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LINDAL DIAGRAM FOR CENTRAL AMERICA

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ABSTRACT

The Lindal diagram is an excellent way to demonstrate the various applications of geothermal fluids in terms of the temperature of the geothermal resource. There are several versions including a wide range of well-established applications that are not specific to a particular climate, market, or region. Engineers and other professionals and developers from different sectors are not always fully aware of the ways in which geothermal energy can be utilized and how it can substitute for processes where heat is required. The Central American version of the Lindal diagram presented herein aims at addressing this gap. In this report, the Lindal diagram has been redesigned to exclude any potential applications that do not apply to Central American conditions, while at the same time adding those that do. This was achieved by doing a market assessment and evaluating the climate conditions of Central America. This work can be used as example for countries in tropical climates and with similar markets.

1. INTRODUCTION

Belize, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama are the seven countries that make up Central America. Belize will not be considered as it is historically, politically, and culturally different but also due to lack of geothermal resources and available data. Central America stretches 1,835 kilometres from northwest to southeast in an arc. Central American countries, with the exception of Belize, have potential resources for geothermal power generation. For indirect uses, the capacity is estimated to be approximately 4,000 MWe (Lippmann, 2006). However, for many reasons, the installed capacity for electricity generation is 650 MWe and for direct uses only 9.35 MWt – the latter based on estimated use in Guatemala, El Salvador, Honduras, and Costa Rica (Lund and Toth, 2020). Low to medium enthalpy resources have not been investigated thoroughly in every country.

The Central America region is still in the starting phase of developing direct uses of geothermal energy and there is a need for planning and promotion tools. This work targets that need.

In 1974, El Salvador and Nicaragua began exploitation of their geothermal resource for electricity generation only. A year before, in 1973, the Lindal diagram was first developed by Baldur Líndal in Iceland using examples from Iceland and other countries. As expected, Líndal focused his work and research in accordance with his experiences from a cold country with a year-round need for heat. The Lindal diagram covers a temperature range of 20-200°C, including the production of electricity. This report will only focus on direct use applications, excluding the generation of electricity. In contrast to

Iceland, Central America is a tropical climate region with temperatures in the range of 17-25°C and humidity from 70% to 95% and, therefore, its needs differ from those of Iceland or other cold climate countries.

The Lindal diagram is a promotional and educational tool that may reach a wide range of people from various backgrounds. However, in its generic form, many specialized processes related to a specific sector, industry, or region have been left out. Although geothermal energy production is a proven technology, engineers and other professional developers are not always fully aware of the ways in which geothermal waters can be utilized, nor of the benefits offered by this energy source, nor of the prerequisites and conditions necessary for its successful application. Therefore, a truly effective tool for engineering professionals, policy makers and developers in Central America is needed.

To this end, the Lindal diagram has been redesigned by leaving out potential applications that do not apply to the region and by adding those that do apply according to the market and climate conditions of the countries. Geothermal power generation has also been included in the diagram, in the special case of cascading projects, but has not been analysed in detail.

2. METHODOLOGY

To achieve the proposed objective of adjusting the Lindal diagram for Central America, the workflow activities shown in Figure 1 were carried out.

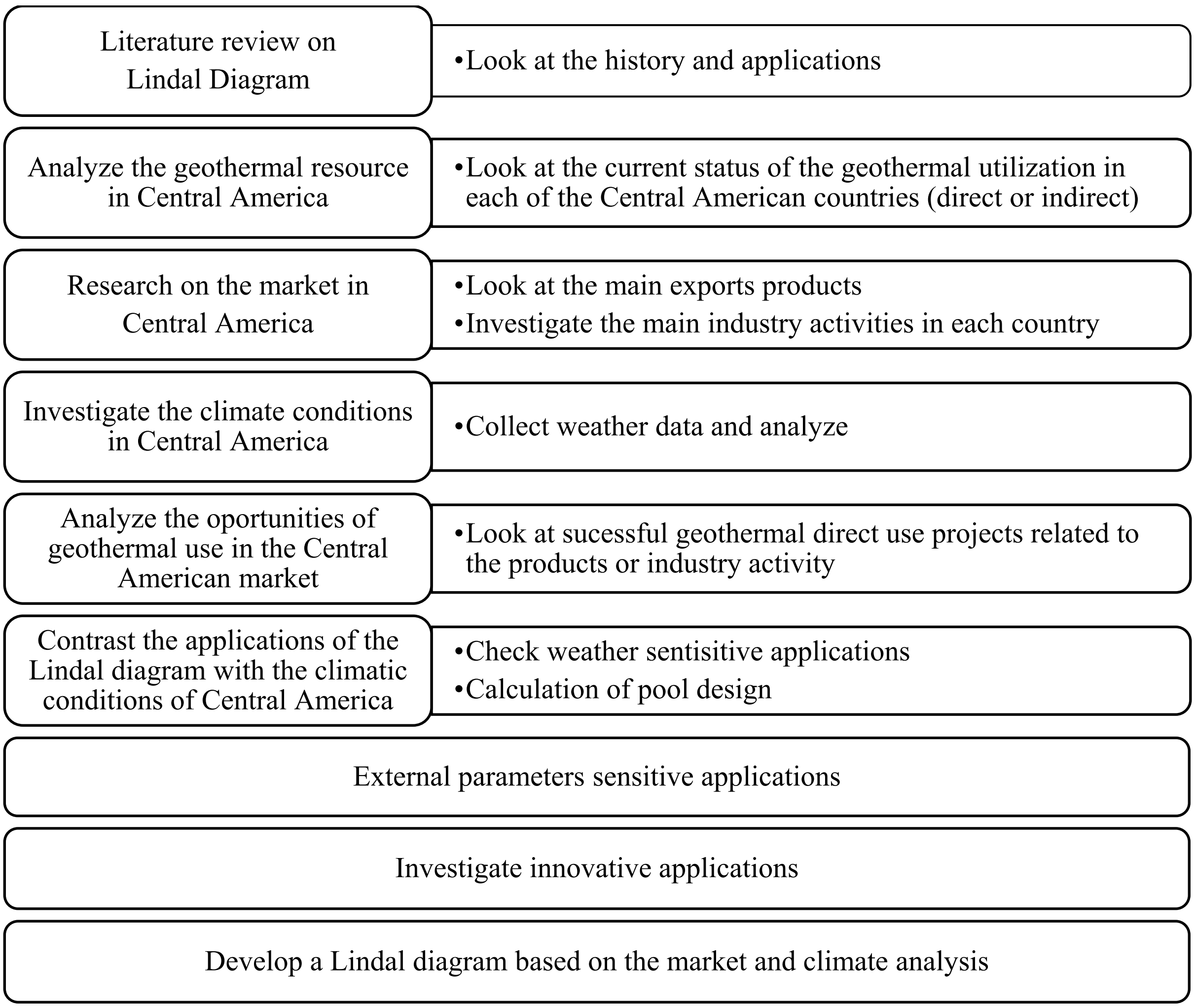


FIGURE 1: Workflowto develop a Lindal diagram for Central America

3. BACKGROUND

3.1 Lindal diagram

It was first called "Lindal diagram" by Gudmundsson et al. (1985) to acknowledge the contribution of Baldur Líndal, an Icelandic chemical engineer. He was one of the pioneers of direct utilization of geothermal energy in the world. He first presented the diagram in 1973 in his article *Industrial and other uses of geothermal energy* in a book entitled *Geothermal energy* published by UNESCO in Paris. Ever since, the Lindal diagram has been very well known in the geothermal community, and has been used by several authors in books, articles, technical reports, seminars, and lecture notes.

Lindal's original diagram shown in Figure 2 covered a wide range of applications that were well-known, such as fish farming, de-icing, swimming pools, soil heating, balneology, heating of buildings and

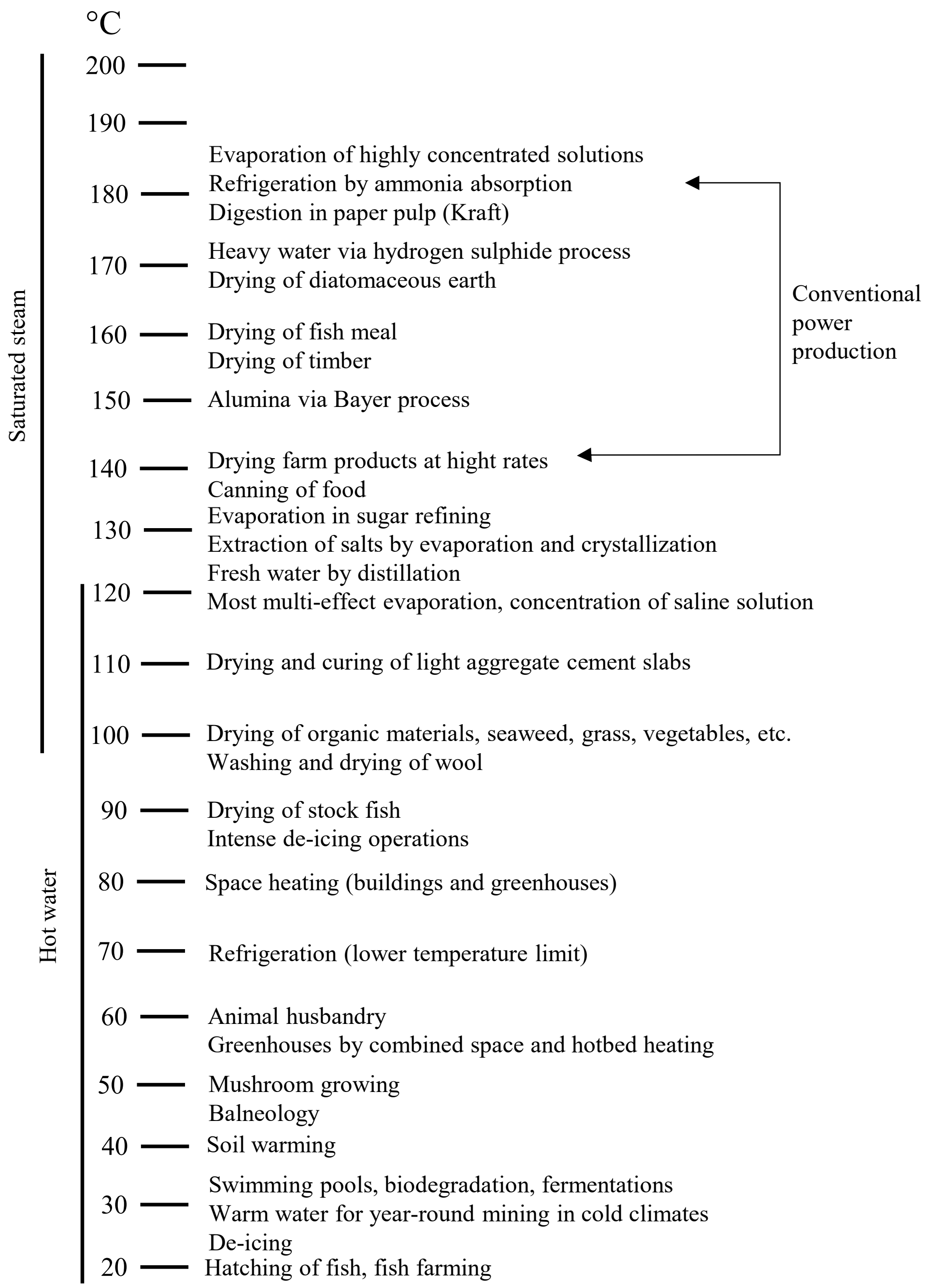


FIGURE 2: Lindal diagram (Gudmundsson et al., 1985)

greenhouses, drying of organic products, evaporation and canning of food, as well as pulp digestion and ammonia absorption refrigeration. Subsequent versions of the diagram were no longer restricted to direct use applications, but were expanded to include electric power production from dry steam, flash steam and binary power cycles (Gudmundsson et al., 1985; Lund et al., 2011).

In most geothermal applications water is employed over a wide temperature range rather than at a particular temperature point. Steam is used in applications at the high end of the temperature scale, while hot, liquid geothermal water is used in applications at the low end. However, while conventional geothermal energy production from dry steam and flash sources is usually at the high end of the scale, the binary technology can be used with lower resource temperature. Furthermore, geothermal water can be used directly across the whole temperature range, which can be extended down to 22°C for heat pump applications (Gudmundsson et al., 1985; Lund et al., 2011).

The applications included in the Lindal diagram are applications from experiences in Iceland, the United States, and other countries with similar needs due to the market and climate conditions (Gudmundsson et al., 1985).

3.2 Central American conditions

3.2.1 Geothermal resource in Central America

Central America has abundant geothermal resources, but only a small percentage of them have been exploited and are now used to produce mainly electricity. El Salvador, Nicaragua, and Guatemala began geothermal exploration in the 1950s and late 1960s, identifying some promising areas. El Salvador began the commercial exploitation in Ahuachapán in 1975, followed by Momotombo in Nicaragua in 1983, Berlin in El Salvador in 1992, Miravalles in Costa Rica in 1994, Zunil in Guatemala in 1998 and so on.

The Pacific rim volcanic zone encompasses Central American countries (with the exception of Belize). According to Birkle and Bundschuh (2007), Central America's geothermal (or hydrothermal) systems are linked to the active volcanic belt and get their heat from magmatic sources at shallow to intermediate depths. High enthalpy resources are found in active and dormant volcanoes, calderas, and other volcano tectonic structures in Central America according to Pullinger (2009), whereas medium enthalpy resources are found in tectonic structures that allow deep fluid circulation or older volcanoes that contain residual heat. As indicated in Figure 3, geothermal resources are concentrated along the Pacific rim from Guatemala to Northern Costa Rica (Rodriguez and Henriquez, 2007). The figure shows the geothermal fields in operation, generating electricity, where there is also a big opportunity to develop cascading or combined systems.

According to Lippmann (2002), the capacity for energy generation from geothermal resources in Central America could range from 2,000 to 16,000 MWe. However, only a small fraction has been utilized for power generation. In this area of abundant geothermal resources, the installed capacity in 2018 was only 650 MW. High temperature resources have been used to generate electricity with traditional steam turbines, but medium temperature geothermal resources have also been used in the region by utilizing binary cycle generation technologies.

Lund and Toth (2020) published data on the direct use of geothermal resources, primarily for agricultural drying, bathing, and swimming pools in Guatemala, El Salvador, Cost Rica, and Honduras.

Most of the direct use applications of geothermal heat in the region is informal, like bathing and spas, and mostly in remote areas. It is therefore very difficult to quantify how much energy is being used. The total thermal capacity according to Lund and Toth (2020) is 9.35 MW_t and the total energy use is estimated as 53.46 GWh/year. Table 1 shows the thermal capacity and energy estimated for each country of the region.

FIGURE 3: Location of active geothermal fields and major geothermal sites in Central America (Salas, 2012)

TABLE 1: Direct geothermal utilization in Central America (Lund and Toth, 2020)

Country	**Thermal capacity estimated (MW_t)**	**Thermal energy estimated (GWh/year)**
Costa Rica	1.75	9.72
El Salvador	3.36	15.56
Guatemala	2.31	15.68
Honduras	1.93	12.50
Nicaragua	0	0.00
Panama	0	0.00
Total	**9.35**	**53.46**

Geothermal resource classification

There is not a standardized classification for geothermal resources. The most commonly used is the classification by temperature or enthalpy. Table 2 shows the classification based on enthalpy according to Muffler and Cataldi (1978). Table 2 shows that direct use can also be applied at higher temperatures, e.g. in intermediate enthalpy fields in a combined or cascade scheme.

Low- and intermediate-temperature geothermal energy resources, as well as waste heat and cascading water from geothermal power plants all provide potential for agricultural and agro-industrial use.

TABLE 2: Geothermal resource classification (Muffler and Cataldi, 1978)

Geothermal resource	Temperature range	Geothermal utilization
Low enthalpy	< 90°C	Direct uses of geothermal energy
Intermediate enthalpy	90°C - 150°C	Direct uses of geothermal energy – cascading and combined Electricity generation using binary cycle plants
High enthalpy	> 150°C	Electricity generation using single, double flash power plants Cascading and combined systems

The majority of direct-use applications are in the 20-120°C temperature range. Low to intermediate temperature geothermal resources have been utilized for centuries, initially for bathing and then for space heating and agriculture.

The geothermal resource of each country in Central America will be addressed, including the status of exploitation and the geothermal potential. Additionally, the promising sites for indirect or direct uses were investigated. It is important to mention that direct use projects can be combined with indirect projects.

Guatemala

Zunil and Amatitlán geothermal power plants with installed capacities of 25.2 MW and 24 MW, respectively, provide about 3.1 percent of Guatemala's electricity. A single-phase 300°C resource was found in the Zunil I well, which was drilled in 1991. Amatitlán, a deep chloride-rich geothermal system with a temperature of 285°C, was proven by an exploration well drilled in 1993 (Asturias, 2008).

According to Asturias and Grajeda (2010), a 1990 assessment of the Moyuta area revealed that the reservoir is divided into two subsystems with predicted temperatures of 210°C and 170°C.

A regional survey in 1981 discovered 13 geothermal zones, with 7 of them having temperatures ranging from 230°C to 300°C as shown in Figure 4. These are Amatitlán, Tecuamburro, Zunil I, Zunil II, San Marcos, Moyuta, and Totonicapan, listed in decreasing order of priority. Los Achiotes, Palencia, Retana, Ayarza, Atitlan, Motagua, and Ipala are second priority locations with low temperatures (Merida, 2012).

Geothermal energy in Guatemala has traditionally been utilized for medicinal, agricultural, and domestic purposes. The thermal bath houses and spas at Totonicapan, Quetzaltenango, and Amatitlán are renowned tourist destinations. Bloteca, a construction company, was the first to successfully use geothermal steam directly in the curing process of concrete products (Merida, 1999).

The Agroindustrias Las Laguna fruit dehydration business was founded in 1998 to dry fruits using hot water from a spring in the Amatitlán geothermal area. The company makes dehydrated pineapple, mango, banana, apple, and chili peppers (Lund and Toth, 2020).

El Salvador

El Salvador is Central America's largest geothermal energy generator; the power stations Ahuachapán (95 MW) and Berlin (109.4 MW) provide about a quarter of the country's electricity. According to Herrera et al. (2010), geothermal resource temperatures are 250°C in Ahuachapán, 300°C in Berlin, 230°C in San Vicente, 240°C in Chinameca, and other resources with temperatures below 200°C are found throughout the volcanic chain.

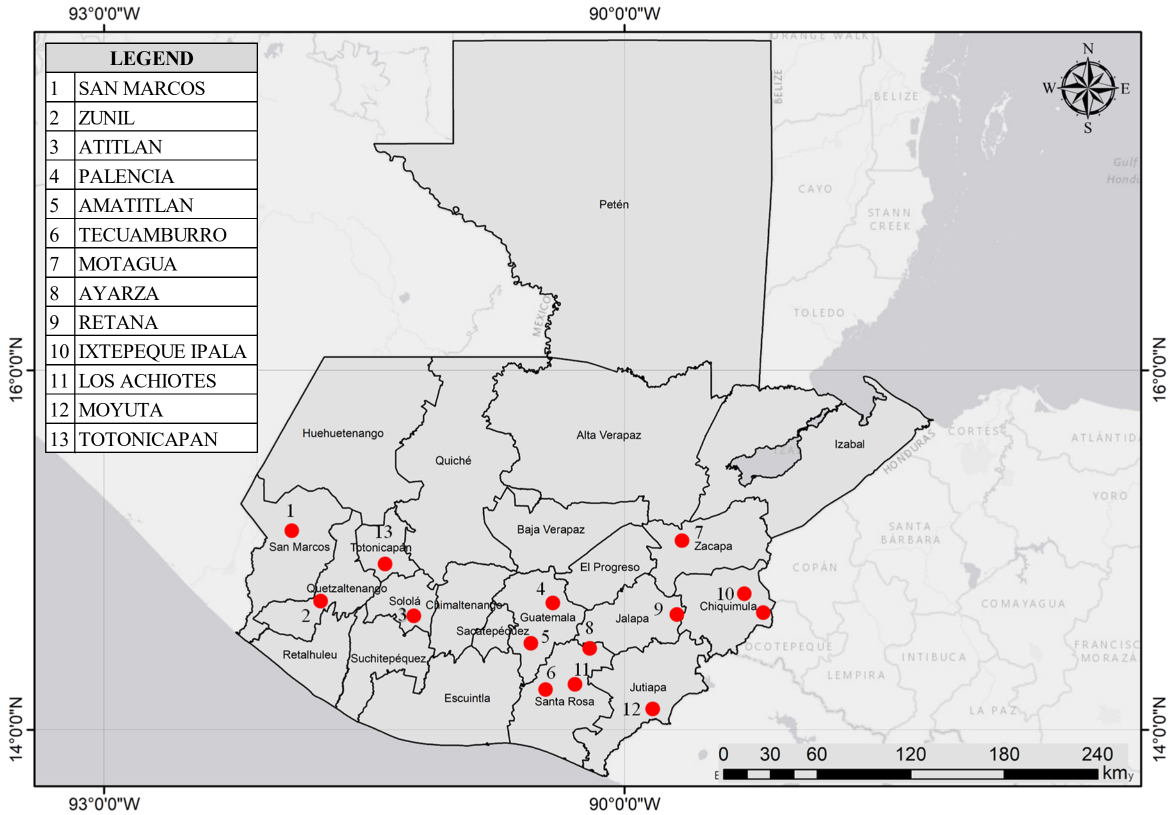


FIGURE 4: Geothermal areas in Guatemala. Modified after Merida (2012).

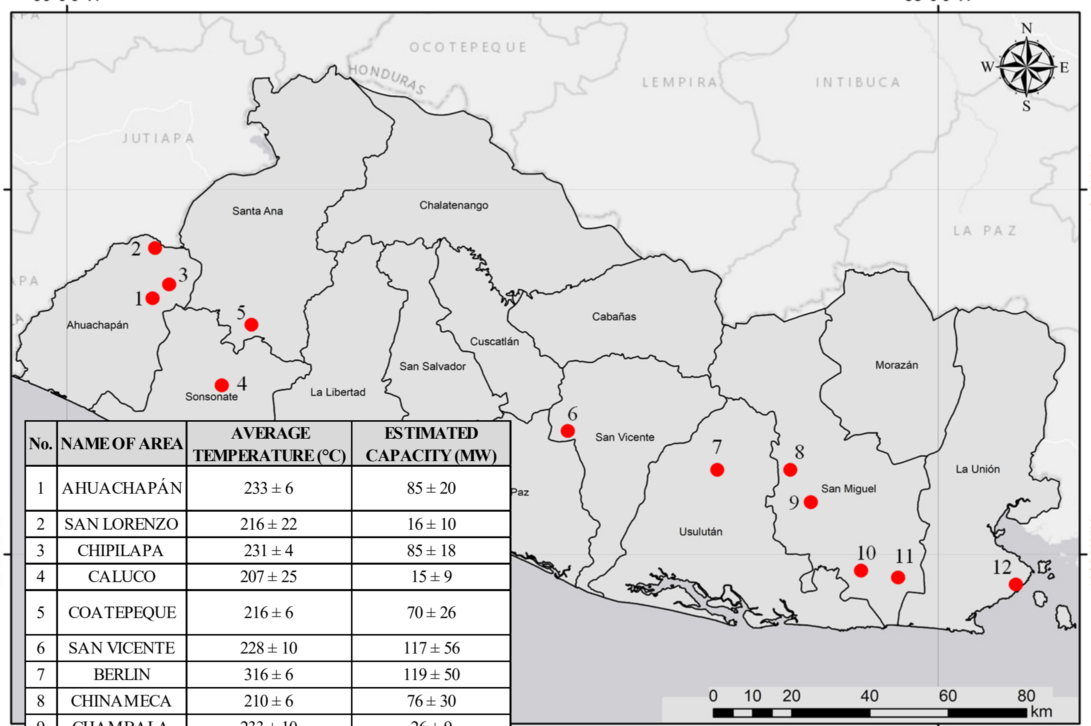
According to Pullinger (2009), an early pre-feasibility study in the mid-1990s discovered a promising resource with temperatures of around 220°C in the Coatepeque geothermal zone. Resources with estimated temperatures of 180°C to 220°C have been uncovered in geological, geochemical, and geophysical field studies of medium enthalpy deposits such as Conchagua, Chilanguera, and Obrajuelo. Figure 5 shows the 12 identified geothermal areas in El Salvador and their temperature ranges.

According to Lund and Toth (2020), there have been minor advancements in greenhouse heating, fish aquaculture, and fruit drying. Proceso de deshidratado Natural Geotermico, also known as Geo Fruit or FundaGeo, is drying coffee, pineapples, apples, coconuts, and other fruits and vegetables in the Berlin geothermal area by using heat from a reinjection well and lowering the temperature with a heat exchanger since the lowest temperature in the field is 138°C. These fruits are prepared for local consumption in Berlin, Usulután.

Honduras

In 2017, the first electric power generation plant in Honduras, located in the western part of the country, was put into operation with a capacity of 35 MW (Henriquez, 2011). The Pavana and Azacualpa projects are currently being investigated. According to Lagos and Gomez (2010), temperatures between 160°C and 165°C were detected at shallow depths in the assessment of Platanares, while geothermometers showed resource temperatures between 200°C and 225°C. According to updated research, Azacualpa has a capacity of 23 MW at temperatures between 170°C and 180°C, and Pavana has a potential of 18 MW at temperatures between 140°C and 150°C. Platanares, El Olivar, Azacualpa, Sambo Creek, San Ignacio, Pavana, and El Tigre Island were the principal geothermal regions discovered during surface investigation in the 1970s, as indicated in Figure 6.

In 2014, Honduras collaborated on the project "Feasibility Study for the Development of Low and Medium Temperature Geothermal Resources for Industrial Processes" with the 4E-GIZ initiative to promote geothermal resource usage. Among the recommended projects were the production of a type of local cheese and the drying of agricultural products. Two places in the northern part of the county, Valle de Sula and Sambo Creek, were identified as potential sites, as hot springs with temperatures ranging from 30°C to 105°C had been discovered there. Several swimming pools are known to be powered by geothermal energy, according to Lund and Toth (2020).



No.	NAME OF AREA	AVERAGE TEMPERATURE (°C)	ESTIMATED CAPACITY (MW)
1	AHUACHAPÁN	233 ± 6	85 ± 20
2	SAN LORENZO	216 ± 22	16 ± 10
3	CHIPILAPA	231 ± 4	85 ± 18
4	CALUCO	207 ± 25	15 ± 9
5	COATEPEQUE	216 ± 6	70 ± 26
6	SAN VICENTE	228 ± 10	117 ± 56
7	BERLIN	316 ± 6	119 ± 50
8	CHINAMECA	210 ± 6	76 ± 30
9	CHAMBALA	233 ± 10	26 ± 9
10	CHILANGUERA	153 ± 20	11 ± 6
11	OLOMEGA	163 ± 13	11 ± 7
12	CONCHAGUA	180 ± 12	13 ± 7

FIGURE 5: Geothermal areas in El Salvador. Modified after Montalvo and Guidos (2009).

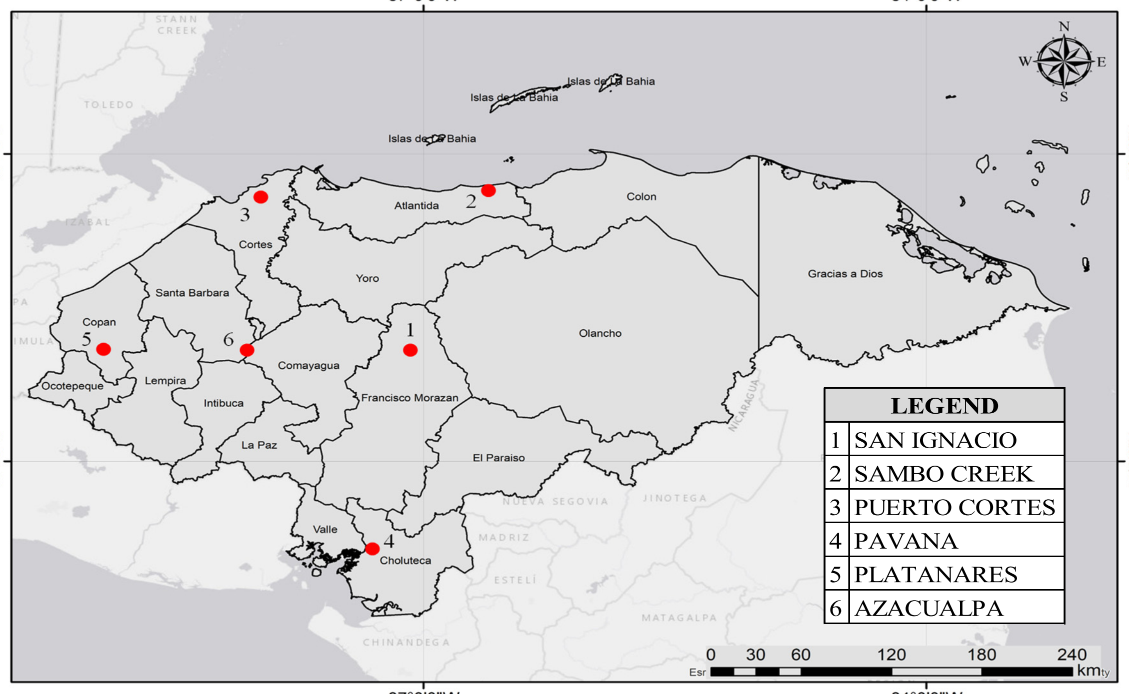


FIGURE 6: Geothermal areas in Honduras. Modified after Henriquez (2011).

In 2014, Honduras collaborated on the project "Feasibility Study for the Development of Low and Medium Temperature Geothermal Resources for Industrial Processes" with the 4E-GIZ initiative to promote geothermal resource usage. Among the recommended projects were the production of a type of local cheese and the drying of agricultural products. Two places in the northern part of the county, Valle de Sula and Sambo Creek, were identified as potential sites, as hot springs with temperatures ranging from 30°C to 105°C had been discovered there. Several swimming pools are known to be powered by geothermal energy, according to Lund and Toth (2020).

Nicaragua

In Nicaragua, there are two geothermal areas that are exploited. According to the statistical data of the Nicaraguan Energy Institute, in 2020 the Momotombo power plant had 76.24 MW of installed capacity and San Jacinto Tizate 77 MW.

More than 44 exploratory wells (up to 2,500 m in depth) have been drilled in Momotombo with temperatures over 330°C (Mostert, 2007). Pullinger (2009) stated that many wells were drilled (up to 2,200 m in depth) in the San Jacinto Tizate geothermal area, confirming the presence of temperatures ranging from 260°C to 290°C. In addition, temperatures of 220°C (at 2,000 m) were discovered in the El Hoyo Monte Galán geothermal area. According to Zuniga (2005), Managua-Chiltepe and Masaya-Granada-Nandaime are more promising geothermal sites. Some of these areas are shown in Figure 7.

Touristic possibilities are found in a few thermal swimming pools that have been documented, such as Aguas Termales in Tipitapa and Aguas Claras spa in Boaco, which are heated by natural geothermal water discharges with temperatures of around 50°C (Fichtner, 2016).

FIGURE 7: Geothermal areas in Nicaragua (González, 2009)

Costa Rica

Some sources estimate geothermal power potential in Costa Rica to be as high as 900 MW (Salas, 2012). Since 1994, Miravalles (165.5 MW) has been Costa Rica's first operational geothermal power plant. The Las Pailas geothermal power plant (35 MW), located on the Rincon de La Vieja Volcano, began operations in 2011. The Miravalles geothermal field has a water-dominated reservoir with an average temperature of 240°C. In feasibility studies, the presence of a geothermal reservoir with temperatures near 260°C has been confirmed in the Las Pailes geothermal area (Protti, 2010).

A geothermal area was discovered near Borinquen in 2008, where a drilled production well has the highest recorded bottom hole temperature (275°C) in Costa Rica (Fung, 2008). Pre-feasibility studies were conducted in the geothermal districts of Tenorio and Nuevo Mundo, while reconnaissance studies were also conducted in Pocosol and the north side of the Rincón de la Vieja volcano. Geothermometers in Pocosol indicated a reservoir temperature of 183°C to 217°C. Platanar, Poás, Barva, Iraz, and Turrialba are other potential geothermal regions discovered around the volcanoes. Figure 8 shows a map of some of the geothermal areas mentioned above and their estimated temperatures. The estimated range temperatures are classified in categories A, B, C, and in classes 1 and 2. Additionally, categories A and B have important aquifer formations, and C has no important aquifer formations.

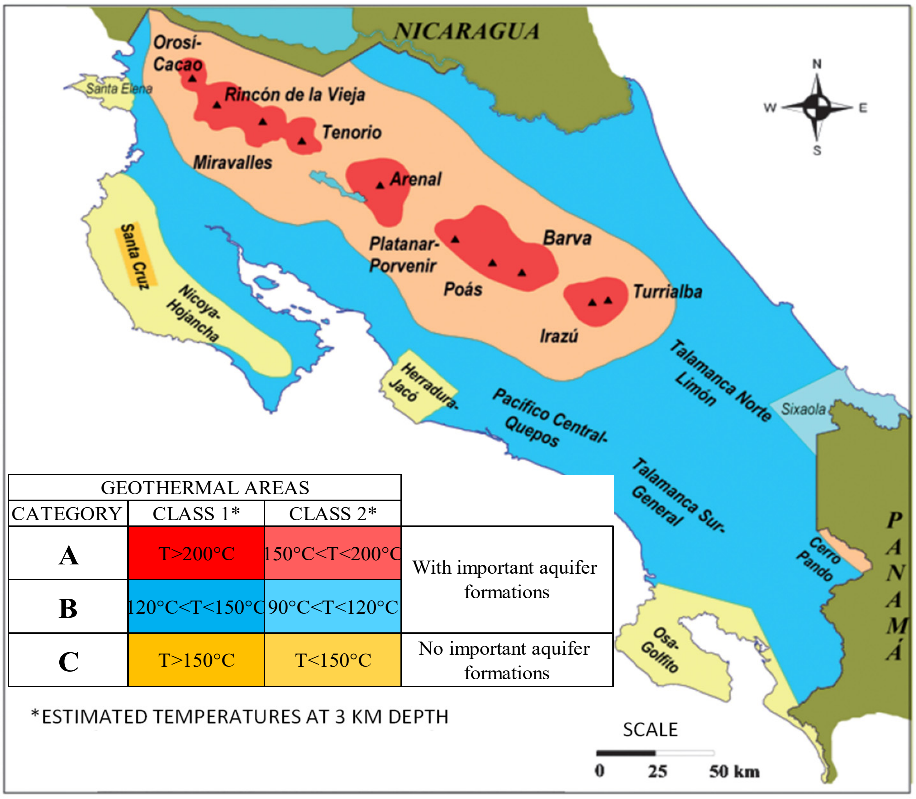


FIGURE 8: Geothermal areas in Costa Rica. Modified after Mainieri and Yock (2009).

The direct utilization of geothermal resources is restricted to low-temperature installations at eco-friendly hotel pools. The usage of these resources has been discouraged due to local circumstances. There is presently no other known usage outside of the Costa Rican Institute of Electricity (ICE), except from smaller residential applications. Because it is unclear how many pools and spas are presently operating in Costa Rica, or even what their individual consumption is, an estimate of equivalent energy output was based on four known geothermal sites dispersed around the central mountain chain of Costa Rica (Sánchez-Rivera et al., 2020).

Panama

Only exploration surveys have been carried out in Panama and no areas of interest have been developed for the exploitation of the resource. Since the 1970s, the potential for geothermal power generation in Panama has been explored multiple times with five major regions being evaluated: Bar-Colorado, Valle de Antón, Coiba Island, Tonos, and Chitre de Calobre. The conclusions of the various studies differed, but the total geothermal potential for Panama was estimated to be between 100 and 450 MW (Giardinella et al., 2011). No information about direct usage of geothermal energy was reported in Lund and Toth (2020).

3.2.2 Climate conditions

The average annual temperature at the Pacific coast of Central America is between 26°C and 27°C, with maximums of 28°C in areas of Guatemala, Nicaragua, Honduras, and northwest Costa Rica according to PREVDA (2010). In Central America, the factor that has the largest impact on the thermal regime is the altitude. The average yearly temperature of the areas between sea level and 600 meters on the Pacific and Caribbean sides fluctuates between 24°C and 27°C. The average annual temperature in the middle sections of the ridges and mountains, between 600 and 1,200 meters, is between 19°C and 23°C, while the average annual temperature in the areas between 1,200 and 1,800 meters is between 17°C and 20°C. The central areas of Nicaragua, Honduras, El Salvador, and Panama are the most affected by these variances in average air temperature. According to the collected weather data for Central American countries, the relative humidity varies from 60% to 95%, with an average of 80%. In this report, a maximum dry air temperature of 28°C and relative humidity of 80% is used.

Representative weather data collected over many years is used to ensure good results for the climate analysis. Weather data was collected and processed from the Solar and Wind Energy Resource Assessment (SWERA), a collection of 12 typical months with 8760 data points, including monthly mean outdoor dry bulb temperature, precipitation, wind speed, and relative humidity for many years.

Figure 9 shows the points where the available weather data was collected. Table 3 shows the elevation and the average temperature on these points. Samples were also obtained from different elevations throughout Central America to be able to contrast the average temperatures at these different sites with possible direct geothermal applications.

FIGURE 9: Weather data collection stations

Figures 10-15 show the outdoor temperature profile, outdoor temperature duration curve, monthly mean outdoor temperature, monthly mean wind speed, monthly precipitation, and relative humidity.

TABLE 3: Weather stations

Location	Elevation (m.a.s.l.)	Average temperature (°C)
Aurora – Guatemala	1489	19
San Salvador – El Salvador	621	23
San Pedro Sula – Honduras	31	26
Managua – Nicaragua	50	27
San Jose – Costa Rica	1300	20
Tocumen – Panama	41	27

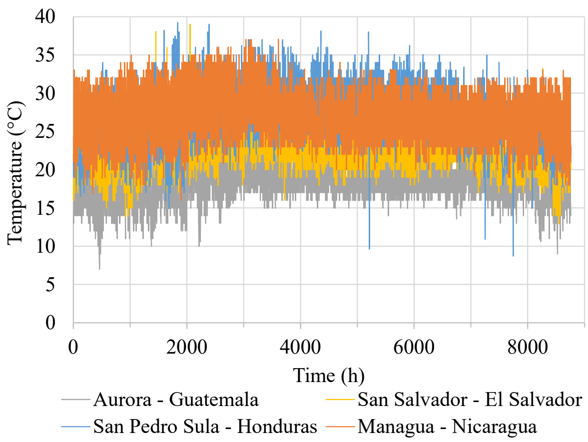


FIGURE 10: Outdoor temperature profile based on hourly values

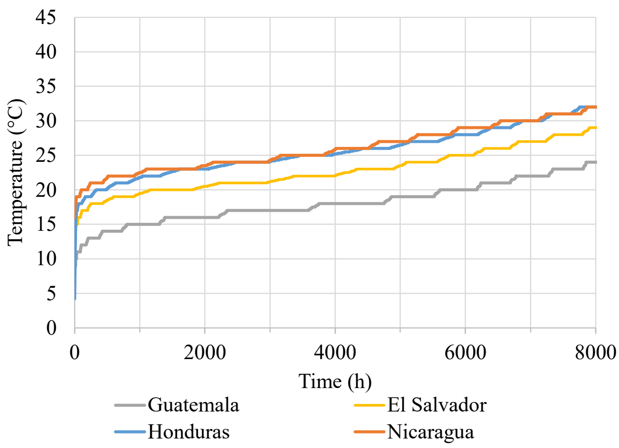


FIGURE 11: Outdoor temperature duration curve based on hourly values

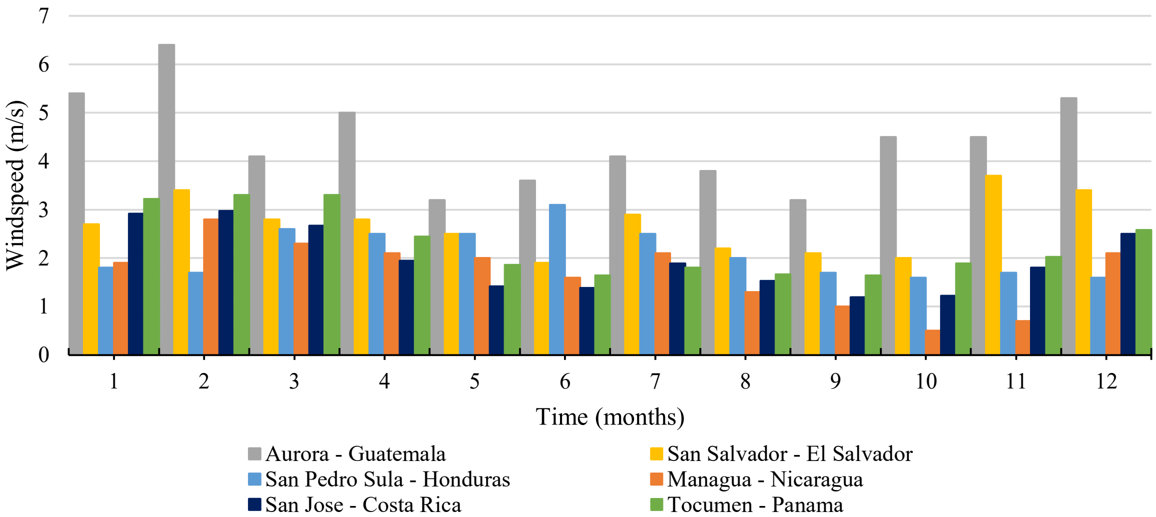


FIGURE 13: Monthly mean wind speed

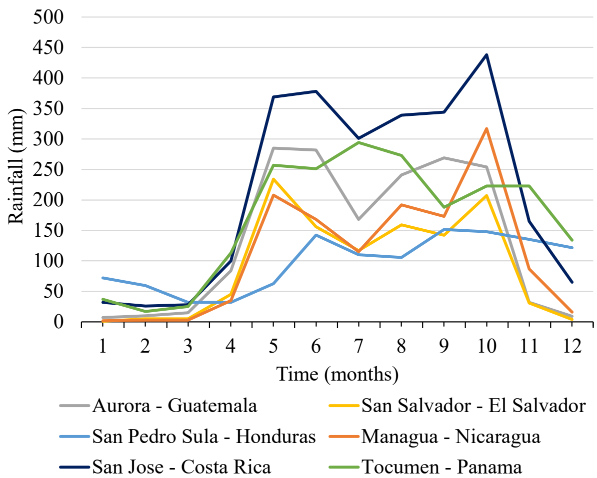


FIGURE 14: Monthly accumulative precipitation

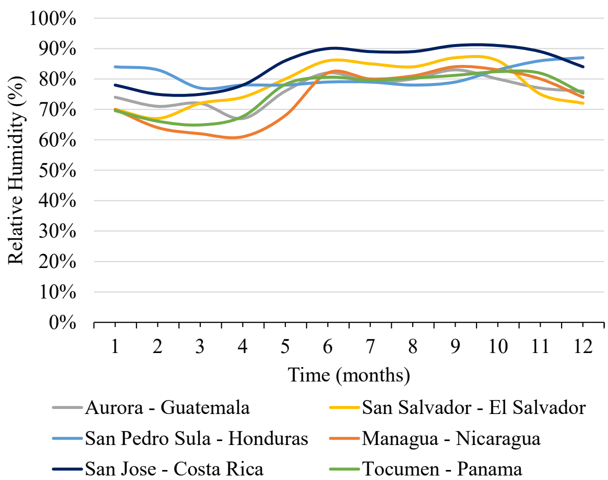


FIGURE 15: Monthly relative humidity %

Meteorological data were collected to assess the feasibility of applications that may be affected by temperature, humidity, wind speed and rainfall. In addition, temperature averages in different areas of Central America were looked at throughout the year to see the variations and to evaluate if geothermal energy was required at any time of the year. Furthermore, it was investigated which applications of the Lindal diagram could be eliminated and if the design of some of them was affected. The design of swimming pools and aquaculture is very similar and was looked at in detail.

3.2.3 Market in the region

In the whole of Latin America and the Caribbean, Central America has the sixth biggest economy. According to the 2020 projection, Central America has 50.3 million inhabitants. For the year 2019, exports of goods and services amounted to USD 76,842.4 million and 28.5% of GDP. Central America is the third largest exporter of coffee worldwide and is among the top 30 exporters of medical instruments worldwide, as well as exporter of textiles and clothing. It is the world's largest pineapple and cardamom exporter and the second largest exporter of bananas. These goods are transported through 20 international airports, 47 seaports and an interoceanic canal (SIECA, 2021).

Manufacturing exports were the primary driver for the increase in the region's goods exports. Central America's export structure was modified as a result of this. It has not only shifted away from the heavy reliance on agricultural exports, but it also created a strong reputation for manufacturing exports which it might exploit more effectively in the future.

The region has been a successful exporter of food items for many decades, the most important of which are shown in Table 4.

TABLE 4: Exported products (Ulku and Zaourak, 2021)

Country	Main items
Costa Rica	Bananas, pineapples, coffee, food preparations
Guatemala	Sugar, bananas, coffee, palm oil, spices
Honduras	Bananas, coffee, palm oil, seafood
Nicaragua	Coffee, beef, seafood, sugar, dairy products
El Salvador	Sugar, coffee, corn, rice, beans
Panama	Bananas, rice, corn, coffee, sugarcane

For the collection of data, a market analysis tool developed by the Secretariat for Central American Economic Integration (SIECA) was used. It is an interactive module that allows the user to analyse aspects related to the competitiveness of Central American exports in various markets. The total values in millions of US dollars and volume in tons of the main products export items were collected from the tool, as shown in Figure 16.

The main industrial activities for each country are shown in Table 5 (Ulku and Zaourak, 2021).

4. DISCUSSION

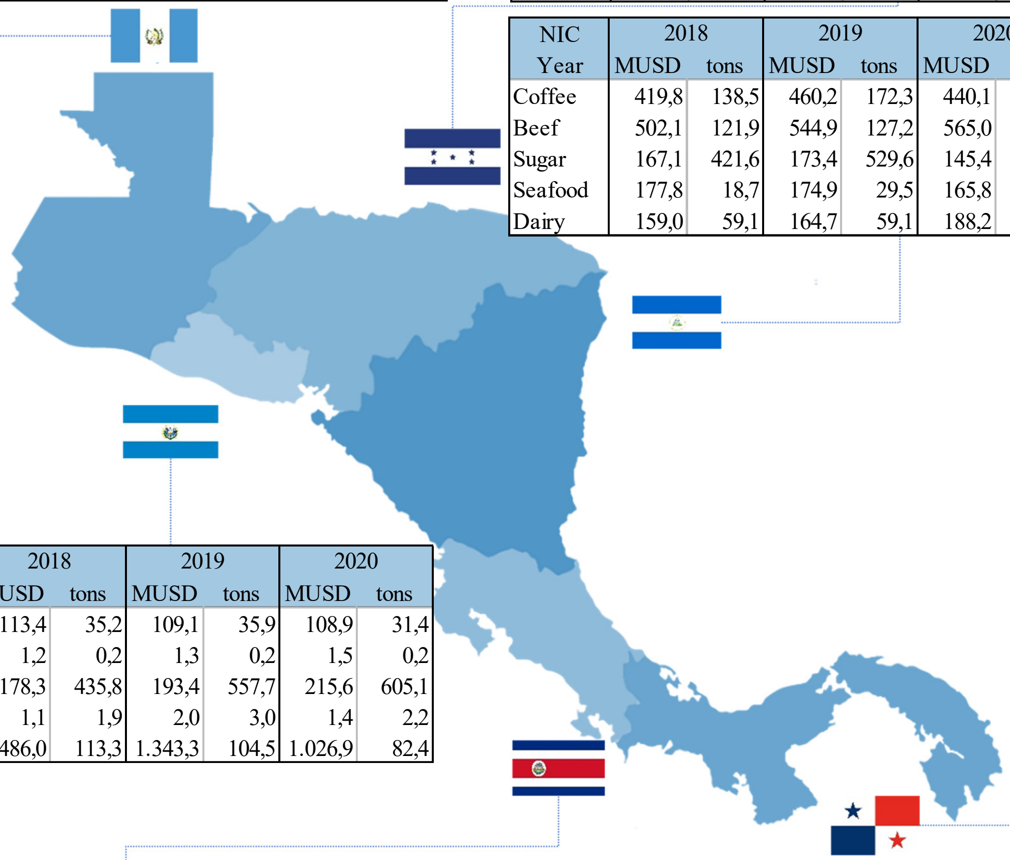
4.1 Analysis of the market in Central America

The main food products exported from Central America were investigated to see if the production of those goods could benefit from the direct utilization of geothermal energy. We analysed both final products and raw materials. For serving products or raw material there is an opportunity to create a business model. For other finished products, geothermal fluid could replace the heat source if needed. It is important to mention that this will depend on important factors such as the technology and how it can be modified. Table 6 shows a summary of the main products exported from Central America and their traditional processing methods. The recommended geothermal temperature range is also listed.

GUAT	2018		2019		2020	
	MUSD	tons	MUSD	tons	MUSD	tons
Coffee	680,9	205,9	663,7	216,2	651,8	188,4
Spices	438,4	38,9	652,1	38,6	1.138,3	66,9
Banana	90,7	238,9	102,4	260,6	114,3	272,8
Palm Oil	447,6	818,1	393,9	811,8	471,7	748,3
Sugar cane	632,9	1.660,2	694,6	2.029,2	576,8	1.657,8

HOND	2018		2019		2020	
	MUSD	tons	MUSD	tons	MUSD	tons
Coffee	1.119,1	430,5	950,0	407,7	873,0	317,5
Pineapple	32,4	64,3	33,3	66,9	34,1	65,9
Banana	0,6	1,3	0,5	0,8	0,6	0,5
Palm oil	290,9	476,1	287,2	518,8	337,6	483,7
Seafood	341,7	45,5	358,8	48,3	382,4	49,6

NIC	2018		2019		2020	
Year	MUSD	tons	MUSD	tons	MUSD	tons
Coffee	419,8	138,5	460,2	172,3	440,1	150,3
Beef	502,1	121,9	544,9	127,2	565,0	132,7
Sugar	167,1	421,6	173,4	529,6	145,4	428,0
Seafood	177,8	18,7	174,9	29,5	165,8	31,4
Dairy	159,0	59,1	164,7	59,1	188,2	67,3



ELSL	2018		2019		2020	
	MUSD	tons	MUSD	tons	MUSD	tons
Coffee	113,4	35,2	109,1	35,9	108,9	31,4
Spices	1,2	0,2	1,3	0,2	1,5	0,2
Sugar	178,3	435,8	193,4	557,7	215,6	605,1
Rice	1,1	1,9	2,0	3,0	1,4	2,2
Clothing	1.486,0	113,3	1.343,3	104,5	1.026,9	82,4

CR	2018		2019		2020	
Year	MUSD	tons	MUSD	tons	MUSD	tons
Coffee	318,5	75,6	279,4	63,5	329,0	70,1
Pineapple	1.038,2	2.333,9	981,0	2.216,4	922,7	2.047,3
Banana	1.030,9	2.488,8	999,7	2.384,8	1.083,0	2.628,1
Melon	87,5	172,4	87,3	177,6	71,3	149,4
Sugar	86,0	205,4	75,1	204,6	78,9	193,1

PA	2018		2019		2020	
	MUSD	tons	MUSD	tons	MUSD	tons
Seafood	111,5	32,4	77,0	20,7	74,8	23,6
Banana	106,1	298,4	127,1	611,9	151,7	700,4
Coffee	19,0	1,7	26,4	2,4	24,9	2,4
Sugar cane	28,6	51,8	24,9	46,1	25,9	44,1
Fruits	130,1	349,3	148,7	657,9	171,6	740,0

FIGURE 16: Main product exports from Central America in values and in volume (SIECA, 2021)

TABLE 5: Main industrial activities in Central America

Country	**Industries**
Guatemala	Sugar, textiles/clothing, furniture, chemicals, petroleum, metals, rubber, tourism
El Salvador	Food processing, beverages, petroleum, chemicals, fertilizer, textiles, furniture, light metals
Honduras	Sugar processing, coffee, woven and knit apparel, wood products, cigars
Nicaragua	Food processing, chemicals, machinery and metal products, knit/woven apparel, petroleum refining/distribution, beverages, footwear, wood, electric wire harness manufacturing, mining
Costa Rica	Medical equipm., food processing, textiles/clothing, constr. materials, fertilizer, plastic products
Panama	Construction, brewing, cement / other construction materials, sugar milling

TABLE 6: Summary of products and their traditional method and recommended geothermal temperature

Product	Traditional method	Recommended geothermal temperature range
Pineapple	Exported and consumed fresh. Only small-scale dehydration projects using sun and geothermal energy.	40°C – 80°C
Banana		
Spices	Drying using fossil fuels or the sun.	45°C – 60°C
Coffee	Sun drying (weather dependent), it is not a uniform drying, fungi may appear. Fossil fuel or electricity, better control of the heat.	~ 50°C
Beans		~ 50°C
Corn		~ 60°C
Palm oil	Industrial boiler using fossil fuel.	45°C – 100°C
Sugar	Industrial processes are using electricity or fossil fuels.	130°C – 140°C
Dairy		70°C – 90°C
Beef	Electricity for cooling storage is used.	150°C – 180°C
Seafood		

In the case of fresh fruits like bananas and pineapple of which all Central American countries are big exporters, there is the possibility to dehydrate the fruits if there is excess or to create a new final product. This can be achieved with geothermal energy at temperatures between 40°C to 80°C.

All Central American countries are great exporters of coffee. El Salvador and Panama export rice, and El Salvador corn. All these products have gone through a drying process. In this case it is easy to identify and replace the type of energy or heat that is used in the drying process, which often comes from fossil fuel oils or electricity to meet industry standards. But the most common drying agent is the sun, which brings many disadvantages because it depends on weather conditions. The drying is not uniform, and diseases and fungi can occur when drying is not done continuously. Coffee drying takes place at 50°C according to Prasetyo et al. (2018). To avoid rice cracking, the rice drying temperature is kept below 40°C (Popovski et al*.,* 1992).

Guatemala and Honduras are the main exporters of palm oil in the region. There are various components in crude palm oil plants that require heating, most notably the crude palm oil purifier. For purification procedures, the heating temperature should be approximately 45-100°C, and for boiling fruits, it should be around 140°C. This heating process is carried out using an industrial boiler in conventional crude palm oil facilities (Utami et al., 2019).

The drying of cardamom and other spices has big potential for growth in the region, including using geothermal fluid as a heat source for it. The temperature for agricultural drying ranges from 45°C to 60°C. Guatemala is the biggest exporter in this domain.

The drying of fresh food is a method of preservation to prevent it from deteriorating quickly, but the drying of meats or seafood is not a part of the culture of Central Americans. That is why these two products need refrigeration. There are large beef and seafood companies that require cold rooms for storage. And here absorption systems can be an option to supply that need. Nicaragua and Honduras are the biggest exporters of these goods in the region, with great potential. The temperatures for these applications are in the ranges of 150°C to 180°C.

The manufacturing industry plays a big role in the growth of the gross domestic product (GDP) for Central American countries. However, the agricultural industry cannot be left aside, as it is the one that allows the export of the main products from these countries, including bananas, sugar cane, coffee, seafood, spices, and timber, as mentioned in the previous chapter.

The manufacturing industry is dedicated exclusively to the transformation of different raw materials into finished products and goods ready to be consumed or to be distributed by those who will bring them to the final consumers. And included in this transformation of raw materials are different processes that require heat. Some of the processes that could use geothermal resources according to Gudmundsson et al. (1985) are: Drying, process heating, evaporation, distillation, space air conditioning, refrigeration, washing, desalination, chemical extraction, and other processes are. These processes can be used in the main industrial activities in the region for producing food products, beverages, textiles, machinery and equipment, wood products, paper, chemical products, metal products and more.

Products that are not exported and are consumed locally, such as beer and liquors, should also be mentioned. The processing of these products requires heat, which can be supplied through geothermal energy. The temperatures of these processes are between 60°C and 80°C (Chiasson, 2006).

4.2 Description of applications

Worldwide direct use applications are dominated by heat pumps, representing 70% of the total installed capacity, followed by space heating with 12%, bathing and swimming (Table 7). Other applications, such as greenhouses, industrial uses and crop drying, which can possibly be developed in Central America represent only 1% worldwide. Apart from heat pumps, space heating dominates the geothermal direct uses worldwide, but in Central America there is no need for this due to the average temperatures of the countries. Guatemala has the lowest temperatures but not to the point of needing heating year-round. Even though Central America does not have extreme hot temperatures, cooling is needed for housing, tourism, industry, and commerce due to the tropical humid climate.

TABLE 7: World-wide capacity of geothermal utilization (Lund and Toth, 2020)

Utilization	2020	
	MWt	TJ/year
Geothermal heat pumps	77,547	599,981
Space heating	12,768	162,979
Greenhouse heating	2,459	35,826
Aquacultural pond heating	950	13,573
Agricultural drying	257	3,529
Industrial uses	852	16,390
Bathing and swimming	12,253	184,070
Cooling / snow melting	435	2,589
Other	106	1,950
Total	107,727	1,020,887

Table 8 shows how many countries are using geothermal direct use applications. Here, Central America can be part of the bolded categories, but at the moment it only belongs in two of them. The first of those categories is bathing and swimming, and the second one is crop drying, which Guatemala and El Salvador engage in.

The highlighted applications in Table 8 will be discussed and other factors influencing the development of these applications, apart from market and climatic conditions, will be evaluated.

4.2.1 Bathing and swimming

Thermal waters have been utilized for centuries all throughout the world. The popularity of hot spring resorts is enormous. In certain regions, the therapeutic properties of the thermal waters are widely known and health centres have operated for decades or centuries. In Iceland geothermal pools are part of the culture and they have been used for mandatory swimming lessons for kids since 1940. They offer saunas, pools, bubble baths, physical therapy pools and whirlpools, and are seen as venues for social activity and entertainment. The resource's temperature and mineral composition are critical factors.

Safety issues must be considered: Slipperiness, potential for drowning and injury, microbial hazards, chemical hazards, as well as water and air quality (Jóhannesson, 2021a). In Central America, bathing in thermal waters or geothermal pools is not a popular activity and there are not many of them. If more people learn the benefits of bathing in geothermal waters, this market could be developed to attract tourism to the countries. More promotion and marketing are needed.

TABLE 8: Direct uses of geothermal energy worldwide (Lund and Boyd, 2015)

Direct uses	Number of countries
Bathing and swimming	**70**
Geothermal heat pumps	45
Greenhouse heating	31
Space heating	28
Aquaculture	**21**
Agricultural crop drying	**15**
Industrial process heating	**15**
Other uses	13
Snow melting and space cooling	6

4.2.2 Drying

The purpose of drying vegetables and fruits is to avoid spoiling in storages. The drying process slows down microbial and other chemical processes, allowing vegetables to be preserved for extended periods of time. By lowering the water content of vegetables, their flavor, smell, and nutritional value are preserved. The drying process reduces bulk, making transportation and storage more convenient (Basak et al., 2014). Central American countries are still developing countries, highly dependent on agriculture and agroindustry. In this sector there are a lot of vegetables and fruits that never reach the market and the producers need to discard them. One third of the of annual food production is wasted according to the Food and Agriculture Organization of the United Nations (FAO, 2011). Another scenario is over-production where the harvest is lost. In other words, there is a lot of waste of fresh fruits and vegetables. One solution for this is to dry them and package for sale locally or for export. Using geothermal energy for these purposes can help to increase food availability, reduce reliance on fossil fuels, mitigate price volatility, and reduce harmful emissions from the industry. Additionally, it has the potential to drastically decrease food waste (FAO, 2011).

The drying systems must be operational continuously and practically throughout the year to provide a profitable business (base load requirement). Because geothermal energy is a base load source, it meets this condition. Otherwise, due to a low load factor and a small number of full load hours, efficiency is decreased. Therefore, the harvest time of the products needs to be investigated and an individual facility must be able to dry more than one product to comply with this requirement.

4.2.3 Aquaculture

Aquaculture or aqua farming is the practice of raising aquatic animals such as fish, crustaceans, mollusks, and aquatic plants, in a controlled setting. The most common species grown are catfish, bass, tilapia, sturgeon, shrimp, and tropical fish. One of the objectives is to improve the rate of growth. Another common use is livestock farming. The type of aquatic animals raised, as well as the quality and content of the water, influence the usage of geothermal fluid in aquaculture. The geothermal fluid is typically utilized to provide heat directly to the pond or pool. If the geothermal fluid is inappropriate for the aquatic animals being reared, a heat exchanger may be required. The temperature of the water is usually between 13°C and 30°C (Jóhannesson and Chatenay, 2014).

4.2.4 Industrial processes

Despite the fact that the Lindal diagram depicts a wide range of potential industrial and process applications for geothermal energy, the world's applications are very limited. The oldest industrial usage is in Larderello, Italy, where geothermal brines have been used to produce boric acid and other borate chemicals since 1790 (Lund, 1997). Most of the industrial initiatives are located in Iceland, the United States, and New Zealand. Examples include a diatomaceous earth drying facility in northern Iceland, a pulp, paper, and wood processing factory in Kawerau, New Zealand, and two onion dehydration factories in Nevada, United States (Lund and Lienau, 1994).

The use of geothermal resources in Central America has the potential to grow this sector, but one important challenge is the distance between the industry and the geothermal resource, because over long distances, heat can only be provided to a certain extent.

4.2.5 Cooling system

A cooling system, sometimes known as a refrigeration system, is a process of extracting heat from an item, particularly in a small area, and rejecting the unwanted heat into a desired environment; the cooling process can also be described as a method to reduce an object's temperature. The compression cooling system and the absorption cooling system are the two most popular cooling systems (Tesha, 2009). Heat pumps can be used to successfully cool spaces using geothermal energy (Jóhannesson and Chatenay, 2014).

A compression cooling system uses a mechanical compressor and an electric motor to force heat transfer mechanically from a low to a high temperature. Two heat exchange devices, a generator (desorber) and an absorber, replace the mechanical compressor in an absorption cooling system, allowing heat to be transferred from a low to a high temperature. An electric pump is employed in an absorption cooling system as a simple way to circulate the working fluid from the low-pressure level to the high-pressure level. Although this electric pump consumes energy, it is little in comparison to the total system (Tesha, 2009).

There is great potential for this application in the Central American countries. Due to the warm and humid climate, cooling is needed in various areas such as supermarkets, industries, and residential areas. Cooling storage is an alternative for the agro-industry, used instead of drying the surplus production or wasting these products. In the aquaculture sector, cooling systems can offer a good solution to store the products.

4.3 Weather sensitive applications

Applications like de-icing, heating buildings, district heating, and greenhouses are applications specific for cold climates, applicable in some countries. Central America has an average temperature of 28°C with a relative humidity of 80% and an average windspeed of 2.5 m/s. These are tropical weather conditions that rule out certain applications in the Lindal diagram. Instead of the need for heating, there is a need for cooling buildings, houses, greenhouses, and for refrigeration systems, which so far is being done by using fossil fuels and electricity.

By investigating the applications sensitive to weather conditions, it was found that most of these applications are set up indoors like pasteurization of milk, candle making, drying, evaporation in sugar refining, and canning of food, where the temperature is controlled. In outdoor applications like swimming and aquaculture, the weather plays an important role when it comes to designing. Based on an example of Jóhannesson (2021a), a calculation was done to evaluate the heat losses by changing the weather parameters according to the region.

The main design parameters for pools are desirable pool temperature, outdoor temperature, windspeed and relative humidity. Design is based on heat losses calculation. The amount of heat lost is determined by the weather conditions of the site (Jóhannesson, 2021a).

Heat in a spa or a swimming pool is lost mainly through:

- Convection; and
- Evaporation.

Other contributors of heat loss are:

- Radiation;
- Conduction; and
- Rain.

A large pool in Iceland is used as an example where we can assume that the conduction losses can be neglected, flow through or circulation is 120 minutes, the pool temperature is 38°C, the average outdoor temperature is 5°C, and the average wind speed is 5 m/s. The values for higher outdoor temperature were extrapolated.

Table 9 shows heat losses as functions of outdoor temperature and windspeed, as these are the main parameters affecting the heat losses. Heat loss values closest to average temperature and windspeed in both Iceland (5°C, 5 m/s) and Central America (30°C, 5 m/s) are specially noted. The heat losses are lower for higher outdoor temperatures, meaning less geothermal water is needed to maintain the given pool temperature. In Iceland the temperature and windspeed range from –10°C to 10°C and from 0 m/s to 5 m/s, requiring the design to be robust and sophisticated. On the other hand, in Central America the temperature and windspeed year-round are from 10°C to 39°C and 0 m/s to 7 m/s on average, making the design easier and less complex.

TABLE 9: Heat losses (W/m^2) based on windspeed and outdoor temperature for a given pool temperature of 38°C. Modified table from Jóhannesson (2021a).

Windspeed Outdoor temp.	**0 m/s**	**5 m/s**	**10 m/s**	**15 m/s**
-10°C	2.129	3.529	4.93	6.331
-5°C	1.906	3.241	4.575	5.91
0°C	1.691	2.957	4.223	5.488
5°C	1.479	2.669[1]	3.859	5.048
10°C	1.266	2.369	3.471	4.573
15°C	1.051	2.051	3.05	4.049
20°C	0.835	1.773	2.71	3.647
25°C	0.62	1.479	2.337	3.194
30°C	0.405	1.185[2]	1.963	2.741
35°C	0.19	0.891	1.59	2.288

1: Average conditions Iceland; 2: Average conditions Central America.

These results indicate that this type of project is suitable for the region. Weather plays a role in the design and losses will be highly dependent on temperature and windspeed, but other factors need to be considered like the hygiene, market, quality of water and freshwater availability.

In Iceland there are two regulations for pools and spas: One is for natural spas and the other one is for swimming pools. In Central America, there are no such regulations; therefore tools and guidelines need to be developed.

4.4 Innovative applications

This subchapter deals with applications that do not yet have a market in the region. Table 10 shows existing and non-existing applications in the world. It is likely that a market will not be created in the region, but there is always the opportunity to look for markets abroad, such as the United States, Europe, or Asia. The idea is to develop a business model such as an industrial park where various economic activities can be developed based on heat from geothermal sources, among others. Various applications could potentially be developed.

TABLE 10: Innovative applications worldwide

Application	Countries	Source
Candy dryer	Iceland	Valdimarsson, 2021
Wasabi	Iceland	Jóhannesson, 2021b
Alfalfa drying for cattle feed	New Zealand	Pirrit and Dunstall, 1995
Palay drying	Philippines	Aligan, 2010
Asparagus drying	Greece	Andritsos et al., 2003
Apricots drying	Greece	Andritsos et al., 2003
Figs drying	Greece	Andritsos et al., 2003
Seaweed drying	Iceland	Hallsson, 1992
Wheat and cereal drying	Serbia	Martinovic and Milivojevic, 2008
Tobacco drying	Kenya	Mangi, 2014
Cotton drying	Greece	Mangi, 2014
Beef jerki drying	USA	Lienau, 1978; Lund and Lienau, 1994
Bouillon drying	USA	Lienau, 1978; Lund and Lienau, 1994
Macaroni drying	USA	Lienau, 1978; Lund and Lienau, 1994
Coconut oil	Indonesia	Tesha, 2009
Drying of cod heads	Iceland	Arason, 2003
Pulp and paper plants	New Zealand	Carter and Hotson, 1992
Diamatoceous earth plant	Iceland	Ragnarsson, 1996
Heap leaching	USA	Trexler et al., 1990
Salt plant	Iceland	Ragnarsson, 1996
Boric acid	Italy	Lindal, 1973
Mushroom growing	Indonesia	Surana et al., 2010
Methanol production	Iceland	Tran and Albertsson, 2010
Extraction of lithium	USA	Stringfellow and Dobson, 2021
Ice museum	USA	Holdmann, 2006
Nutmeg drying	-	-
Cardamon drying	-	-

5. RESULTS

5.1 New Lindal diagram for Central America

Compiling all the applications mentioned in the subchapters before, a new Lindal diagram was created. Figure 17 shows the main applications based on the existing market in Central America and the climatic conditions. The applications only applicable in cold climates were removed from the diagram, as well as those that are not developed yet in Central America.

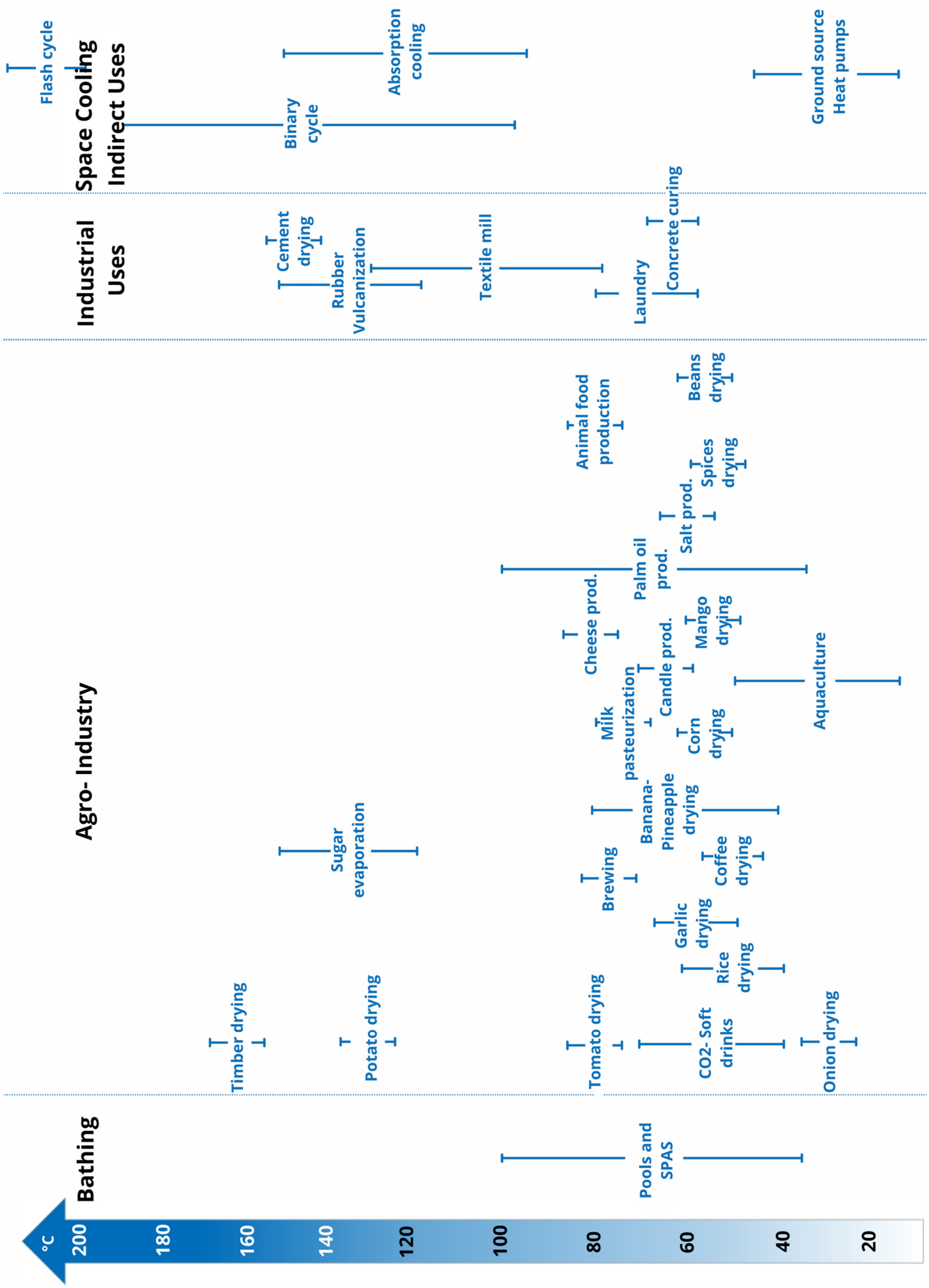


FIGURE 17: Lindal Diagram for Central America

5.2 Guideline to create a Lindal diagram for a region or country

Based on the methodology applied in this report, a guideline to create a Lindal diagram for any country or region was developed (Figure 18).

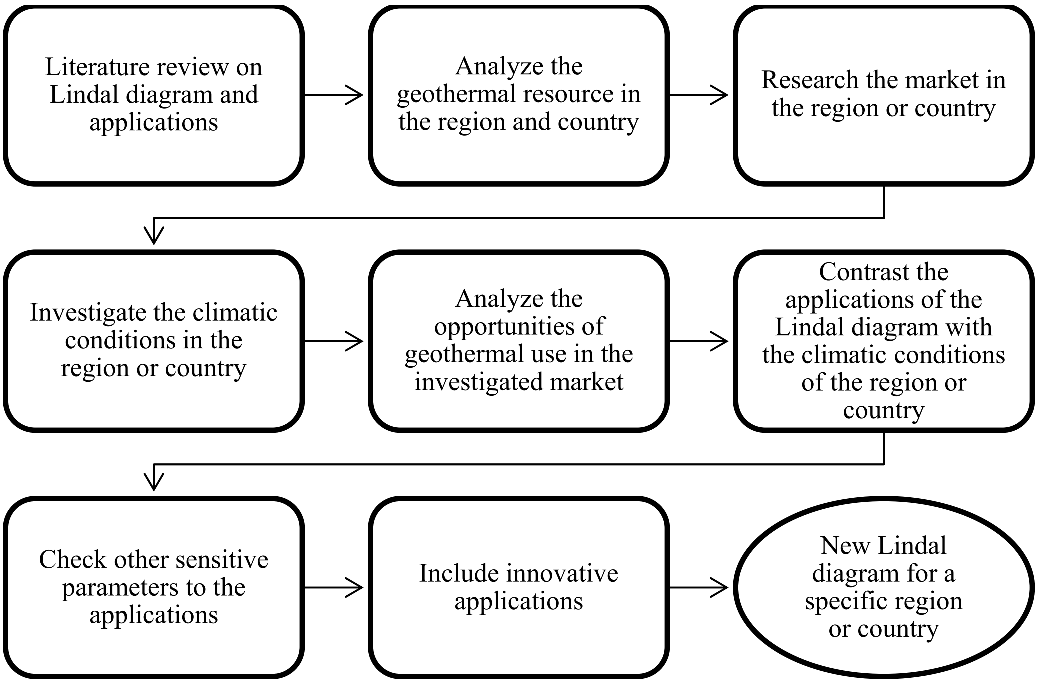


FIGURE 18: Guideline to create a new Lindal diagram

6. CONCLUSIONS

One new Lindal diagram was adapted to the Central American context. It is based on the main exports and key industrial activities in the six countries in Central America investigated in this report. An innovative applications table was created that might be applicable in the region. The main export products in the region are: Bananas, pineapple, coffee, sugar, palm oil, spices, seafood, beef, dairy products, corn and beans. For all those products there is the possibility of using geothermal resources to transform or substitute a heat source for a specific process.

Central American is still focusing on geothermal energy for electricity production. Only very few direct use applications were found in the region and they are mostly for bathing. Currently, some countries are starting to develop dehydration of crops. The identification of geothermal zones has traditionally been concentrated on high enthalpy areas, mostly because the state electrical companies that develop them are primarily concerned with electricity generation.

Because of the warm, tropical climate, the region's implementation of heating systems (for houses or buildings) and greenhouses is restricted, with a greater emphasis on agro-industrial activities, industrial processes, and cooling systems.

Heat is necessary in many processes for the transformation of primary to secondary products. That is why it is important that industry and agro-industry know about these applications and the benefits of geothermal resources, and a good way to show this is by using the Lindal diagram for the region.

It is recommended to do a mapping of the industry already in place as well as the geothermal manifestations and overlaying them to have a better tool to make decision regarding the development of direct use projects. Any direct applications business using geothermal energy could provide jobs and economic benefits to local communities.

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