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Development of Geothermal Greenhouses in Costa Rica

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ABSTRACT

The direct use of geothermal energy has dramatically increased over the past decades, attributable to the development of new technologies. Although there is a wide availability of geothermal resources in Costa Rica and there have been geothermal power plants for more than twenty years, the direct use of geothermal energy is very limited and focused in touristic activities. This paper presents a feasibility study exploring the use of geothermal energy in direct use to implement heating systems for greenhouses. A description of the Costa Rican fruit and vegetable market, resource availability, local weather, and regulatory requirements are considered to evaluate the feasibility of the project. A guide to calculating the heat load, its respective pipeline, and heat exchanger design are discussed. Through this analysis, it was found that it is feasible to increase the production of conventional and non-conventional crops with high demand in specific locations within the country. However, it is necessary to study detailed technical solutions, and economic feasibility before real systems are set up.

1. INTRODUCTION

Geothermal energy allows exploiting resources in a reliable, renewable, and sustainable way. It comes naturally from the core of the Earth, where the heavy radioactive elements lose stability and release heat that moves through the different layers of the Earth reaching the surface. Depending on the temperature of the geothermal fluid, it could be used for power generation or for direct use.

Direct use of geothermal energy allows developing economical and environmentally friendly processes in a wide range of applications. Each application has different requirements, specific ranges of temperature, and general conditions to perform in the right way. In most of the cases, it requires a higher initial investment than the conventional applications, but the savings in operational costs make it feasible through time. In addition, the resource can be found in different sources such as natural springs, or through the sequence of geothermal disposal fluids from power generation in a cascade system.

The power installed for direct use in 2015 was 5.88×10^5 TJ/year (IGA, 2015), and Thain et al. (2006) estimated there are 5×10^{15} TJ available on earth for direct use. Therefore, at the current utilization, geothermal energy can be exploited for direct use for approximately 10^{10} years.

Although the geothermal resources are widely spread in most of Costa Rica and the geothermal power generation is well developed, there is almost no exploitation of the geothermal resource for direct use. Only 21 TJ were exploited for direct use in 2015, representing 0.003% of the world total for that year (IGA, 2015). The main reason for this to happen is that Costa Rica has very warm temperatures and constant weather all year. As there are only two seasons, dry and wet, there is no need for space heating. The conditions are favorable for natural agriculture as well, which is one of the most important economic activities of the country.

Currently, some natural springs in the surroundings of the Miravalles, Rincón de la Vieja, and Arenal Volcanoes are extensively used for bathing and tourism. In addition, some of the disposal water from Miravalles Geothermal Field is used to dry onions by the local farmers (MAG, 2007). Another possibility is to use the available for greenhouse heating, which has not been practiced in the country until now.

Most of the agriculture takes place in the traditional open fields. The first greenhouses appeared in the decade of 1980 when a group of producers needed to increase the exportation of non-traditional products to the market, keeping or increasing the quality, lowering the production costs, taking more advantage of small spaces, and avoiding weather and pest related issues that happen in open spaces.

The majority of the greenhouses are located in the surroundings of the Irazú Volcano and Poás Volcano in the Central Volcanic Range. This range is located in the central area of the country where most of the national economy takes place, and the soil has adequate properties for the crops. There is also the Guanacaste Volcanic Range in the northern zone of Costa Rica. The majority of the geothermal direct use activities and all the power generation are located in this range.

The usage of greenhouses continued on a small scale in the next years. In addition, the government has promoted the activity through different development and educational programs to increase the economic income of rural areas.

Despite the importance of the greenhouses in Costa Rica and the availability of geothermal resources, none of the greenhouses are heated using geothermal fluid. The main reasons are the stable warm weather throughout the year and that the soil by itself is an excellent source of nutrients for the crops. However, as the greenhouse technology is developed and accepted in the country, there is an opportunity to apply geothermal energy in the process.

The use of geothermal energy in greenhouses has gained popularity in the last few years. According to IGA (2015), thirty-one countries all over the world use this resource for greenhouse heating. Most of them are European countries that have well defined seasons with big changes in temperature during the year. They can produce the demanded vegetables and fruits that would be impossible to grow in winter conditions with a high success rate, avoiding high expenses in importations or in electricity/fuel to heat the greenhouses.

It is necessary to understand the needs of the different crops according to each production place to create new opportunities that decrease the costs, such as producing certain crops in non-conventional locations and making the design a success. In this way, the use of geothermal fluid for heating will be more feasible.

Every crop has a different requirement for temperature, humidity, and heat intake to achieve the right size, color, and flavor (Worley, 2009). Hence, every greenhouse must have a specific design. It will also depend on the weather conditions of the area, the size of the greenhouse (demand of the products), and the properties of the resource available. With this information, it is possible to determine the necessary heat load, the required mass of fluid, and the minimum temperature of the geothermal and secondary fluid. If there is not enough energy available through the geothermal fluid to achieve the production requirements, it is possible to determine the maximum production that can be successfully achieved.

Besides the mentioned properties, it is necessary to plan the operation of the greenhouse in the long-term to justify the investment with a feasible return. Moreover, many designing details must be taken into account, such as reducing the distance between the geothermal source and the greenhouse and selecting the adequate pipe materials to minimize the heat losses and reduce the initial costs. The agronomical side, the economic side, and the engineering side must always be taken into consideration from the beginning to develop a successful project.

2. GEOTHERMAL ENERGY SYSTEMS FOR GREENHOUSES

There are different ways to use geothermal energy in greenhouses. The most common is heating the space to achieve a constant optimum temperature of growing for each crop. The geothermal fluid can heat secondary water that circulates buried in the ground through the greenhouse (Thain et al., 2006). It is not recommended to directly circulate geothermal fluid to avoid scale problems. The heat exchange from the geothermal fluid to the secondary water is usually done through a plate-type heat exchanger. Then, the pipelines with heated water exchange the heat with the ground through conduction, and the ground exchanges heat with the air in the greenhouse through convection. In this way, the roots of the crop get heated first at a constant rate. Most of the times, this method is combined with air heating to allow complete heating of the greenhouse without overheating the roots (Thain et al., 2006).

If it is not recommended to heat the crops from the roots, the heated pipelines can be placed on the ground instead of getting buried (Thain, 2006). Most of the heat transfer is going to occur by convection with the air, and another small part will occur through conduction with the ground. The system will heat the crop from the stem and fruit to the roots.

Another option is to place the pipes with heated water suspended in the air at different heights (Thain et al., 2006). The air inside the greenhouse can be heated uniformly and heat the crops from the top. This method is recommended when the roots of the crop do not need to be heated in a significant way, or when the type of crop grows totally in the surface. If the heat demand significant, it is possible to use fans to force the movement of the air through the greenhouse. In this case, it is necessary to increase the area of contact of the pipeline structure with the air coming from the fans.

Using a different system than the required one could inhibit the production. Hence, it is essential to work very closely with an agronomist or expert in the field to assure that the heat is provided in the best way according to the needs of the crop.

Moreover, it is known that the geothermal fluid commonly has different minerals that can be beneficial for growing the crops. Some of these elements include silica, nitrogen, potassium, calcium, magnesium, sulfur, and phosphor (Guzmán, 2004), which are commonly present in commercial fertilizers. Hence, the fluid could be directly injected or spread inside the greenhouse as a fertilizer or even used directly in hydroponic applications. In hydroponics, the crops (mostly vegetables) are placed in a pipeline with mineral fluid instead of the ground, which can be mixed with geothermal fluid in a controlled proportion that prevents scaling in the pipes. The fluid could be stationary or circulated with a pump.

There are some proposals to use the CO_2 from power generation to create a better ambiance for photosynthesis in the greenhouses. The use of CO_2 in the right concentration could help the growth of the crops, instead of using commercial gas, which can be very expensive. This situation creates an opportunity to use the content of CO_2 present in the geothermal fluid. However, most of the time, there is also a high presence of H_2S, which is extremely poisonous for the crops. Just a few species, such as lettuce, show benefit from the intake of small amounts of this gas (Dunstall & Graeber, 1997).

3. RECOMMENDED MATERIALS FOR GREENHOUSES

The selection of the material for the greenhouse is a crucial factor for the productivity and efficiency of the process. Each material allows the solar light to enter into the greenhouse in different intensities. Hence, it has a direct impact on the photosynthesis process. They define the heat transfer between the outside and inside of the greenhouse and therefore the heat load, and they will establish the humidity and transpiration of the plant. All of these characteristics will have a direct impact on the quality and size of the crop.

The following list summarizes the most common materials for greenhouses, using as reference the research from Papadakis et al. (2000), Worley (2009), and GeoHeat Centre (1989).

- Glass: it has superior light transmission quality to other materials which would help the crops that need more light to grow healthy. It is highly available on the market, but it is more expensive due to its manufacturing process. It has low thermal expansion, and it transmits most of the energy from the outside to the inside of the greenhouse reducing its energy efficiency. Moreover, as it is very heavy, it requires more structural support which complicates the installation process. The most common types of glass configurations for greenhouses are the horticultural glass, the low emissivity glass, and the double-wall glass.

- Fiberglass: it has a lower initial investment, it is easier to install, and it requires less structural support than the glass. It has high thermal expansion and low efficiency.
- Plastic: it is the less expensive material, although it is not commonly available in the dimensions required for greenhouses, and it is straightforward to install. It could be extremely efficient when it is structured in two layers separated by air. However, as it gets damaged by ambient factors such as wind, solar light, and air, it needs to be replaced after a few years of usage (generally three years). The most common configurations for plastic in greenhouses are acrylic, polycarbonate, polyvinyl chloride, polyethylene, ethylene-vinyl acetate copolymer, and thermal polyethylene.
- Combination of materials: the materials can be combined to achieve certain properties in the greenhouse for specific needs, always trying to reach low cost and high efficiency.

There are two properties of the material that will have a direct influence when designing a heating system for the greenhouse: heat loss and air changes per hour. The heat loss of the material would determine the energy lost through transmission, and it also depends on the wind speed. The air changes per hour will determine the heat loss through ventilation, as each material has different structural characteristics that allow the air to enter the greenhouse at singular rates. Table 1 shows the design properties for the most common materials used for greenhouses.

Table 1. Heat loss and air changes per hour for the most common greenhouse materials. (GeoHeat Centre, 1989).

Material	Heat Loss: Average Wind Speed 25 km/h	Heat Loss: Average Wind Speed 50 km/h	Air changes per hour
Glass	20.43 kJ/m^2/°C	20.43 kJ/m^2/°C	2.5 to 3.5
Single polyethylene	23.5 kJ/m^2/°C	25.13 kJ/m^2/°C	0.5 to 1.0
Double polyethylene	14.3 kJ/m^2/°C	15.03 kJ/m^2/°C	0.0 to 1.0

Another factor that will determine the heat loss and thus, the design of the greenhouse is its geometry. The shape is usually determined according to the selected material, the requirements of the crop, resistance to the location conditions such as rain or snow, terrain, seismic incidence, and drainage. One of the most popular designs is the polytunnel, which is an arc shape that reaches the ground. It is beneficial as it does not need a complex structure, and it allows a more uniform distribution of heat and light for the crops. Figure 1 shows the different geometries used for greenhouses nowadays.

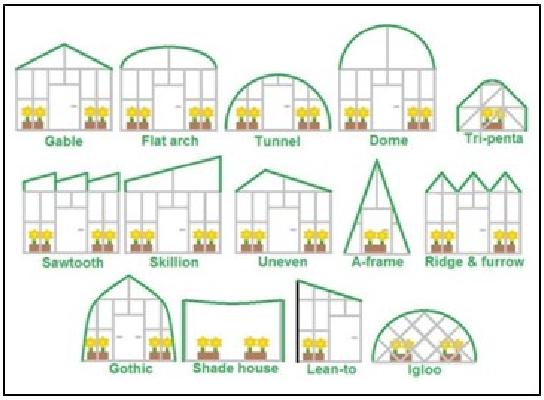

Figure 1. Common designs for greenhouses. (Brooks, 2017)

Another fundamental parameter in the design stage is the pipeline material. It depends on the temperature of the fluid, the chemical properties of the fluid, and the application of the system. There are three different fluid cases for geothermally heated greenhouses.

Geothermal fluid: the geothermal fluid usually implies scaling and corrosion issues for the pipelines depending on the specific composition of the fluid. Therefore, it is necessary to determine the chemistry of the fluid to decide the required measurement and decrease the intensity of the scaling and corrosion. The most common material for geothermal pipelines is carbon steel. The implementation of international standards such as ASME B31.3 will determine the properties of the pipeline (diameter, schedule, thickness) depending on the material, flow rate, pressure, and velocity required.

Secondary fluid: the most common secondary fluid for a geothermally heated greenhouse is water. Therefore, the recommended materials for the application are carbon steel, galvanized steel, and copper. The different properties of the pipeline will also be determined by the implementation of international standards such as ASME B31.3.

Hydroponic fluid: the most common material used is PVC due to its low cost and its simple handling. The material is strong enough to support the weight of the crops and the fluid.

The selection of the materials and geometry for greenhouses should be done in a cooperative work between the agronomist, the material engineer, the structural engineer, and the mechanical engineer of the project, to assure that all the crop requirements, structural requirements, and energy requirements will be accomplished with the lowest investment and maintenance cost.

4. COSTA RICAN MARKET FOR GEOTHERMALLY HEATED GREENHOUSES

4.1 Demand for Main Vegetables and Fruits

Table 2 and Table 3 show the fruits and vegetables with the highest demand in Costa Rica. For each crop, the national demand, national production, the selling price, and the total selling are indicated. For each crop, it is indicated whether the product is seasonal or not, defining seasonal as the availability of the product through the year due to weather conditions which most of the time includes variability in prices. According to these properties, the top five key products from each type are selected. A key product is defined as the crop which has a possible opportunity of development in the greenhouse market with the following criteria: there is less production than demand, the crop is seasonal, and the crop represents a high value of total selling in the year. For each crop, the accomplishment of the criteria is highlighted in orange.

Table 2. Fruits with highest demand. Cells in orange represent the accomplishment of the key products criteria.

Fruit	Demand (ton) [1]	National Production (ton) [2]	Seasonal [3]	Selling Price (USD/ton) [4]	Total Selling (MMUSD/year)	Key Product
Banana	141,646.31	2,008,155.00	No	468.42	66.35	
Orange	136,292.67	226,844.00	Yes	652.44	88.92	
Pineapple	122,633.38	2,771,577.00	No	543.70	66.68	
Watermelon	95,114.67	72,438.00	Yes	1,338.33	127.29	X
Papaya	88,860.42	90,000.00	No	1,087.39	96.63	X
Apple	57,989.43	5,904.72	Yes	3,847.70	223.13	X
Mango	28,619.46	38,462.00	Yes	1,003.75	28.73	
Cantaloupe	19,613.34	177,724.00	Yes	460.00	9.02	
Tangerine	18,812.79	NA	Yes	1,338.33	25.18	
Grapes	16,611.29	NA	Yes	5,353.32	88.93	X
Strawberry	15,160.31	5,440.00	Yes	4,851.45	73.55	X

Table 3. Vegetables with the highest demand. Cells in orange represent the accomplishment of the key products criteria.

Vegetable	Demand (ton) [1]	National Production (ton) [2]	Seasonal [3]	Selling Price (USD/ton) [4]	Total Selling (MMUSD/year)	Key Product
Tomato	93,963.89	68,000.00	Yes	1,171.04	110.04	X
Potato	92,162.66	90,576.00	Yes	1,296.51	119.49	X
Cabbage	64,844.09	32,790.00	No	836.46	54.24	X
Carrot	34,823.68	33,308.00	No	627.34	21.85	
Lettuce	24,166.43	51,930.00	No	1,338.33	32.34	
Squash	41,428.17	35,000.00	Yes	418.23	17.33	
Onion	26,668.13	41,928.00	No	669.16	17.85	
Cucumber	18,462.55	NA	Yes	669.16	12.35	X
Capsicum	15,810.75	12,059.00	No	2,342.08	37.03	X
Cassava	24,266.50	136,425.00	No	710.99	17.25	
Cauliflower	27,768.88	3,476.76	No	543.70	15.10	
Broccoli	15,460.51	4,909.20	No	1,505.62	23.28	

[1]: Demand for crop per year in Costa Rica (PIMA, 2016) with a total population of 5,003,402 people (INEC, 2018). [2]: National production per year for each crop in Costa Rica (Infoagro, 2017). [3]: Availability of the product depending on weather through the year (PIMA, 2018).[4]: Price per ton for each crop (SIM, 2018) using an exchange rate of 597.76 CRC / USD according to the official rate of the Central Bank of Costa Rica on October 25th, 2018.

4.2 Required Growing Conditions for Vegetables and Fruits

To determine the actual possibility of each crop to be developed in greenhouses in Costa Rica, it is necessary to know the required conditions for each one to grow in a healthy way. If the optimum temperature is not reached, there is a possibility that the crop grows small or does not grow at all, the fruit does not have a quality taste, or the crop grows with pests on it. If the temperature is greater than required, the crop will grow small and will get burned and dried. Table 4 shows the required day/night temperature conditions for each key crop.

Table 4. Optimum growing temperatures for key crops.

Crop	Day Time (°C)	Night Time (°C)	Reference
Watermelon	29-32	18-22	Rimol, 2014
Papaya	20-27	20	MAG, 2018
Apple	0-8	-7	MAG, 2018
Grapes	25-32	20	Goldammer, 2013
Strawberry	10-20	10	MAG, 2018
Tomato	21-25	17-20	Thain, 2006
Potato	20-25	10 -15	MAG, 2018
Cabbage	15-20	15	MAG, 2018
Cucumber	25-28	21	MAG, 2018
Capsicum	18-27	12 -16	MAG, 2018

Another weather requirement for the healthy growth of the crops is the relative humidity. There is no consensus for the specific optimum relative humidity per each crop in the reviewed literature. However, a range from 60% to 70% is commonly accepted for most of the crops. In rainy countries like Costa Rica, the relative humidity is extremely variable. Therefore, it would require a higher heat load to maintain the optimum relative humidity inside the greenhouse. The recommendation is designing for the average relative humidity and having additional mechanisms to de-humidify the greenhouse.

4.3 Weather Conditions in Possible Production Zones

The required conditions for each key crop and the actual conditions for each possible production zone must be compared to determine whether the use of geothermal fluid is achievable.

Table 5 shows the weather properties for each proposed location: maximum and minimum temperature per month and average relative humidity. The locations are low-income rural areas which would benefit from developing agricultural activities. They were selected according to the proximity of available geothermal resources presented in Figure 2.

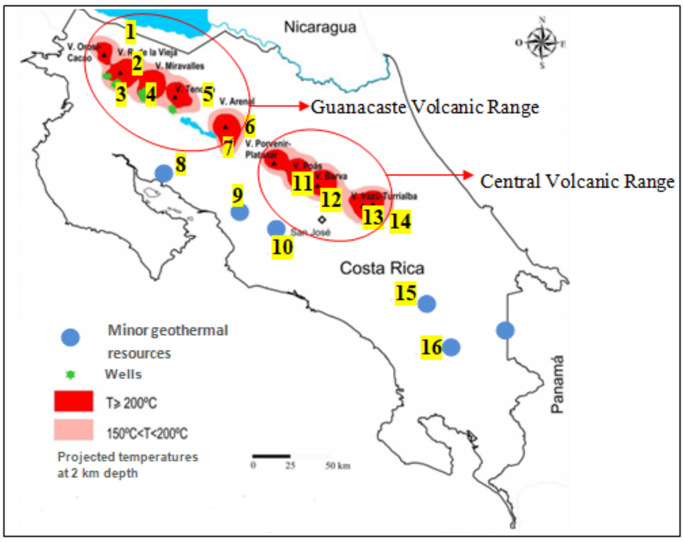

Figure 2. Location of the geothermal resources and possible production zones in Costa Rica (Adapted from Sánchez, 2017). The volcanic ranges are circled in red. The green points show the areas with drilled wells. The blue points show the areas with minor geothermal resources. The areas in red show the geothermal resources with projected temperatures at 2 km depth greater than 200°C. The pink-colored areas show the geothermal resources with projected temperatures at 2 km depth between 150 °C and 200 °C.

It is important to note that there was no selection for the farthest location at the south-east of the country, close to the border with Panama. The reason is that the area is completely covered by primary forest, and there is no population living close to the zone.

Table 5. Weather conditions for possible production zones (IMN, 2018).

Location	Location in Map (Figure 2)	Lowest Temperature in the Year (°C)	Average Temperature in the Year (°C)	Average RH in the Year (%)
Santa Cecilia	1	19	25	87
Dos Ríos	2	19	23	90
Curubandé*	3	15	21	75
Guayabo*	4	17	21	82
Katira	5	17	23	90
La Fortuna	6	15	21	87
Monteverde	7	11	19	91
Paso Tempisque	8	24	30	65
El Roble	9	24	27	85
Orotina	10	21	25	85
Poás	11	11	17	83
Barva	12	11	17	83
Chicuá	13	7	11	81
Turrialba	14	9	13	81
San Gerardo	15	7	11	83
Buenos Aires	16	19	26	87

*The communities of Curubandé and Guayabo could use the residual water from Pailas and Miravalles power stations respectively, due to their proximity.

4.4 Selection of Crops for Each Location

A comparison between Table 4 and Table 5 is conducted to determine which crops can be produced in a geothermally heated greenhouse for a location. If the optimum growing day temperature of the crop is higher than the average temperature of the location, and the optimum growing night temperature of the crop is higher than the lowest temperature of the location, then there is an opportunity to apply a geothermal system for heating the greenhouse. Considering the high relative humidity values in Costa Rica shown in Table 5, an increase in the temperature would also reduce the relative humidity giving more favorable conditions for the growth of the crop.

If the optimum growing day temperature of the crop is lower than the average temperature of the location, a cooling system would be needed to produce. If the optimum growing night temperature of the crop is lower than the lowest temperature of the location, it means that the night temperature will always be greater than the recommended temperature and a cooling system would be needed. In these cases the crop is disregarded for the corresponding location as a cooling system using geothermal fluid is not usually feasible, and it presents many operational problems. Nevertheless, the geothermal fluid could still be applied as a natural fertilizer or as a hydroponic fluid.

If the average temperature of the location is inside the optimum growing day temperature range, and the lowest temperature of the locations is lower than the optimum growing night temperature, then there is no need to heat the greenhouse as the crop would grow naturally in those weather conditions. However, a geothermal heating system could be applied to slightly increase the temperature and reduce the relative humidity to reach the recommended values. In these cases, it is just necessary to evaluate whether the final temperature after reducing the relative humidity is still inside the optimum interval for the crop.

Table 6 shows the results of the comparison of resource location and crops for fruits and vegetables, respectively. The color green indicates the selected locations for applying a geothermal system to heat the greenhouse in relation to each crop. The color yellow indicates the selected locations to apply a geothermal heating system for reducing the relative humidity in relation to each crop, even if heating is not strictly required. The color red indicates the rejected locations per crop that are not suitable to apply a feasible geothermal application.

As it is shown in Table 6, the communities of Paso Tempisque and El Roble are ruled out for applying a geothermal heating system due to their high average temperatures. Also, the possibility of producing apples using a geothermal heating system is discarded due to the especially low temperatures needed for the crop to grow.

Table 6. Comparison between production locations and crops. Green cells: locations per crop suitable for geothermally heated greenhouses. Yellow cells: locations per crop suitable for relative humidity geothermal reduction. Red cells: locations per crop unsuitable for geothermal heating systems.

	Location															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Watermelon	Green	Green	Green	Green	Green	Green	Green	Red	Red	Green	Green	Green	Green	Green	Green	Green
Papaya	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Green	Red	Red	Red	Green	Green	Green	Green	Green	Red
Apple	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Grapes	Yellow	Green	Green	Green	Green	Green	Green	Red	Red	Red	Green	Green	Green	Green	Green	Yellow
Strawberry	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Green	Green	Green	Green	Red
Tomato	Red	Red	Green	Yellow	Red	Green	Green	Red	Red	Red	Green	Green	Green	Green	Green	Red
Potato	Red	Red	Yellow	Red	Red	Yellow	Green	Red	Red	Red	Green	Green	Green	Green	Green	Red
Cabbage	Red	Red	Red	Red	Red	Red	Green	Red	Red	Red	Green	Green	Green	Green	Green	Red
Cucumber	Yellow	Green	Green	Green	Green	Green	Green	Red	Red	Yellow	Green	Green	Green	Green	Green	Yellow
Capsicum	Red	Red	Yellow	Red	Red	Yellow	Yellow	Red	Red	Red	Green	Green	Green	Green	Green	Red

5. DESIGN OF GEOTHERMAL HEATING SYSTEMS IN GREENHOUSES: THE COSTA RICAN CASE

Once the locations are selected, the conditions of each location are known, and the requirements for each crop are determined, it is possible to proceed with the design of the heating system for the greenhouse. The most important parameters for designing are the heat load required considering the change of temperature, the flow rate for both geothermal and secondary fluid, the heat exchanger parameters, and the inner pipeline length.

5.1 Final Temperature Calculation for Relative Humidity Reduction

The air is capable of carrying a certain amount of suspended water before it condensates, and it is dependent on the ambient pressure and the temperature of the air. The total amount of suspended water is known as absolute humidity, while the proportion between the absolute humidity and the maximum quantity of water that can be carried by air at that pressure and temperature is known as relative humidity. The changes in temperature will determine the relative humidity of the system, as the ambient pressure remains constant for a location.

The easiest way to reduce the relative humidity in a system is increasing the temperature, with no change in the absolute humidity. This process is known as simple heating. When the temperature is increased, the saturation of the air decreases. Thus, the air can carry more water (absolute humidity) before it condenses, reducing the relative humidity. The change in temperature to achieve the required relative humidity in the greenhouse will determine the heat load for the system and thus, the design of the heating system.

If for any reason it is required to reduce the absolute humidity, it is necessary to increase the relative humidity to 100%. In this case, the temperature would be decreased, the water in the air will condense, and it can be mechanically removed. Finally, the air must be heated again to reach the original temperature, and the relative humidity will decrease.

For the crops per location shown in Table 6, in the cases where is not strictly necessary to have a heating system, the following calculations could be used to determine the required final temperature to reduce the relative humidity to acceptable values. First of all, it is needed to define the relative humidity numerically. According to Çengel (2008), relative humidity is defined as

$$\phi = \frac{\omega P}{(0.622+\omega)P_g} \tag{1}$$

Where *φ, ω, P, Pg* are relative humidity, absolute humidity, ambient pressure, and saturation pressure at the ambient temperature, respectively.

For a simple heating process, the absolute humidity and the ambient pressure remain constant between two different relative humidity values. It must be noted that the saturation pressure will change as a result of temperature variation. Thus, the next equation could be applied:

$$\frac{\phi_1}{\phi_2} = \frac{P_{g2}}{P_{g1}} \tag{2}$$

In our case, the initial relative humidity and the initial ambient temperature are known from Table 5. The final relative humidity will be selected as equal to 70% to reach the required growing conditions for the crops. The final temperature of the greenhouse will be the saturation temperature at P_{g2}, and the next step would be to continue with the heat load calculations. This temperature should be checked with the maximum recommended growing temperature for each crop. If the final temperature is lower than the growing temperature, the heating system could be applied to reduce the relative humidity.

The papaya crop for the Santa Cecilia location is selected to give an example of the calculation. The following values are needed:

Φ_1 = 87% initial relative humidity in Santa Cecilia from Table 5

Φ_2 = 70% final relative humidity recommended for the crops

T_i = 25 °C average temperature in Santa Cecilia from Table 5

$P_{sat@25°C}$ = 0.03170 bar

T_{rm}= 27 °C maximum recommended day temperature for the papaya crop from Table 4

Using Equation (2), $P_{sat@Tf}$ was calculated as 0.03940 bar.

The corresponding saturation temperature is T_f = 28.7 °C. As $T_f > T_{rm}$ the heating system to reduce the relative humidity in Santa Cecilia for papaya must be ruled out. The process is repeated only for the crops per location considered for relative humidity reduction. Table 7 shows the results obtained. The acceptable results are highlighted in green; the non-acceptable results are highlighted in red.

Table 7. Final temperature required to reduce relative humidity, per location, per crop. Green cells represent acceptable locations per crop. Red cells represent rejected locations per crop.

	Crop											
	Papaya		Grapes		Tomato		Potato		Cucumber		Capsicum	
Location	T_{rm}	T_f	T_{rm}	T_f	T_{rm}	T_f	T_{rm}	T_f	T_{rm}	T_f	T_{rm}	T_f
1	27	28.7	32	28.7					28	28.7		
2	27	27.2										
3	27	22.1					25	22.1			27	22.1
4	27	23.6			25	23.6						
5	27	27.2										
6	27	24.6					25	24.6			27	24.6
10									28	28.7		
16			32	29.3					28	29.3		
7											27	23.3

5.2 Heat Load and Flow Rate Calculation

Once the required change in temperatures is known, it is possible to calculate the corresponding heat load per crop and location, for a specified material and geometry of the greenhouse. The recommended calculations were obtained from GeoHeat Centre (1989).

The design heat loss Q_T (kW) in a greenhouse is determined by two different values: the heat loss through the transmission of the walls and roof Q_1 (kW), and the heat loss due to infiltration and ventilation Q_2 (kW). The values can be calculated as follows:

$$Q_1 = \sum_1^n \frac{A_n x F_n x \Delta T}{3600} \tag{3}$$

$$Q_2 = \frac{V_T\ x\ ACH\ x\ \Delta T\ x\ U_{air}}{3600} + Q_v \tag{4}$$

$$Q_T = Q_1 + Q_2 \tag{5}$$

Where, A_n, F_n, ΔT, V_T, ACH, U_{air}, *and* Q_v, are the superficial area of the structure, the heat loss factor, the difference between the growing temperature and the outdoor design temperature, the volume of the greenhouse, the air changes per hour, the air heat transfer coefficient, and the heat load of artificial ventilation, if any.

Now, the flow rate of the geothermal fluid (m_{geo}) and secondary fluid (m_{sec}) can be calculated as follows:

$$m_{geo} = \frac{Q_T}{\eta_{HE} x \Delta h_{geo}} \tag{6}$$

$$m_{sec} = \frac{Q_T}{\Delta h_{sec}} \tag{7}$$

Where η_{HE}, Δh_{geo}, Δh_{sec} are the heat exchanger efficiency, the enthalpy change of initial and final condition for the geothermal fluid in kJ/kg, and the enthalpy change of the initial and final conditions for the secondary fluid in kJ/kg, respectively.

For the Costa Rican applications, Table 8 and Table 9 show the initial and final temperatures to calculate ΔT for humidity reduction and heating. As there is no recommendation for the chosen locations in the ASHRAE manual, T_{min} was chosen as the lowest temperature shown in Table 5. This temperature will determine the maximum possible heat load of the system.

Table 8. Initial and final temperatures (°C) per location for the relative humidity reduction case.

	Location								
	1	2	3	4	5	6	7	10	16
T_i	25	23	21	21	23	21	19	25	26
T_f	28.7	27.22	22.13	23.6	27.22	24.59	23.27	28.7	29.32

Table 9. Growing and minimum temperature (°C) matrix per location, per crop, for the heating case. Green cells represent the selected locations per crop.

		WM T_{grow}	PP T_{grow}	GP T_{grow}	SB T_{grow}	TM T_{grow}	PT T_{grow}	CB T_{grow}	CC T_{grow}	CS T_{grow}
Location	**T_{min}**	32	27	32	20	25	25	20	28	27
1	19									
2	19									
3	15									
4	17									
5	17									
6	15									
7	11									
10	21									
11	11									
12	11									
13	7									
14	9									
15	7									
16	19									

WM: watermelon; PP: papaya; GP: grapes; SB: strawberry; TM: tomato; PT: potato; CB: Cabbage; CC: cucumber; CS: capsicum

The watermelon crop in San Gerardo is chosen to exemplify the calculations as it has the biggest change in temperature. The following assumptions are made:

The greenhouse is a single unit with a superficial area of 1,200 m^2 and a volume of 3,300 m^3. The material is double polythene as it is the most common and the most efficient. The average wind velocity is 25 km/h, as there is no official wind map for Costa Rica. There is no artificial ventilation in the greenhouse. The heat exchanger has an efficiency of 95%. The initial temperature of the geothermal fluid is 90 °C. For each location, a study of the geothermal source is required to determine the actual temperature. The final temperature of the geothermal fluid is 50 °C. The initial temperature of the secondary fluid is 25 °C. The final temperature of the secondary fluid is 55 °C.

Given the previous assumptions, the following values are known: A_n = 1,200 m^2, F_n = 14.3 kJ/m2/°C from Table 1, ΔT = 25 °C, V_T = 3,300 m^3, ACH = 0.5 from Table 1, U_{air} = 1.207 kJ/h/m^2/°C, Q_v = 0 kW

By using Equation (3) – (7), we got that Q_1 = 119.17 kW, Q_2 = 13.83 kW, Q_T = 133 kW, m_{geo} = 0.84 kg/s, m_{sec} = 1.06 kg/s.

The calculations were repeated for the selected crops for each location, considering the same assumptions. Table 10 and Table 11 show the example of results of heat load and geothermal and secondary flow rate for different cases:

Table 10. Heat load and flow rates results per location for relative humidity decrease case.

Location	Q_T (kW)	m_{geo} (kg/s)	m_{sec} (kg/s)
1	19.68	0.124	0.157
2	22.44	0.141	0.179
3	6.00	0.038	0.048
4	13.83	0.087	0.110
5	22.44	0.141	0.179
6	19.08	0.120	0.152
7	22.73	0.143	0.181
10	19.68	0.124	0.157
16	17.68	0.111	0.141

Table 11. Heat load and flow rates result for cucumber, tomato, potato, and capsicum per location.

	Cucumber			Tomato			Potato			Capsicum		
Location	Q_T (kW)	m_{geo} (kg/s)	m_{sec} (kg/s)	Q_T (kW)	m_{geo} (kg/s)	m_{sec} (kg/s)	Q_T (kW)	m_{geo} (kg/s)	m_{sec} (kg/s)	Q_T (kW)	m_{geo} (kg/s)	m_{sec} (kg/s)
3				53.20	0.334	0.424						
6				53.20	0.334	0.424						
7	47.88	0.301	0.382	74.48	0.468	0.594	74.48	0.468	0.594			
11	47.88	0.301	0.382	74.48	0.468	0.594	74.48	0.468	0.594	85.12	0.534	0.679
12	47.88	0.301	0.382	74.48	0.468	0.594	74.48	0.468	0.594	85.12	0.534	0.679
13	69.16	0.434	0.551	95.76	0.601	0.764	95.76	0.601	0.764	106.40	0.668	0.848
14	58.52	0.367	0.467	85.12	0.534	0.679	85.12	0.534	0.679	95.76	0.601	0.764
15	69.16	0.434	0.551	95.76	0.601	0.764	95.76	0.601	0.764	106.40	0.668	0.848

5.3 Pipeline Length Calculation and Heat Exchanger Design

The heat from the geothermal fluid to the secondary fluid will be transferred through a plate heat exchanger. A shell and tube heat exchanger is not recommended because it requires a higher initial investment, and it requires more maintenance than a plate type. Moreover, it is not possible to increase the heat transfer if the conditions of the greenhouse change.

The first step to designing the plate heat exchanger is to determine the log mean temperature difference (*LMTD*) in °C. It is defined as follows:

$$LMTD = \frac{\Delta T_a - \Delta T_b}{ln(\Delta T_a - \Delta T_b)} \qquad (8)$$

Where ΔT_a, ΔT_b are the difference between the geothermal fluid initial temperature and the secondary fluid final temperature and are the difference between the geothermal fluid final temperature and the secondary fluid initial temperature, respectively.

Continuing with the previous example, the *LMTD* was calculated as 4.34°C.

As a result, the surface area of the heat exchanger *AHE* in m^2 can be calculated. With the area, it is possible to select the quantity of the plates according to the single superficial area given by the manufacturer.

$$A_{HE} = \frac{Q_T}{U \; x \; LMTD \; x \; C_f} \qquad (9)$$

Where *QT, U,* C_f are the peak heat load in kW, the heat transfer coefficient of the heat exchanger in kW/m^2/°C usually given by the manufacturer, and the correction factor, respectively.

It is dependent on the fluid configuration, and it has been experimentally calculated. Different literature, for example, Marriot (1971), suggests the use of charts to calculate it. In geothermal applications, the usual value is between 0.85 and 1.

A value of U = 1.2 kW/m^2 °C and a C_f of 0.85 are assumed to continue with the example. Hence *AHE* was calculated as 30 m^2 by using Equation (9).

The heat from the secondary fluid to the greenhouse will be transferred through the pipelines carrying the fluid in contact with the air. It is necessary to calculate the pipeline length L in m to achieve the required heat transfer. This is calculated using the following equation:

$$L = \frac{Q_T}{LMTD \; x \; U_p} \qquad (10)$$

Where U_p is the heat transfer coefficient of the pipeline in kW/m^2/°C.

For the *LMTD* value, ΔT_a is the difference between the secondary fluid final temperature and the growing temperature, and ΔT_b is the difference between the secondary fluid initial temperature and the growing temperature

A value for U_p = 0.0121 kW/m^2/°C for steel with aluminum fins is assumed to continue with the example.

Using Equation (8) and (10), *LMTD* and *L* were calculated as 8.82°C and 1246 m, respectively.

It is important to note that the pipeline is very long; therefore, the project will require a high investment in pipelines. This could make the project unfeasible, and a re-design of the system would be necessary to improve the feasibility.

Other elements should be added to the system to increase efficiency and avoid operational problems. One example is to use a three-way valve and a regulation valve to deviate the fluid in case the ambient temperature increases, and the heat requirement is different. Also, as the crops are very delicate, automatic control is highly recommended to respond in time to the monitored changes in the different conditions of the greenhouse. Moreover, there are elements absolutely necessary for the operation of the greenhouse, such as pumps for the different fluids.

Table 12 and Table 13 show examples of superficial areas and pipeline lengths required for the selected crops and locations.

Table 12. Superficial area of the heat exchanger and pipeline length per location for the relative humidity reduction case.

	Location								
	1	2	3	4	5	6	7	10	16
A (m^2)	4.4	5.1	1.4	3.1	5.1	4.3	5.1	4.4	4
L (m)	184.4	210.3	56.2	129.6	210.3	178.7	213	184.4	165.6

Table 13. Superficial area of the heat exchanger and pipeline length per vegetable crop per location for the heating case.

	Tomato		Potato		Cucumber		Capsicum	
Location	**A (m^2)**	**L (m)**	**A (m^2)**	**L (m)**	**A (m^2)**	**L (m)**	**A (m^2)**	**L (m)**
2					10.8	448.6		
3	12.0	498.5			15.6	648.0		
4					13.2	548.3		
5					13.2	548.3		
6	12.0	498.5			15.6	648.0		
7	16.8	697.8	16.8	697.8	20.4	847.4		
11	16.8	697.8	16.8	697.8	20.4	847.4	19.2	797.5
12	16.8	697.8	16.8	697.8	20.4	847.4	19.2	797.5
13	21.6	897.2	21.6	897.2	25.2	1046.8	24.0	996.9
14	19.2	797.5	19.2	797.5	22.8	947.1	21.6	897.2
15	21.6	897.2	21.6	897.2	25.2	1046.8	24.0	996.9

6. REGULATORY REQUIREMENTS

Another vital lineament that must be taken into consideration for the project is the regulatory requirements. It is especially important to start the procedures to get permits in the early stages and apply all the requirements to the design. Moreover, the development of the project by itself could represent a negative impact on the environment.

In Costa Rica, the natural resources (geothermal and non-geothermal) are widely protected through a series of institutions and international and national laws, including the National Constitution. It establishes that all the residents of the country have the right to live in a healthy and environmentally balanced environment, and the government must assure this condition. In addition, it is imperative to protect the resources in Protected Areas, as the ecotourism represents the highest economic income for the country.

For the geothermal greenhouse heating system, it is fundamental to determine the exact source of the geothermal fluid, the amount needed, and the location where it is going to be rejected after the process. As it was calculated in section 5, the geothermal fluid requirement for the different greenhouses is very low, and it should not be an issue for the permits. However, this must be determined by an environmental impact assessment carried by a government representative.

All the selected locations for possible greenhouses are very close to National Parks. In Costa Rica, it is forbidden to enter and exploit a protected natural resource in any way. Thus, if the geothermal fluid needs to be extracted from the Protected Area, the project cannot be developed. Moreover, if the source is not inside the Protected Area, but it is close to it, it is highly recommended to use the smallest possible area and avoid any damage to the natural resources.

All the permits must be processed by the Ministry of the Environment and its auxiliary departments. The environmental assessment must follow the procedure established in the regulation number DE-31849, and the specific requirements depend on the magnitude of the project, which would be determined by the national authorities. As Guido (2010) specifies:

“If the impacts are considered as low significance the developer only needs to present an environmental declaration. If the impacts are moderate the developer needs to present an environmental management program, and if the significance is high, depending on the importance of the impacts the authority could require a partial or full EIA, and it is necessary to make a money deposit as a guarantee in case of nonconformance. If any noncompliance occurs, the company can lose its money. And if the impacts are considered to be extensive, the project can be stopped" (p.1).

In addition, according to the document DA-GRH-0021 of the Ministry of the Environment, it is necessary to report the results of an environmental impact study, and the results of an environmental feasibility study directly carried by the corresponding government institution.

After the procedure is completed, the request will be published in the official newspaper of the country, and the reception for complaints against the project will be opened. If there are no complaints, the Ministry will assign a supervisor to develop a field inspection and give technical recommendations. If there is no inconvenience, one lawyer of the Ministry will dictate the final decision. In case of approval, the applicant should periodically pay for a water use right. It is not until all the permits are obtained that the geothermal water can be exploited to heat the greenhouse.

7. CONCLUSIONS

There is an opportunity to participate in the fruit and vegetable market in Costa Rica, as many of the most consumed products with high profits are currently being imported. These products are being imported because the production zones do not naturally correlate with the weather growing requirements of the crops. In this way, the greenhouses are an excellent option to produce these crops, and they can be heated with a wide range of geothermal resources available in most zones of the country.

After the market analysis, the products that would be more profitable to develop in geothermally heated greenhouses are watermelon, papaya, grapes, strawberry, tomato, potato, cabbage, cucumber, and capsicum. Each one can be produced in one or more of the following locations: Santa Cecilia, Dos Ríos, Curubandé, Guayabo, Katira, La Fortuna, Monteverde, Orotina, Poás, Barva, Chicuá, Turrialba, San Gerardo, and Buenos Aires. The communities of Paso Tempisque and El Roble were disregarded due to their high temperatures all over the year.

The geothermal heating systems in the greenhouses can be used to reach a certain required temperature or to reach a certain required relative humidity through a simple heating process. The temperature differences for the selected crops and locations are in the range of 8 °C to 25 °C, and the relative humidity differences are in the range of 5% to 21%.

The peak loads obtained are in the range of 6 kW to 133 kW; the geothermal fluid rates obtained are in the range of 0.038 kg/s to 0.835 kg/s; the secondary fluid rates obtained are in the range of 0.048 kg/s to 1.061 kg/s. For the different crops and locations, the heat load, and thus, the geothermal fluid intake is considered low due to the favorable natural weather conditions in Costa Rica. The heat exchangers would need a superficial area from 1.4 m^2 to 56.2 m^2, and the pipelines would need a length between 30 m and 1246.1 m to accomplish the heating requirements.

However, it is necessary to work in a multi-disciplinary team to select the appropriate materials, heat exchanger, and pipelines design to assure the healthy development of the crops. An economic analysis must be carried out for each of the selected crops and for all the selected locations to determine the actual feasibility of the project, and all the regulatory requirements must be accomplished.

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