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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, 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 America 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 will be achieved by doing a market assessment and evaluating the climate conditions of Central America. This work can be used as an example for tropical climates and with similar markets countries.

1. INTRODUCTION

Belize, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama are the seven countries that makeup Central America. Belize will not be considered as it is historically, politically, and culturally different but mainly due to the lack of geothermal resources and available data. Central America stretches 1,835 kilometers from northwest to southeast in an arc. Central American countries, except for Belize, have actual or potential resources for geothermal power generation. It is estimated for indirect use 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 MWth (Lund, 2020). Low to medium enthalpy resources have not been in every country investigated thoroughly.

According to Lund et al., 2020 in their last report of direct use utilization Worldwide Review, only Costa Rica, Guatemala, El Salvador, and Honduras reported direct uses of geothermal energy applications. 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 proposes to target that need.

By 1974 El Salvador and Nicaragua began the exploitation of their geothermal resource for electricity generation only. A year before 1973 the Lindal diagram was first developed by Baldur Lindal in Iceland using examples from Iceland and other countries. As expected, Lindal focused its work and research according to experience from a cold country with a year-round need for heat. The Lindal diagram covers temperature ranges from 20 – 200°C including the production of electricity. This report will only focus on the applications of the direct use, excluding the generation of electricity. In contrast, Central America is a tropical climate region with temperatures in the ranges of 17-27 °C and humidity from 70% to 95%, where the need differs from Iceland or 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 specific sectors or industries, or regions have been left out. Although geothermal energy 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 Central America for engineering professionals, policymakers, and developers is needed.

To this end, the Lindal diagram has been redesigned by leaving out potential applications that do not apply to the region and adding those that do 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 analyzed in detail.

2. METHODOLOGY

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

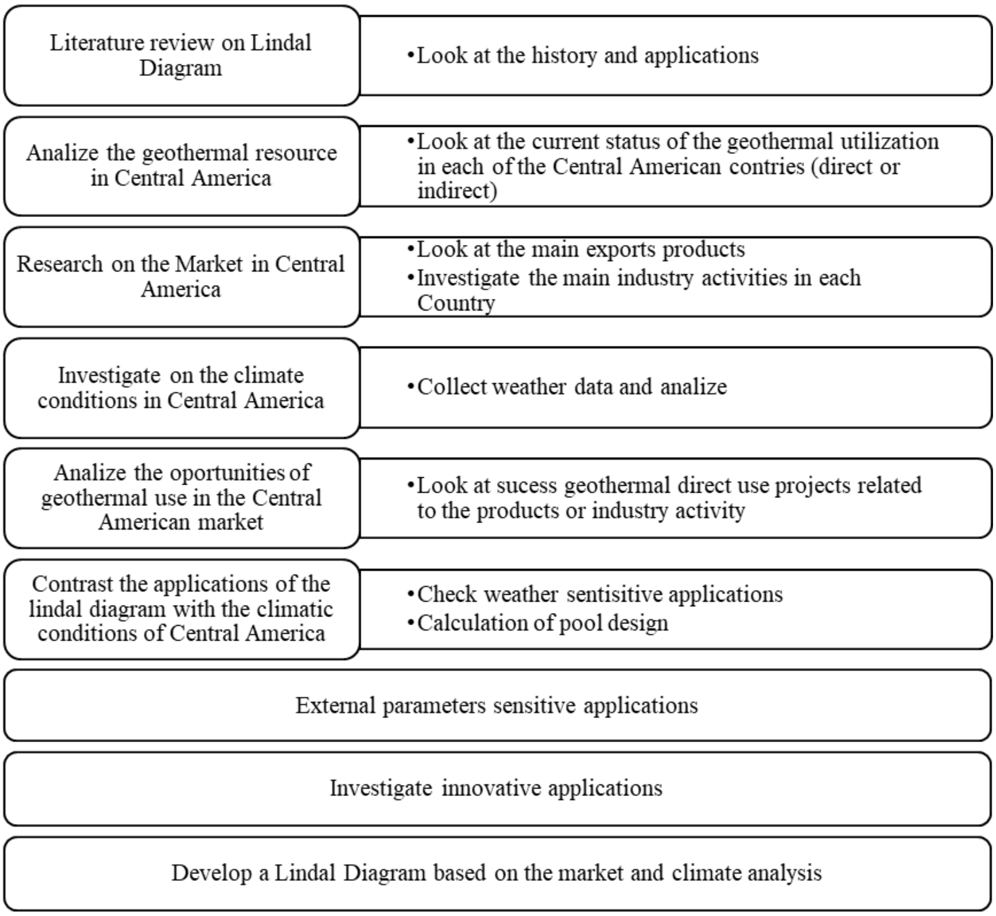


Figure 1: Flow work to develop a Lindal Diagram for Central America

3. BACKGROUND

3.1 Lindal diagram

It was first called “Lindal Diagram” by Gudmundsson, et al., 1985 to acknowledge the contribution of Baldur Lindal, an Icelandic chemical engineer. He was one of the pioneers of the direct utilization of geothermal energy in the world. He first presented the diagram in 1973 in Lindal´s Article “Industrial and Other Uses of Geothermal Energy,” in a book entitled Geothermal Energy published by UNESCO in Paris. Ever since, the Lindal diagram is very well known in the geothermal community and has been used by several authors and has been included 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 and soil heating; and balneology; heating of buildings and greenhouses; drying of organic products, evaporation, and canning of food; as well as pulp digestion and ammonia absorption refrigeration. Subsequent versions of the diagram showed that it was no longer restricted to direct use applications but was expanded to include electric power production from dry steam, flash steam, and binary power cycles (Gudmundsson et al., 1985; Lund et al., 2011).

Water is employed in most geothermal applications 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, binary energy starts at the midpoint of 84°C. Furthermore, geothermal water may be used directly across the whole temperature range, extending below 22°C for heat pump applications (Gudmundsson et al., 1985; Lund et al., 2011).

The applications included in the Lindal diagram were 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).

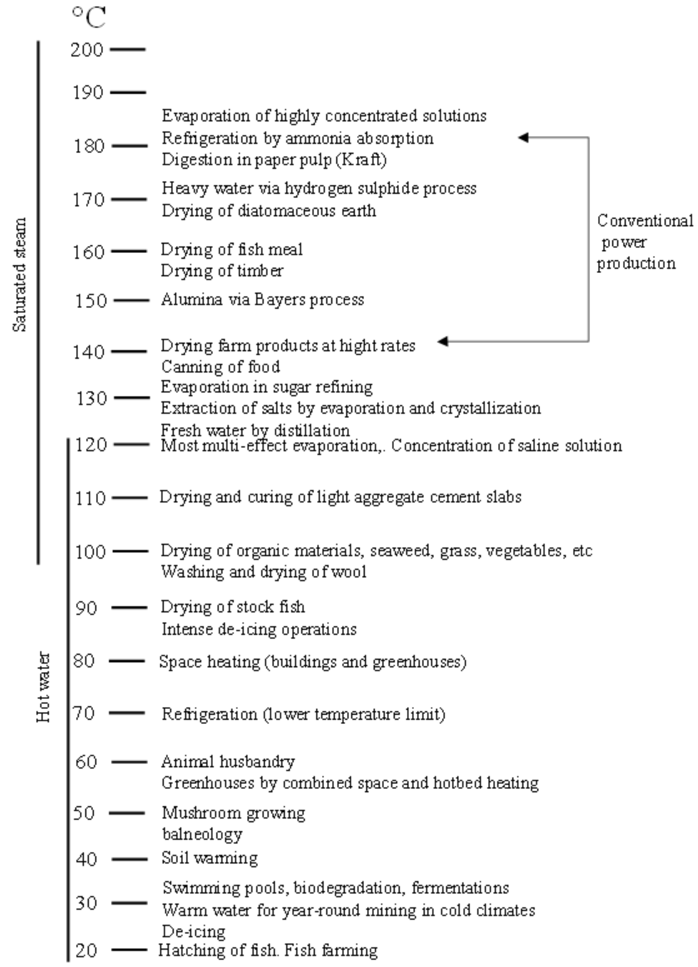


Figure 2: Lindal diagram (Gudmundsson et al., 1985).

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 explorations in the 1950s and late 1960s, identifying some promising areas. El Salvador began the commercial exploitation in Ahuachapán in 1975 followed by Momotombo, 1983 in Nicaragua, again in El Salvador, Berlin in 1992, Miravalles, Costa Rica in 1994, Zunil, Guatemala in 1998, and so on.

The Pacific Rim volcanic zone encompasses Central American countries (except for 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 levels. 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, according to Rodriguez and Henriquez, 2007. It is showing the geothermal fields in operation generating electricity, where there is a big opportunity to develop cascading or combined systems.

According to Lippmann, 2002, the capability of 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 an area with abundant geothermal resources, the installed capacity as of 2018 was only 650 MWe. High temperature resources have been used to generate electricity, as well as using binary cycle generation technologies, electricity production from low temperature geothermal resources has also been used in the region.

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

In Guatemala, El Salvador, Costa Rica, and Honduras, Lund et al., 2020 published data on the direct use of geothermal resources, primarily for agricultural drying, bathing, and swimming pools.

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

Table 1: Direct geothermal utilization in Central America (Lund, 2020).

Country	Thermal capacity estimated MWt	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**

3.2.2 Geothermal resource classification

There is not a standardized classification for geothermal resources. The most common used is the classification by temperature or enthalpy. Table 2 shows the enthalpy classification according to Muffler and Cataldi, 1978. Table 2 shows that direct use can also be achieved in high temperature ranges such as in the intermediate in a combined or cascade scheme.

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≥200°C	Electricity generation using single, double flash power plants Cascading and combined systems

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

Most 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 geothermal potential. Additionally, the promising sites to develop geothermal projects for indirect or direct uses were investigated. It is important to mention that direct and indirect uses projects can be combined.

3.2.3 Guatemala

Zunil with an installed capacity of 25.2 MW and Amatitlan with 24 MW are geothermal power plants providing 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. Amatitlan, 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 and 170°C.

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

Geothermal energy in Guatemala has traditionally been utilized for medicinal, agricultural, or domestic purposes. The thermal bath houses and spas at Totonicapan, Quetzaltenango, and Amatitlan 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 Amatitlan geothermal area. The company makes dehydrated pineapple, mango, banana, apple, and chili peppers (Lund et al., 2020).

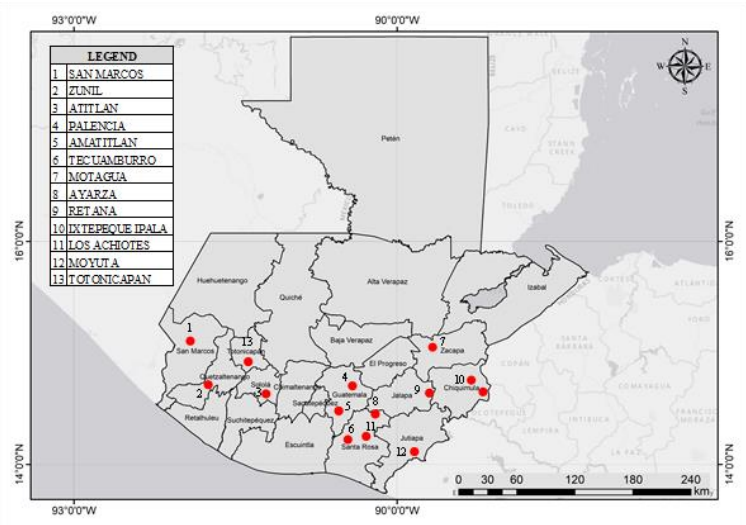


Figure 4: Geothermal areas in Guatemala (Modified after Merida, 2012).

3.2.4 El Salvador

El Salvador is Central America's largest geothermal energy producer; 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 range from 250°C in Ahuachapán to 300°C in Berlin, 230°C in San Vicente, and 240°C in Chinameca, with other resources below 200°C found throughout the volcanic chain.

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 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 identified 12 geothermal areas in El Salvador and the ranges of temperature in those areas.

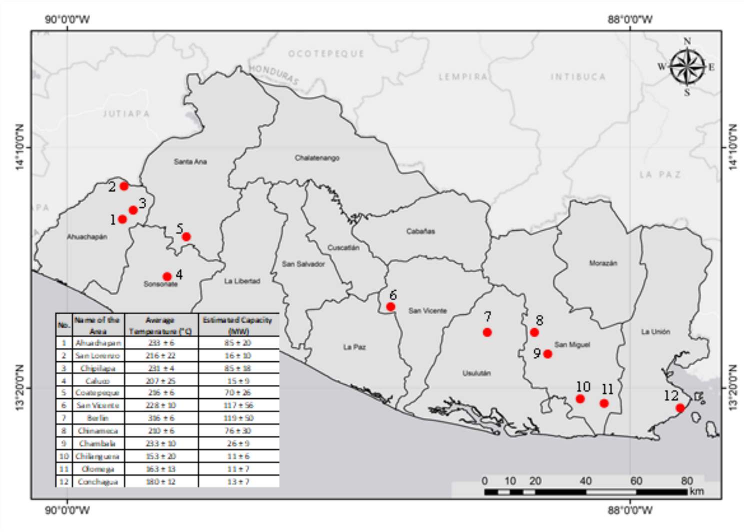


Figure 5: Geothermal areas in El Salvador (Modified after Montalvo and Guidos 2009)

According to Lund et al., 2020, there have been some minor advancements in greenhouses, 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, Usulutan.

3.2.5 Honduras

In 2017, the first electric power generation plant in Honduras came into operation with a capacity of 35 MW, and it is in the western part of the country (Henriquez, 2011). The Pavana and Azacualpa projects are currently being investigated. According to Lagos and Gomez (2010), higher temperatures between 160 and 165°C were detected at shallow depths in the assessment of Platanares, while geothermometers showed resource temperatures between 200 and 225°C. According to updated research, Azacualpa has a capacity of 23 MW at temperatures between 170 and 180°C, and Pavana has a potential of 18 MW at temperatures between 140 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.

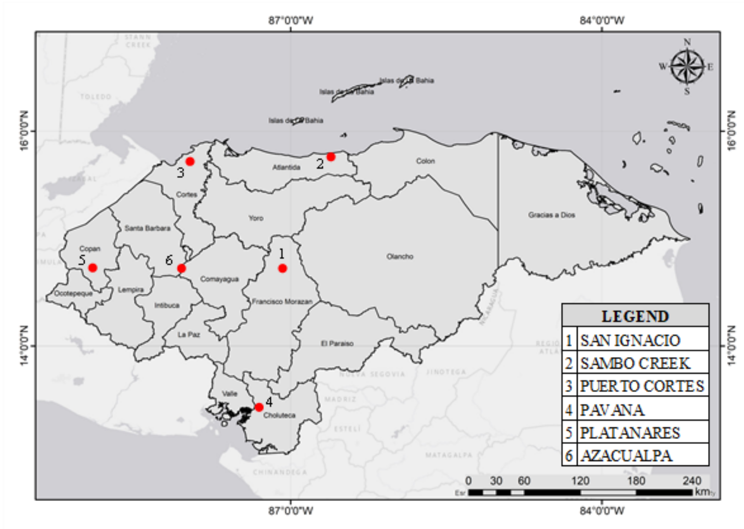


Figure 6: Geothermal areas in Honduras (Modified after Henriquez, 2011).

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 are the production of a type of local cheese and the drying of agricultural products. Two places in the northern section of the county, Valle de Sula, and Sambo Creek, were identified as potential candidates. There were hot springs with temperatures ranging from 30°C to 105°C discovered. Several swimming pools have been known to be powered by geothermal energy according to Lund, 2020.

3.2.6 Nicaragua

There are two geothermal areas that are in exploitation in Nicaragua. According to the statistical data of the Nicaraguan Energy Institute in 2020, the Momotombo power plant has 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 said 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 to 290°C; and temperatures of 220°C (at 2,000 m) were discovered in the El Hoyo Monte Galán geothermal area. Managua-Chiltepe and Masaya-Granada-Nandaime, according to Zuniga ,2005 are more promising geothermal sites. Some of these areas are shown in Figure 7.

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

For tourism purposes, a few thermal swimming pools 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 Report, 2016).

3.2.7 Costa Rica

Some sources estimate the potential geothermal power in Costa Rica to be as high as 900 MW, based on 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 a temperature of 240°C on average. During feasibility studies, the Las Pailas geothermal field confirmed the presence of a geothermal reservoir with temperatures near 260°C (Protti, 2010).

Based on Fung, 2008 a geothermal area was discovered near Borinquen in 2008, where a production well with the highest recorded bottom hole temperature (275°C) in Costa Rica was drilled. 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 to 217°C. Platanar, Poás, Barva, Iraz, and Turrialba are some of the other possible geothermal regions discovered around the volcanoes. Figure 8 shows a map of some of the geothermal mentioned above and the estimated temperatures.

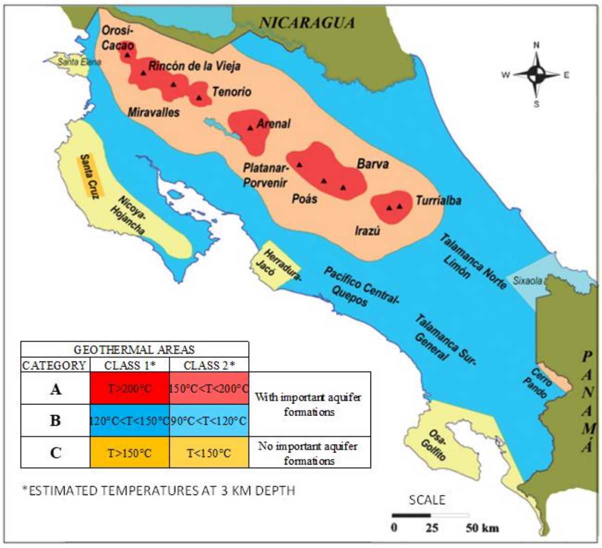


Figure 8: Geothermal Areas in Costa Rica (modified after Mainieri and Yock, 2009)

The utilization of geothermal direct-use resources is restricted to low-temperature developments 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 for 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).

3.2.8 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). Panama has not provided any information on the direct usage of geothermal energy for Lund, 2020 report.

3.3 Climate conditions

The average annual temperature for the Pacific coast of Central America is between 26 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 main impact on the thermal regime is altitude. The average yearly temperature in the Pacific and Caribbean sides of the areas between sea level and 600 meters fluctuates between 24 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 and 23 °C, while the average annual temperature in the areas between 1,200 and 1,800 meters is between 17 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 throughout many years will be used to generate good results for 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 is showing the elevation and the average temperature at these specific points in the country. Within the sites collected, examples were 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

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

Figures 10-13, respectively, illustrate plots of the outdoor: monthly mean outdoor temperature, monthly mean wind speed, monthly precipitation, and relative humidity.

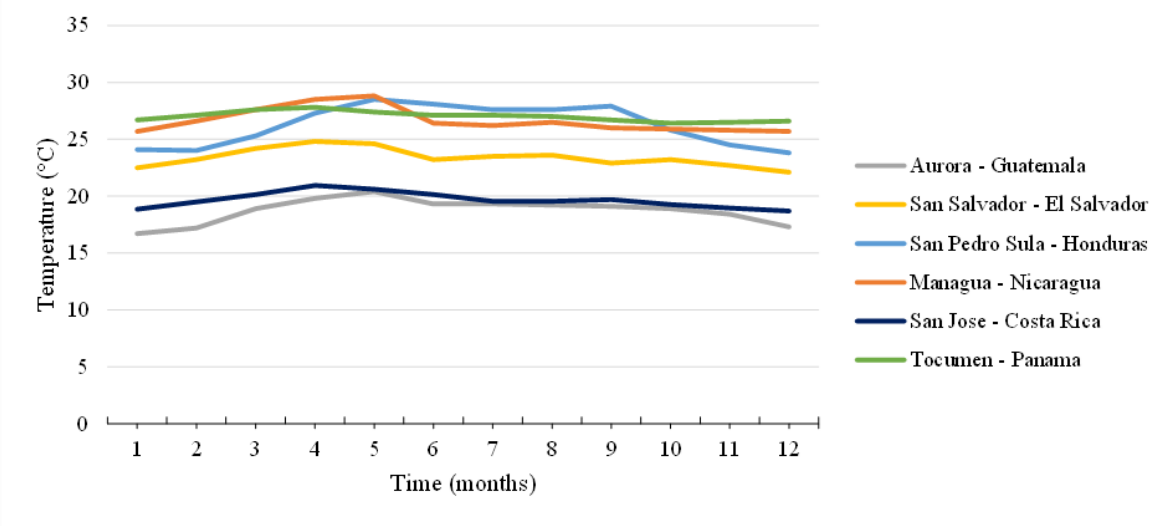


Figure 10: Monthly mean outdoor temperature

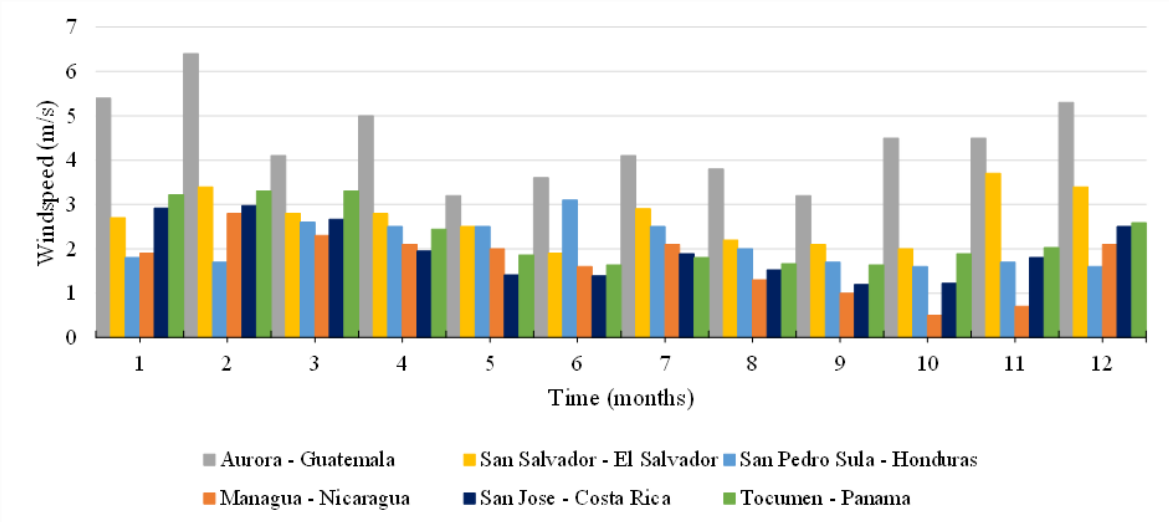


Figure 11: Monthly mean wind speed

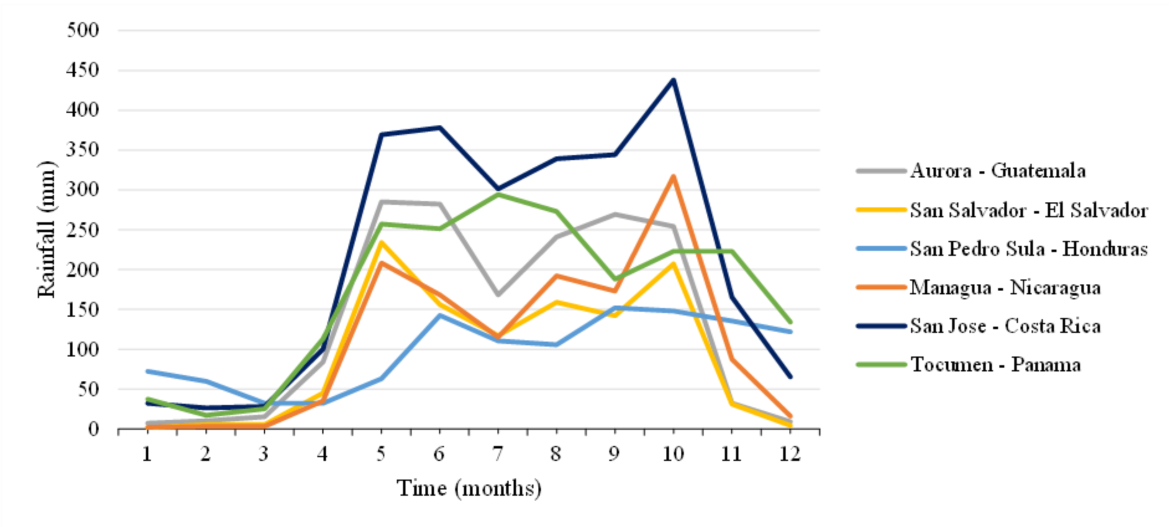


Figure 12: Monthly accumulative precipitation

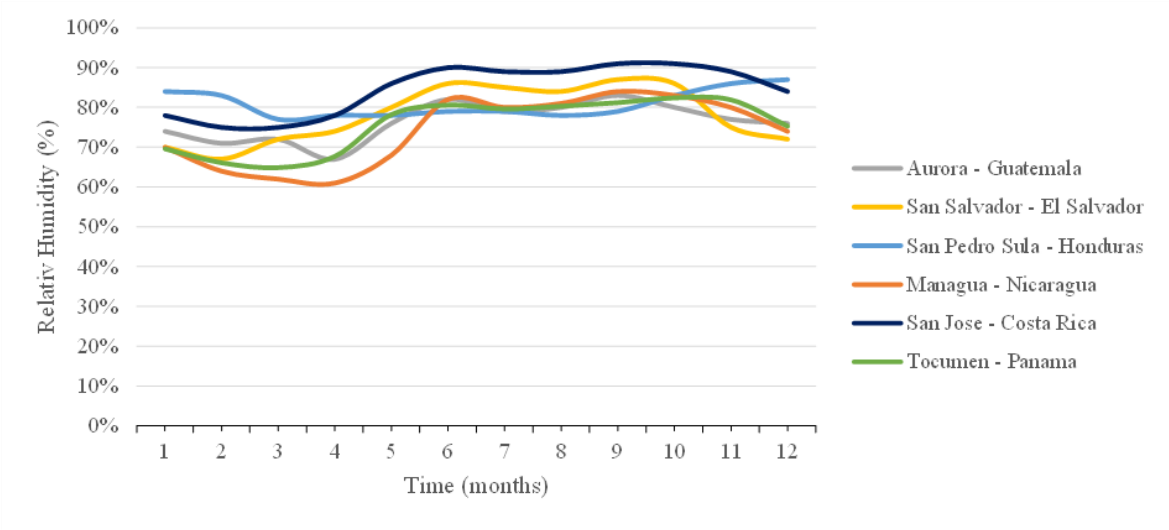


Figure 13: Monthly relative humidity %

Meteorological data were collected to assess which applications were 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 use was required at any time of the year. Furthermore, it was investigated to see which applications of the Lindal diagram could be eliminated and to see how it affected the design of some of them, in this report the design of swimming pools and aquaculture which is very similar, was looked at in detail.

3.4 Market in the region

In 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 million and 28.5% of GDP. Central America is the third largest exporter of coffee worldwide and is in 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. The second largest exporter of bananas. This was achieved by having 20 international airports, 47 seaports, and an interoceanic canal (SIECA, 2021).

Manufacturing exports were the primary driver of the increase in the region's goods exports. Central America's export structure was modified because of this performance. It not only shifted away from heavy reliance on agricultural exports, but it also created a strong reputation for manufacturing exports, which it may exploit more effectively in the future. The region has been a successful exporter of food items for many decades the items are shown in Table 4.

Table 4: Exports products (World Bank Group, 2021).

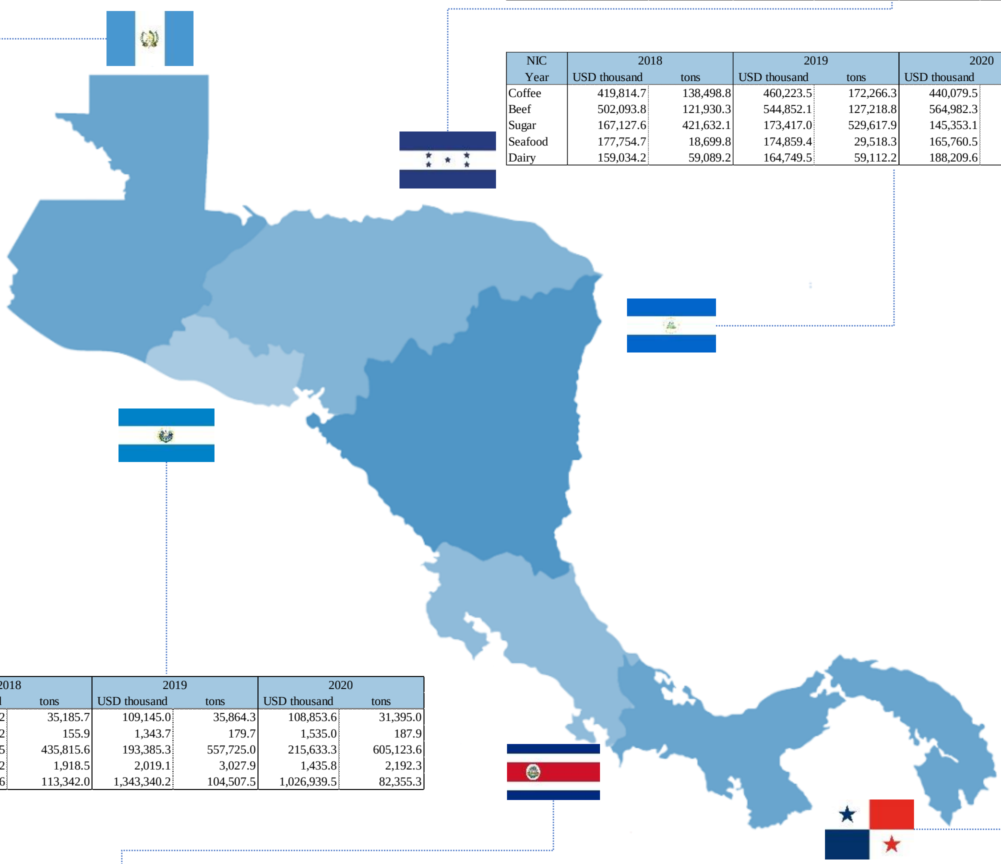
Country	Main items
Costa Rica	Bananas, Pineapples, Coffee, Food preparations
Guatemala	Sugar, Bananas, Coffee, Palm oil, Spices
Honduras	Bananas, Coffee, Palm oil, Seafood
Nicaragua	Coffee, Beef, Seafood, Sugar, Dairy
El Salvador	Sugar, Coffee,Corn, Rice, Beans
Panama	Bananas, Rice, Corn, Coffee, Sugarcane

For the collection of data, a market analysis tool was used developed by the Secretariat for Central American Economic Integration (SIECA, per its Spanish acronym). It is an interactive module that allows the user to analyze aspects related to the competitiveness of Central American exports in various markets. The total values in thousands of US dollars and volume in tons of the main products export items were collected from the tool. In Figure 14 the above-mentioned is shown.

GUAT	2018		2019		2020	
Year	USD thousand	tons	USD thousand	tons	USD thousand	tons
Coffee	680,865.9	205,933.9	663,678.8	216,246.3	651,794.5	188,421.7
Spices	438,410.0	38,902.4	652,054.2	38,551.0	1,138,254.5	66,882.2
Banana	90,732.9	238,901.2	102,422.5	260,553.8	114,333.0	272,770.4
Palm Oil	447,611.3	818,128.3	393,901.7	811,796.8	471,687.3	748,274.5
Sugar Cane	632,883.3	1,660,200.3	694,575.9	2,029,190.6	576,841.5	1,657,822.0

HOND	2018		2019		2020	
Year	USD thousand	tons	USD thousand	tons	USD thousand	tons
Coffee	1,119,146.4	430,450.5	950,041.8	407,712.9	873,014.9	317,467.9
Pineapple	32,365.2	64,283.6	33,289.0	66,882.0	34,120.0	65,906.1
Banana	649.0	1,292.2	471.7	832.5	602.7	513.3
Palm oil	290,894.8	476,074.1	287,192.8	518,767.1	337,559.3	483,684.2
Seafood	341,725.1	45,495.8	358,756.2	48,326.3	382,385.8	49,560.7

NIC	2018		2019		2020	
Year	USD thousand	tons	USD thousand	tons	USD thousand	tons
Coffee	419,814.7	138,498.8	460,223.5	172,266.3	440,079.5	150,296.8
Beef	502,093.8	121,930.3	544,852.1	127,218.8	564,982.3	132,738.6
Sugar	167,127.6	421,632.1	173,417.0	529,617.9	145,353.1	427,989.9
Seafood	177,754.7	18,699.8	174,859.4	29,518.3	165,760.5	31,440.1
Dairy	159,034.2	59,089.2	164,749.5	59,112.2	188,209.6	67,336.2



ELSL	2018		2019		2020	
Year	USD thousand	tons	USD thousand	tons	USD thousand	tons
Coffee	113,403.2	35,185.7	109,145.0	35,864.3	108,853.6	31,395.0
Spices	1,156.2	155.9	1,343.7	179.7	1,535.0	187.9
Sugar	178,295.5	435,815.6	193,385.3	557,725.0	215,633.3	605,123.6
Rice	1,128.2	1,918.5	2,019.1	3,027.9	1,435.8	2,192.3
Clothing	1,486,033.6	113,342.0	1,343,340.2	104,507.5	1,026,939.5	82,355.3

CR	2018		2019		2020	
Year	USD thousand	tons	USD thousand	tons	USD thousand	tons
Coffee	318,485.7	75,607.3	279,442.5	63,508.0	328,998.2	70,130.5
Pineapple	1,038,151.8	2,333,924.4	981,012.2	2,216,371.7	922,741.1	2,047,286.9
Banana	1,030,913.8	2,488,769.0	999,701.7	2,384,820.7	1,082,969.7	2,628,146.3
Melon	87,482.5	172,431.3	87,295.2	177,623.1	71,326.7	149,415.4
Sugar	85,984.7	205,430.8	75,126.4	204,609.0	78,851.2	193,134.1

PA	2018		2019		2020	
Year	USD thousand	tons	USD thousand	tons	USD thousand	tons
Seafood	111,499.7	32,420.4	77,011.8	20,746.6	74,798.7	23,637.3
Banana	106,072.2	298,368.9	127,103.8	611,872.4	151,715.6	700,366.7
Coffee	19,041.8	1,745.6	26,422.7	2,369.4	24,895.9	2,360.7
Sugar Cane	28,627.8	51,816.9	24,900.2	46,109.8	25,895.7	44,082.6
Fruits	130,072.2	349,310.6	148,715.7	657,902.2	171,568.9	740,007.5

Figure 14: Main product exports in Central America in values and in volume (SIECA, 2021)

According to the World Bank Group, 2021, the main industry activities for each country are shown in Table 5.

Table 5: Main industrial activities in Central America

Country	Industries
Guatemala	Sugar, textiles and 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 and woven apparel, petroleum refining and distribution, beverages, footwear, wood, electric wire harness manufacturing, mining
Costa rica	Medical equipment, food processing, textiles and clothing, construction materials, fertilizer, plastic products
Panama	Construction, brewing, cement and other construction materials, sugar milling

4. DISCUSSION

4.1 Analysis of the market in CA

The main food products being exported in Central America were investigated to see if the exported products had the potential to utilize geothermal energy directly. Among the main products, we have final products and raw materials. For the products that serve or are raw materials, there is the opportunity to create a business model with them. And for the other finished products geothermal fluid could replace the heat source of the process needed. It is important to mention that this will depend on other important factors such as the technology to be used and how it should be modified. Table 6 is showing a summary of the main products exported in

Central America with their traditional method to transform them into final products or in the case of raw products a possible way to transform them. It is also shown the recommended geothermal temperature range.

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 dependant), 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 where all central American countries are big exporters there is a chance to dehydrate them if there is excess or just as 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 of rice and El Salvador of corn, these products have gone through drying process. For this case it is easier to identify and replace the type of energy or heat that is used in the drying process which often use fuel oils or electricity to meet the standards, the most common is the drying with the sun, but this brings many disadvantages because it depends on weather conditions. Drying is not uniform, diseases and fungi can occur when drying is not done continuously. Coffee drying happens at 50°C according to Prasetyo et al., 2018. To avoid rice cracking, the rice drying temperature is kept below 40°C based on 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 procedure is carried out using an industrial boiler in conventional crude palm oil facilities (Utami et al., 2019).

The drying of Cardamom, or spices has a lot of potential to grow in the region and to use geothermal fluid as a heat source for it. Temperature ranges are from 45°C to 60°C for agricultural drying. 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 within the culture of Central Americans. That is why the need based on these two products would be 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 exporter on this matter in the region, with great potential. The temperatures for these applications are in the ranges of 150°C to 180°C.

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

The manufacturing industry dedicates 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 in this transformation of raw materials occur different processes that require heat. Some of the processes that could use geothermal resources according to Lindal, 1992 are: drying, process heating, evaporation, distillation, space air conditioning, refrigeration, washing, desalination, chemical extraction, and other processes are possible applications. These processes can be used in the main industrial activities in the region such as food products, beverages, textile production, machinery and equipment, wood industry, paper production, chemical products, and metal products among others.

Finally, we should also mention products that are not exported and are consumed locally, such as beer and liquors. The process to obtain these products requires heat and this can be supplied through geothermal energy. The temperatures of this process are between 60°C to 80°C based on Chiasson, 2006.

4.2 Description of Applications

The applications of direct uses are dominated by heat pumps representing 70% of the total installed capacity worldwide, followed by space heating with 12%, and below that is bathing, and swimming shown in table 7. The other applications such as greenhouses, industrial uses, and crop drying, the possible applications to 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 extremely hot temperatures, cooling needs for residential, tourism, industry, and commerce are there since it is a tropical humid climate region.

Table 8 shows how many countries are using geothermal direct uses. This table is also well known in the geothermal community, here Central America can be part of the highlighted categories but at the moment it only participates in two of them, the first one with 70 other countries in bathing and swimming and the second one Guatemala and El Salvador in crop drying with 15 other countries worldwide.

Table 7: World-wide capacity of geothermal utilization, (Lund 2020)

Utilization	MWt	TJ/year
	2020	
Geothermal heat pump	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

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

Table 8: Direct uses of geothermal Worldwide (Lund and Boyd, 2015)

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

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 centers have operated for decades or centuries. In Iceland, geothermal pools are part of the culture, since 1940 it is mandatory that kids take swimming lessons. It is seen as a social activity and entertainment. It is easy to find in these centres: Saunas, pools, bubble baths, physical therapy pools, and whirlpools. The resource's temperature and mineral composition are critical factors. Other issues to consider are Safety: Slippery, drowning and injury, microbial hazards, chemical hazards, and water and air quality (Jóhannesson, 2021). In Central America bathing in thermal waters or geothermal pools is not a popular activity and there a not many of them. If more people start knowing the benefits of bathing in geothermal waters this market can be developed and attract tourism to the countries. More promotion and marketing are needed.

4.2.2 Drying

The purpose of drying vegetables and fruits is to avoid spoiling in storage. 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, the flavor, smell, and nutritional value of the vegetables are preserved. The drying process reduces bulk, making transportation and storage more convenient (Basak, 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 annual food production is wasted according to the Food and Agriculture Organization of the United Nations, 2011. Another scenario is that there is an overproduction, and 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 them for sale locally or export. Using it 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 minimize food waste (Food and Agriculture Organization of the United Nations, 2011).

The drying systems must be operated 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 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. The agricultural operations are conducted 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, all influence the usage of geothermal fluid in aquaculture. The geothermal fluid is typically utilized to provide heat directly in 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 and 30°C (Jóhannesson, 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, such as a diatomaceous earth drying facility in northern Iceland and a pulp, paper, and wood processing factory in Kawerau, New Zealand, are located in Iceland, the United States, and New Zealand. Two onion dehydration factories in Nevada are two examples in the United States (Lund and Lienau, 1994).

The use of geothermal resources in Central America has the potential to increase this sector; nevertheless, one important difficulty in each instance is the distance between the industry and the geothermal resource, because 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 may also be described as a method of reducing an object's temperature. The compression cooling system and the absorption cooling system are the two most popular (Tesha, 2009). Heat pumps can be used to successfully cool spaces using geothermal energy (Jóhannesson, 2014).

A compression cooling system uses a mechanical compressor and an electric motor to force heat transfer from a low to a high temperature mechanically. 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, despite the fact that these two units replace the function of a mechanical compressor. 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 a solution for the agro industry, instead of drying the overproduction or waste these products could be stored in cooling rooms. In the aquaculture sector, a cooling system can offer a good solution to store the products.

4.3 Weather sensitive applications

Applications like de-icing, heating buildings, district heating, and some types of greenhouses are applications specific to cold climates and the needs according to the country in question. Central America has an average temperature of 28°C with a relative humidity of 80% and an average windspeed of 2.5 m/s, tropical weather conditions that rule out this application in the Lindal Diagram. Instead of the need for heating, there is a need for cooling buildings, houses, greenhouses, and refrigeration systems which by now it is being done by using fossil fuels and electricity.

When investigating the sensitivity of the applications to weather conditions, it was found that most of the applications are being done indoors like pasteurization of milk, candle making, drying, evaporation in sugar refining, and canning of food where the temperature is being controlled. In outdoor applications like swimming and aquaculture, the weather plays an important role when it comes to design, based on an example of Jóhannesson, 2021 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. The design is based on heat loss calculation. The amount of heat lost is determined by the site's weather conditions (Jóhannesson, 2021).

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

- Convection
- Evaporation

Other contributors to heat loss are:

- Radiation
- Conduction
- Rain

The assumptions for the example are for a large pool where the conduction losses are neglected, flow through or circulation 120°min, pool temperature of 38°C, an average outdoor temperature of 5°C, and an average wind speed of 5 m/s for Iceland. The values for higher outdoor temperatures were extrapolated. Table 9 is showing in yellow the result for Iceland and in blue the closest values to the averages in Central America.

Table 9: Heat losses – Outdoor temperature and windspeed.

Modified table from Jóhannesson, 2021.

Heat losses W/m^2		Windspeed, m/s			
Pool Temperature	38°C	0	5	10	15
Outdoor Temperature °C	-10	2.129	3.529	4.93	6.331
	-5	1.906	3.241	4.575	5.91
	0	1.691	2.957	4.223	5.488
	5	1.479	2.669	3.859	5.048
	10	1.266	2.369	3.471	4.573
	15	1.051	2.051	3.05	4.049
	20	0.835	1.773	2.710	3.647
	25	0.620	1.479	2.337	3.194
	30	0.405	1.185	1.963	2.741
	35	0.190	0.891	1.590	2.288

Table 9 is showing fewer heat losses for higher outdoor temperatures meaning less geothermal water will be needed to develop this type of project. Wind and temperature are the main parameter affecting the heat losses, in Iceland the temperature and windspeed difference is big going from – 10 to 10 °C and 0 to 5 m/s making the design robust and sophisticated. On the other hand, in Central America, the temperature and windspeed difference year-round goes from 10 – 39°C and 0 – 7 m/s on average making the design easier and less complex.

With these results it can be said that this type of project in the region is suitable, weather plays a role in the design and losses will be highly dependent on temperature and wind speed. But other factors need to be considered like the hygiene of the water, 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 the region there are no such regulations, therefore tools and guidelines are necessary for the region.

4.4 Innovative applications

This subchapter is important because it 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 may 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 have a business model such as an industrial park where various economic activities can be developed based on, among others, heat from geothermal, and various applications could potentially be developed.

Table 10: Innovative applications Worldwide

Application	Countries	Source
Candy dryer	Iceland	Valdimarsson, 2021
Wasabi	Iceland	Valdimarsson, 2021
Alfafa drying for cattle feed	New Zealand	Pirrit and Dunstall, 1995
Palay drying	Philipines	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
Tabacco drying	Kenya	Mangi, 2014
Cotton drying	Greece	Mangi, 2014
Beef jerki drying	USA	Lienau et al., 1978; Lund and Lienau, 1994
Bouillon drying	USA	Lienau et al., 1978; Lund and Lienau, 1994
Macaroni drying	USA	Lienau et al., 1978; Lund and Lienau, 1994
Coconut oil	Indonesia	Tesha, 2009
Drying of cod heads	Iceland	Arason, 2003
Pulp and paper plant	New Zealand	Carter et al., 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, 2010
Methanol production	Iceland	Albertsson, 2010
Extraction of lithium	USA	Stringfellow, 2021
Ice museum	USA	Holdmann, 2006
Nutmeg drying	-	-
Cardamom drying	-	-

5. RESULTS

5.1 New Lindal Diagram for Central America

Compiling all the applications mentioned in the subchapters before the Lindal diagram was created. In Figure 15 are 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 and the ones that Central America has no activity yet.

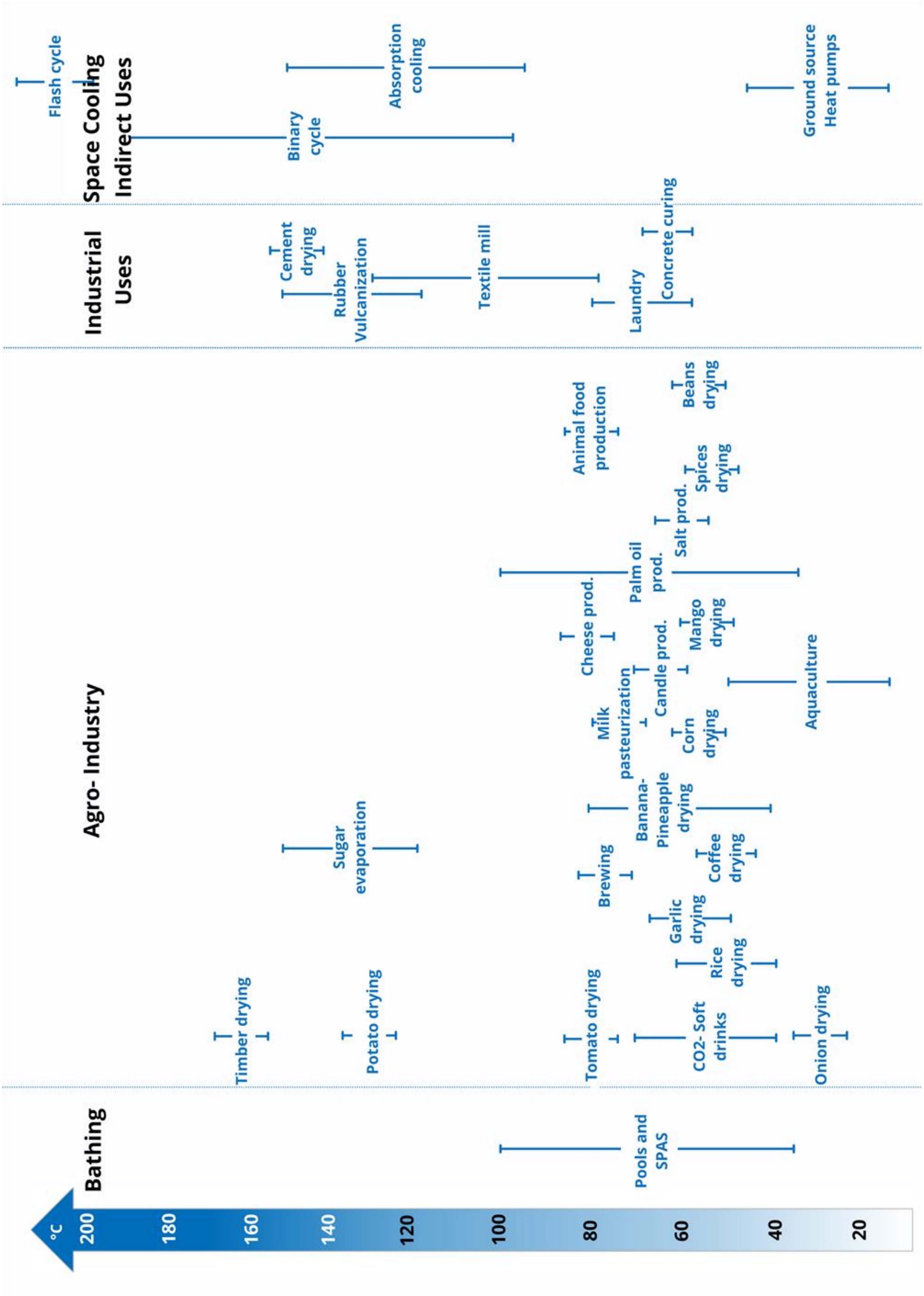


Figure 15: Lindal Diagram for Central America

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

Based on the methodology applied in this report a guideline to create Lindal diagram for any country o region was develop

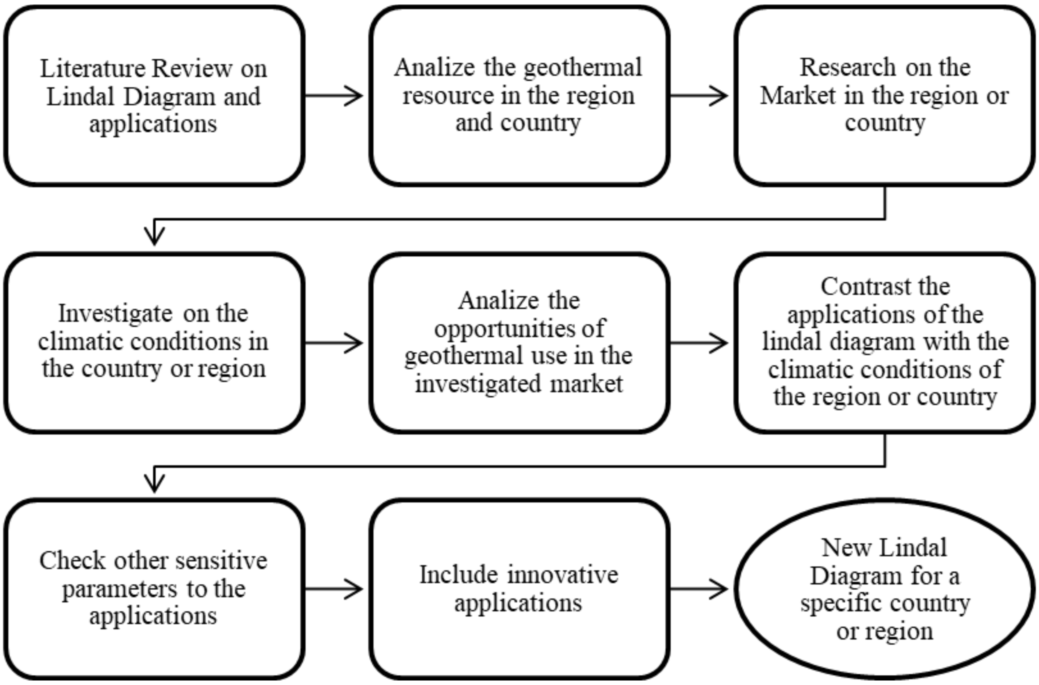


Figure 16: Guideline to create a new Lindal diagram

5. CONCLUSIONS

One new Lindal Diagram was created and adapted to the Central American context. It is based on the main exports and key industry 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. In all of them, there is a chance of using the geothermal resource to transform or substitute a heat source for a specific process.

Central America still is focusing on geothermal energy for electricity production. Only very few 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 concentrated on high enthalpy areas, partly 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 for many processes for the transformation of primary to secondary products, which is why it is important that industry and agro industry know about these applications and the benefits of geothermal resources 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 and the geothermal manifestations and overlaying them to have a better tool to make decisions regarding developing direct uses projects. Any direct applications business using geothermal energy could provide job creation and economic benefits to local communities.

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