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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