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CASCADING UTILIZATION IN WOTTEN WAVEN GEOTHERMAL FIELD DOMINICA – SOCIAL AND ECONOMIC ALTERNATIVES

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ABSTRACT

The Commonwealth of Dominica is an island nation in the Eastern Caribbean with nine (9) active volcanoes and expected to have significant geothermal potential. Consequently, the international scientific community has shown much interest in the exploration of surface manifestations and other natural geothermal features. The Government of Dominica has successfully de-risked geothermal development by accessing grant funding for all exploratory drilling and for parts of the construction of a small power plant. This paper discusses the possibilities for use of the geothermal resources and proposes cascading utilization of geothermal heat and fluid in communities near a proposed power plant as an avenue for economic and social upliftment. The resources are available and the need is apparent.

1. INTRODUCTION

The Commonwealth of Dominica is a 751 km^2, English-speaking nation located in the Eastern Caribbean at 15°20´N and 61°22´W (Figure 1), between the French islands of Martinique and Guadeloupe. It is a region faced with growth and sustainability challenges due to external shocks and natural hazards. Dominica, like other Eastern Caribbean countries, has been trapped in a spiral of low-growth, high-debt and limited fiscal space. Dominica´s economy has historically been heavily reliant on agriculture. Its contribution to the GDP, however, has declined from 30% in the early 1990s to 15% in 2016. Poverty is a pervasive issue, affecting 28% of the population in 2009 (World Bank, 2019).

Dominica is home to a population of 71,293 (Government of Dominica, 2011) and is known as the Nature Island of the Caribbean, touted to have 365 rivers and an abundance of lush rainforests. The steep topography and approximately 27% of the forests are designated as part of either two forests reserves or three national parks, limiting access for commercial or industrial uses. The Morne Trois Pitons National Park is a UNESCO world heritage site covering 6,857 hectares which is roughly 9% of the country's land area. The centrepiece is Morne Trois Pitons, one of five active volcanic centres within the park.

Dominica was impacted by a category five hurricane in September 2017 which led to the destruction of every sector of the economy. The post-disaster needs assessment showed that damages and losses added up to approximately 226% of 2016 GDP of USD 581.48 million. National output was estimated to have declined sharply in the last quarter of 2017 and by as much as 16% in 2018, thereby reducing the tax

FIGURE 1: Map of the Caribbean showing location of Dominica: (Nations Online Project, 2019)

base and creating deficits of about 3% and 13% in FY2017/2018 and FY2018/19, respectively (Government of Dominica, 2017). The 2018/2019 Economic and Social Review notes that operations of the central government for fiscal year 2018/19 resulted in an overall deficit of 18.4% of the GDP, representing considerable deterioration in the fiscal position. Large-scale public investments aimed at rehabilitation, reconstruction, and resilience have outpaced revenue and grant inflows. It is in this context that the geothermal utilization methods described in this paper have been chosen, for maximum impact on the deprived communities and as a part of the national economy rebuilding efforts.

With an electricity rate of USD 0.33/kWh (2016) Dominica has one of the highest rates in the world, powered mostly by imported diesel and hydropower (30% of installed capacity) which is sensitive to weather events. Prior to the hurricane, Dominica´s installed capacity was 26.7 MW of which more than 20 MW was diesel-based while the remaining 6.6 MW were generated by three cascading hydropower plants. The baseload needs were approximately 12 MW and peak demand was 17 MW (Government of Dominica, 2017).

To diversify its energy mix, to improve energy independence and as a key element of a national resilient development strategy, Dominica has designed a risk mitigation project around its geothermal resources. As an underground resource, geothermal energy is not susceptible to weather events and above-ground infrastructure can be constructed robustly. A special purpose vehicle, the Dominica Geothermal Development Company, Ltd. (DGDC), owned by the government of Dominica, was established in 2016 to manage geothermal exploitation in Dominica. Its initial mandate was to implement the Dominica Geothermal Risk Mitigation Project (DGRMP) funded by the World Bank and other development partners and the Government of Dominica. The contribution of the Government included equity in cash for DGDC´s operations as well as assets including three exploratory, one production and one reinjection well drilled previously using grant funding. The operating and maintenance of the power plant are not part of the analysis presented in this paper.

The objective of this paper is to identify and discuss complementary uses of the geothermal resource in the Wotten Waven geothermal field in addition to electricity generation to create socio-economic benefits for the communities in the proximity to the proposed power plant. In this paper we consider primarily non-industrial applications of geothermal energy using the Lindal diagram. The goal of this project is to determine how much energy is available for direct use (supply) and then to calculate how much energy is needed for each utilization taking different regional factors and applications (demand) into consideration. The potential profits of each utilization are then calculated. By displaying the profitability of expanding the use of the current geothermal production system, this methodology and analysis could be used as an incentive to expand the range of benefits to the communities as well as the national economy both through regional job creation and economic well-being.

2. CHARACTERIZATION OF THE RESOURCE AND ENVIRONMENT

This section describes the geothermal resource in the Wotten Waven field and its chemical and mineral characteristics which make it suitable for cascading uses. The communities in the proximity of the field will also be described to provide context.

2.1 Characterisation of the geothermal resource in Wotten Waven field

2.1.1 Background – reservoir profile

In 2005, within the framework of the Eastern Caribbean Geothermal Development Programme "Geo-Caraïbes" funded by the OAS (Organization of American States), exploration surveys were carried out in the Wotten Waven area in Dominica. Subsequently, another programme called "Geothermal Energy in Caribbean Islands" or "Géothermie Caraïbes" was initiated by the E.U., the Commonwealth of Dominica and France within the frame of the European INTERREG IIIB Programme "Espaces Caraïbes". The partners included the Government of the Commonwealth of Dominica, the Regional Councils of Guadeloupe and Martinique, Ademe (Agence de l'Environnement et de la Maitrise de l'Energie), BRGM Group (Bureau de Recherches Géologiques et Minières and CFG Services).

This programme focused on the Roseau Valley geothermal field located about 8 km east-northeast of the capital of Roseau, exhibiting surface manifestations including hot springs, fumaroles, phreatic craters etc. Geoscientific surveys conducted by the BRGM group in 2008 identified a potential geothermal reservoir which required further investigation including deep exploratory wells (Government of Dominica, 2009). The two criteria for the siting of the wells were:

a. Priority sites should offer the maximum probability of success since the immediate discovery of a commercial reservoir would stimulate the interest of the potential investors and thus accelerate the process of financing for future development.
b. The sites should be selected at a reasonable distance from each other to allow an initial assessment of the area of the reservoir and its potential and, if possible, allow the immediate installation of a geothermoelectric unit (Government of Dominica, 2014).

Three exploratory wells were drilled between 2011 and 2012. The main results are presented in Table 1 (Government of Dominica, 2014; Electroconsult, 2013). Results obtained from the 2008 scientific and technical studies (Electroconsult, 2012) and from the three exploratory wells completed in June 2012 (see Figure 2), suggest that the main heat source of the geothermal reservoir is a magmatic chamber from the Micotrin dome located in the northern section of the study area. It is also considered to be the main upflow zone of hot geothermal fluids. The reservoir is liquid dominated with temperatures up to 250°C with a minimum surface area of 9 km^2. It is being recharged by meteoric water and small amounts of seawater.

Based on the results of the surface investigations and data from the exploratory wells, the assumed characteristics of the reservoir can be summarized as follows (Government of Dominica, 2014):

TABLE 1: Parameters from exploratory wells drilled in 2011-2012 in Roseau Valley

Parameter	WW-01	WW-02	WW-03	WW-P1	WW-R1
Wellhead Easting (m)	678,302	679822	n/a	679,461	677,321
Wellhead Northing (m)	1,694,864	1,695,029	n/a	1,695,567	1,694,334
Wellhead elevation (m a.s.l.)	235	580	543	552	187
Total depth (m R.K.B.)	1200	1469	1613	1505	1914
Azimuth (°)	-	-	-	190	-
Throw (m)	-	-	-	465	-
Casing size (“)	7	7	7	9-5/8	9-5/8
Casing shoe depth (m)	303	427.5	590.6	726	607
Liner size (“)	4-1/2	4-1/2	4-1/2	7	Open hole
Liner depth (m)	269-1200	281-1337	569-1612	700-1505	1914

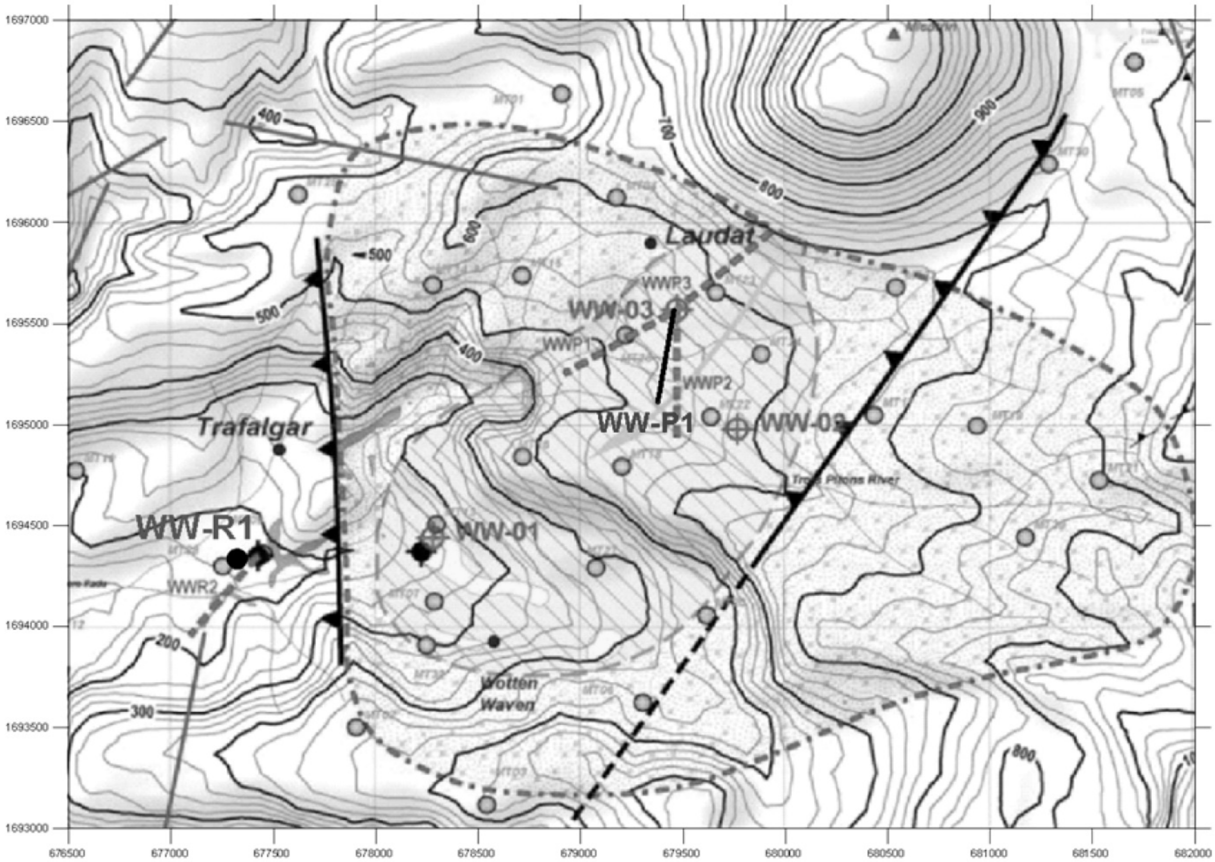

FIGURE 2: Location of wells in the Wotton Waven geothermal field. The production (P1) and reinjection wells (R1) are depicted in black and earlier exploratory wells in grey

a. *Depth* - According to the results of the MT survey, the reservoir is rather shallow, starting at a depth of a few hundred metres. However, the possibility that the MT results reflect the configuration of a shallower sub-reservoir cannot be excluded at this stage.
b. *Lateral extent* - The northern and western limits of the reservoir can be inferred from the MT survey. It is likely that the southern limit corresponds approximately to the southernmost sounding MT03 and coincides with the main outflow zone, while the eastern limit remains totally unknown. Based on the available information, the areal extent of the reservoir may be in excess of 10 km^2.
c. *Thermodynamic conditions* - In accordance with the nature of the manifestations and their geothermometric characteristics, the reservoir is expected to be water dominated with a temperature in the order of 200-210°C. The presence of a steam cap, suggested by CFG, is

unproven, although its existence cannot be excluded considering the shallow depth of the reservoir.

d. *Chemical conditions* - The geothermal fluids are supposed to be neutral with sodium chloride composition, medium salinity, and a Cl content of 2,600 mg/L. Nothing can be said at this stage about the content and composition of non-condensable gases nor about scaling and corrosion caused by the fluids. Influx of seawater into the reservoir is deemed to be negligible.
e. *Potential* - The large lateral extent of the low-conductivity body, possibly reflecting cap rock and hence a reservoir, encouraged CFG to hypothesize that the drilling 50 vertical and directional wells in the potential "high-temperature reservoir" (including a portion of the Desolation Valley zone) could result in a capacity of about 120 MW. A similar figure could be derived considering that most other fields in the world with high enthalpy and water dominated have an average potential of 10-15 MW/km^2.

Based on the results of the exploration wells, one production well (P1) and one reinjection well (R1) were drilled to exploit the resource. Well P1 is located on the same drill pad as WW-3 near the balancing tank in Laudat and R1 is located at approximately 7 km distance in Trafalgar (Figure 2).

Jacobs (2015), in their review of all existing studies and results of wells tests, provided the following recommendations for exploitation:

- For production, well WW-P1 should be used. For variable load operation, this well should be operated in a range of 40-85% of maximum flow and not be shut-in.
- Brine injection should be utilized for wells WW-R1 and WW-01. Flow into WW-R1 should be maximized to reduce injection into WW-01. The safe operating wellhead pressure at WW-01 for injection would need to be confirmed because of the shallow shut-in depth of the casing shoe.
- Condensate injection may require capacity exceeding the possibilities of WW-R1 and WW-01. Initially, well WW-03 could also be used for condensate injection. It has sufficient capacity to allow for brine injection in an emergency situation but should not be used for long-term brine injection. A drilling engineering evaluation should be conducted to determine if a workover of WW-03 is required to ensure safe operation. A 4-½" sleeve would reduce the capacity slightly.
- WW-02 is an alternative well for condensate injection and would be expected to have less long-term detrimental effect on WW-P1 temperatures but would be more expensive to connect and may require pumping.

As injection capacity is critical, it is recommended that thermal stimulation of WW-R1 by injection of cold water is conducted over a 2-3-month period to test if the injection capacity can be improved.

The following monitoring is recommended:

- For WW-01 a tracer test is recommended after one year of operation to check for premature returns to WW-P1.
- A tracer test is also recommended for the exploratory well that will be used for condensate injection.
- Monthly monitoring of WW-P1 discharge chemistry and enthalpy is recommended to allow early detection of any detrimental impact from condensate injection into WW-03/WW-02 or brine injection into WW-01.
- Interference monitoring at well WW-02 (or WW-03) is recommended if it is not used for production or condensate injection.

2.1.2 Available resources – wells, land and finance

The existing wells and drill pads have been transferred as equity and a 40-year concession has been granted to DGDC for the exploitation of the resource. The Government of Dominica (GoCD) as the sole owner of the implementing agency of the Dominica Geothermal Risk Mitigation Project has secured financing for the construction of a 7 MW power plant and associated infrastructure including approximately 7 km of reinjection pipeline. Proposed financing is detailed in Table 2 below.

TABLE 2: Financing for a 7 MW power plant

Financing agency	Contribution (USD mill.)
Government of Dominica (DGDC Investment)	6.5
Government of Dominica (land acquisition)	1.5
World Bank IDA Loan	17.2
CTF contingent grant (additional wells)	9.0
DFID grant	10.0
SIDSDOCK grant	2.0
New Zealand in kind contribution	2.0
Total	**48.2**

In June 2019, additional funds from the Green Climate Fund were made available to the DGDC by the GoCD under the Global Energy Efficiency and Renewable Energy Fund (GEEREF) for investing in renewable energy projects including the Green Industrial Eco Park (GIEP). It is this fund that this paper proposes to be used for implementing cascading uses.

In the implementation of the Dominica Geothermal Risk Mitigation Project, approximately 30 acres of land are earmarked for acquisition. This includes land not specifically required for the physical infrastructure of the power plant and reinjection pipeline, but considered too close to it for other uses. Some local landowners have indicated their unwillingness to continue to inhabit properties near to the proposed development. In addition, an abandoned 37.1 acres property, the former Rainforest Aerial Tram (where exploratory well WW-02 is located), is in liquidation and has been offered to the GoCD for acquisition. Land for construction of infrastructure needed for cascading development is therefore deemed to be available.

2.2 Characterisation of communities in proximity to the resource

2.2.1 Population, social and economic profile by community

Within the Roseau Valley, three communities, Laudat, Trafalgar and Wotten Waven, have been impacted directly by the power plant project. During the preparation of the project and more specifically the Environmental and Social Impact Assessment (ESIA), various consultations have been held in the affected communities. Focus groups of landowners, women, the unemployed, vendors and accommodation owners have been engaged. Figure 3 shows the location of the communities in relation to the proposed power plant and reinjection pipeline.

Approximately 1800 people live in the Roseau valley: just under 1000 in Trafalgar and Shawford, 321 in Laudat and 313 in Wotten Waven, with the remaining located in various hamlets along the roadway. According to the 2011 census, the Roseau Valley gained 500 inhabitants between 2001 and 2011 which is an increase of 32%. The average household size is 2.7 and the breakdown by gender is 52% male and 48% female which is similar to the national average of 51% male and 49% female. The main economic activities are farming and vending at tourist sites or along the roadways during the tourist season which runs from November to April.

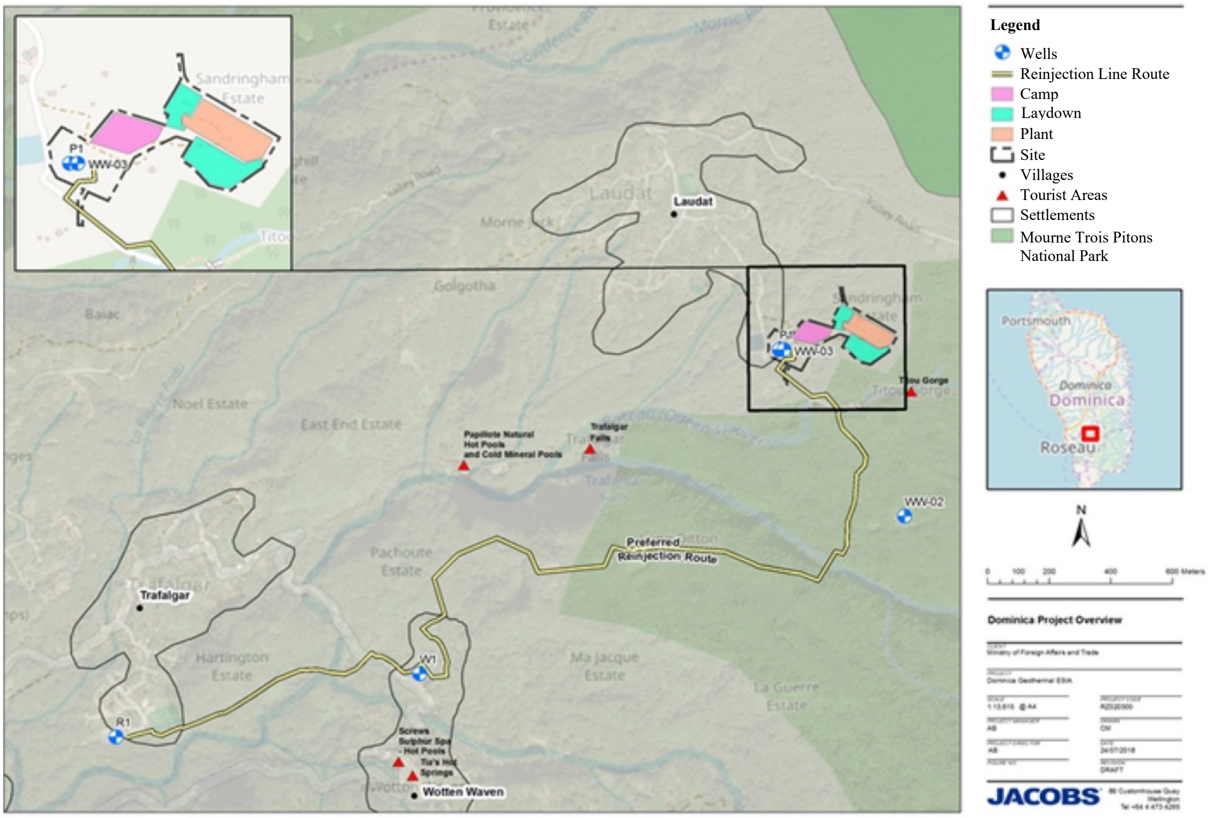

FIGURE 3: Settlements within the Roseau Valley, location of proposed power plant and reinjection pipeline (DGDC-ESIA, 2018)

In September 2017, hurricane Maria devastated the agricultural sector of Dominica. All (100%) crops were lost, trees and livestock were destroyed as well as secondary roads which provide access to arable lands and allow for transport of labour and produce to markets. Tourist sites, facilities, accommodation and hiking trails were also affected. Small communities like those in the Roseau Valley that are solely dependent on agriculture and tourism, were disproportionately affected. Surveys conducted in the Roseau Valley after the hurricane as part of the social impact assessment of the Dominica Geothermal Risk Mitigation Project suggests that 90% of respondents lost their houses and 95% their livelihoods.

Laudat: This small village is sited between 3 mountains and is the home of a hydropower plant and various tourist attractions including the freshwater lake Titou Gorge which is the gateway to the Boiling Lake through the Valley of Desolation. It is a pristine village surrounded by forests. The proposed power plant is sited to the east of the main population area and is close to a water source. The villagers are mostly vegetable farmers, tour guides or are employed in the public and private sector in the capital.

Trafalgar: This community is home to the historic Trafalgar Falls – twin waterfalls that are the most visited tourist site for cruise visitors (Ministry of Tourism, 2019). Most inhabitants earn their livelihoods by vending to tourists and through vegetable farming. Two of the three hydropower plants are located in this community. One reinjection well is located on the southeast corner of this community near the playing field.

Wotten Waven: This community has a population of mainly farmers and tourism service providers.

There are currently five spas operating in the community that use naturally occurring streams of geothermal water for their operations. DGDC monitors flow at these spas to establish a baseline for comparison after reinjection since there is a fear by the community that spas will ´dry up´ with the start of operation of the power plant. The landowner of the site of reinjection well WW-01 plans to establish a spa on adjoining property and the Ministry of Tourism plans an arcade including a spa in approx..2 km distance from the reinjection site.

3. GEOTHERMAL UTILIZATION

Direct utilisation of geothermal resources is the utilization of thermal energy from geothermal systems without conversion into some other form of energy. The generation of electricity is e.g. an indirect use of the resource. The most common uses are balneology/bathing, space heating, including the provision of hot water, agriculture, and aquaculture. Figure 4 shows direct uses of geothermal energy in Iceland.

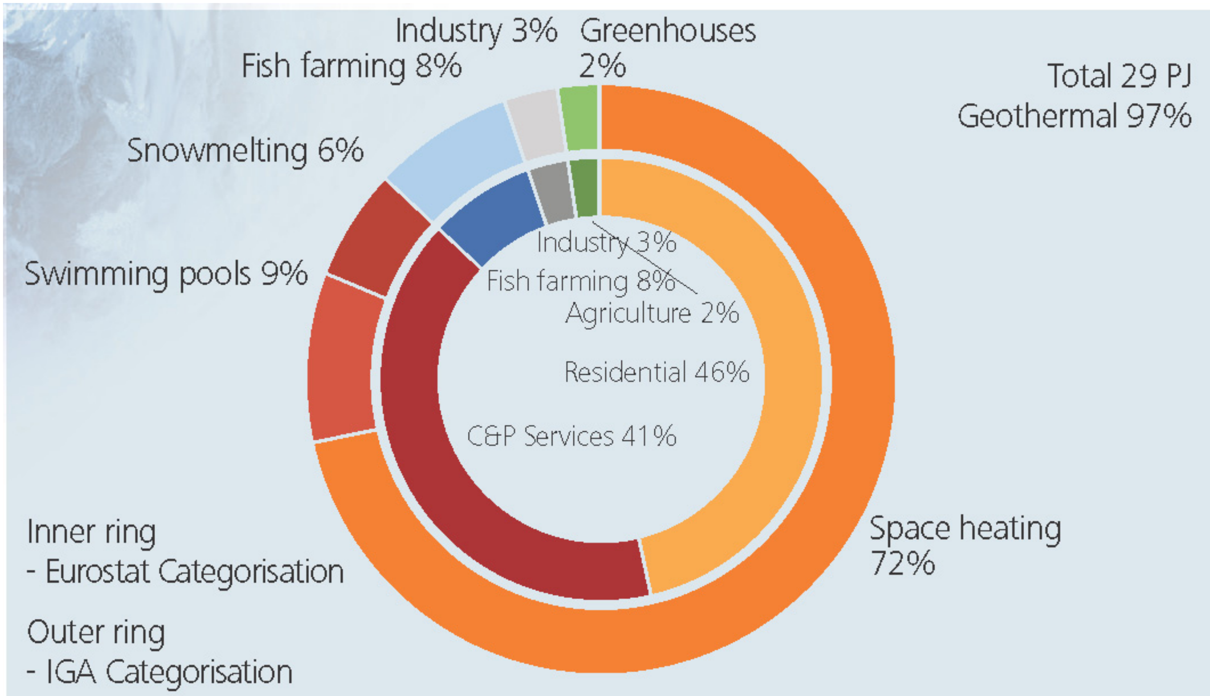

FIGURE 4: Direct use of geothermal energy in Iceland in 2017 (Orkustofnun, 2019)

Common direct uses of geothermal are represented in the adapted Lindal diagram in Figure 5.

3.1 Examples of direct uses of geothermal

China, USA and Iceland, are among the leaders in direct use of geothermal heat for the benefit of their communities, while it has also had a significant impact in countries like Kenya, New Zealand, etc. (Lund and Boyd, 2016). Especially in Iceland, it has made substantial changes to the economic landscape. Geothermal energy is used there for space heating and to provide hot water for Reykjavik and other communities in the capital area. Other uses include baths and spas, greenhouses and industrial uses (as seen in Figure 4), including the drying of fish for export and the production of liquid carbon dioxide (Ragnarsson, 2019)

In Kenya, geothermal energy from the Olkaria high-temperature field supplies not only steam for electric power production of more than 600 MWe, but also for heating the greenhouses of the largest geothermally heated flower farm in the world, thereby creating much needed local work and empowering local communities. Furthermore, a modern spa was opened in the Olkaria geothermal field a few years ago, creating considerable interest from tourists. It is worth noting that the Olkaria geothermal field with its electrical power production and health spa is within the Hell's Gate National Park (Mangi, 2015; 2018). In New Zealand, there is a wide range of industries which utilise geothermal energy directly.

Very-low-temperature resources are also exploited for heat applications using ground-source heat pumps to provide space heating and cooling (Lund and Boyd, 2016).

3.2 Industrial processes and technologies

The largest geothermal direct user in the world is the Norske Skog Tasman pulp and paper mill at Kawerau. The plant uses geothermal fluids to generate clean process steam for paper drying, as a heat source in evaporators, and for timber drying.

Figure 6 is another version of the Lindal diagram. Here, the emphasis is on the various possibilities of industrial direct uses of geothermal heat. The technology is successfully used for industrial processes such as fruit drying, carbon dioxide harvesting, and the production of organic chemicals. None of these uses have been considered for implementation in the Roseau Valley given the sites' proximity to the national parks to preserve the rustic and natural ambience but could be taken into consideration if further geothermal exploration is done in other parts of Dominica.

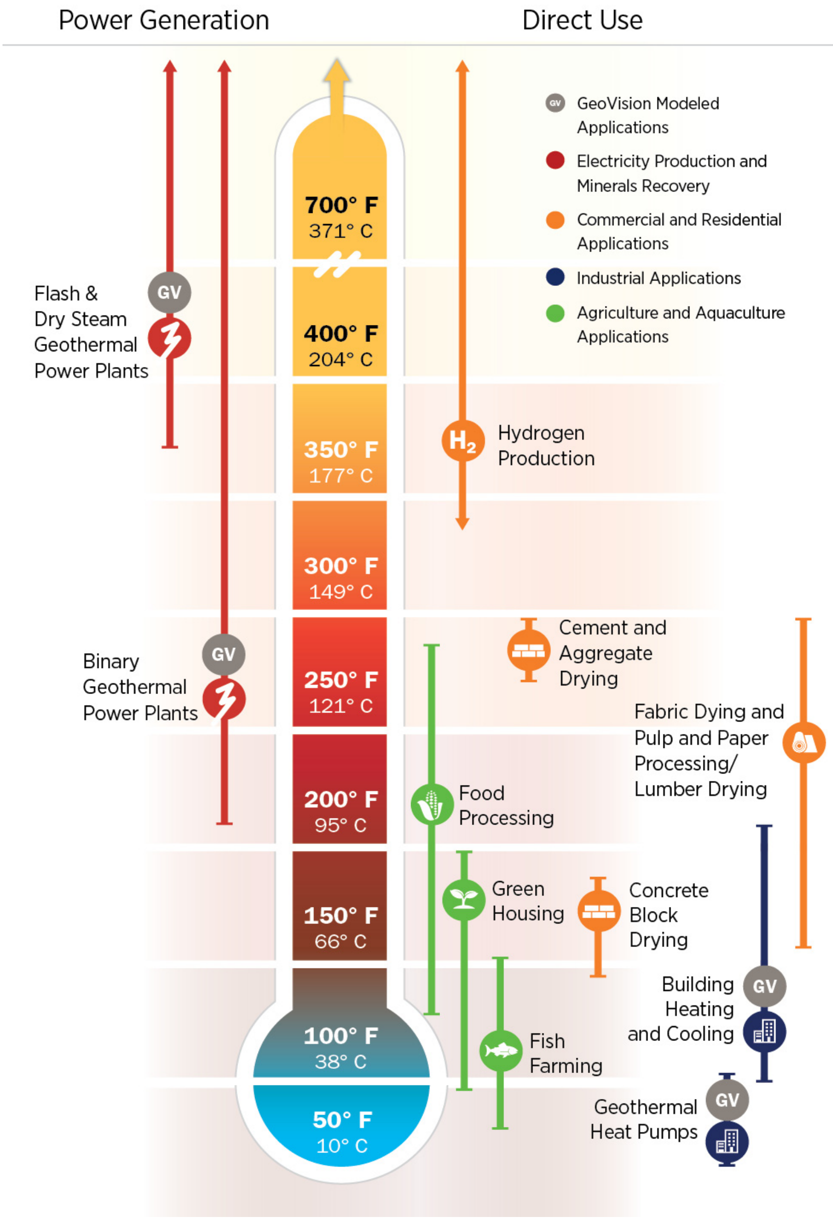

FIGURE 5: Adapted Lindal diagram. (US-DoE, 2019)

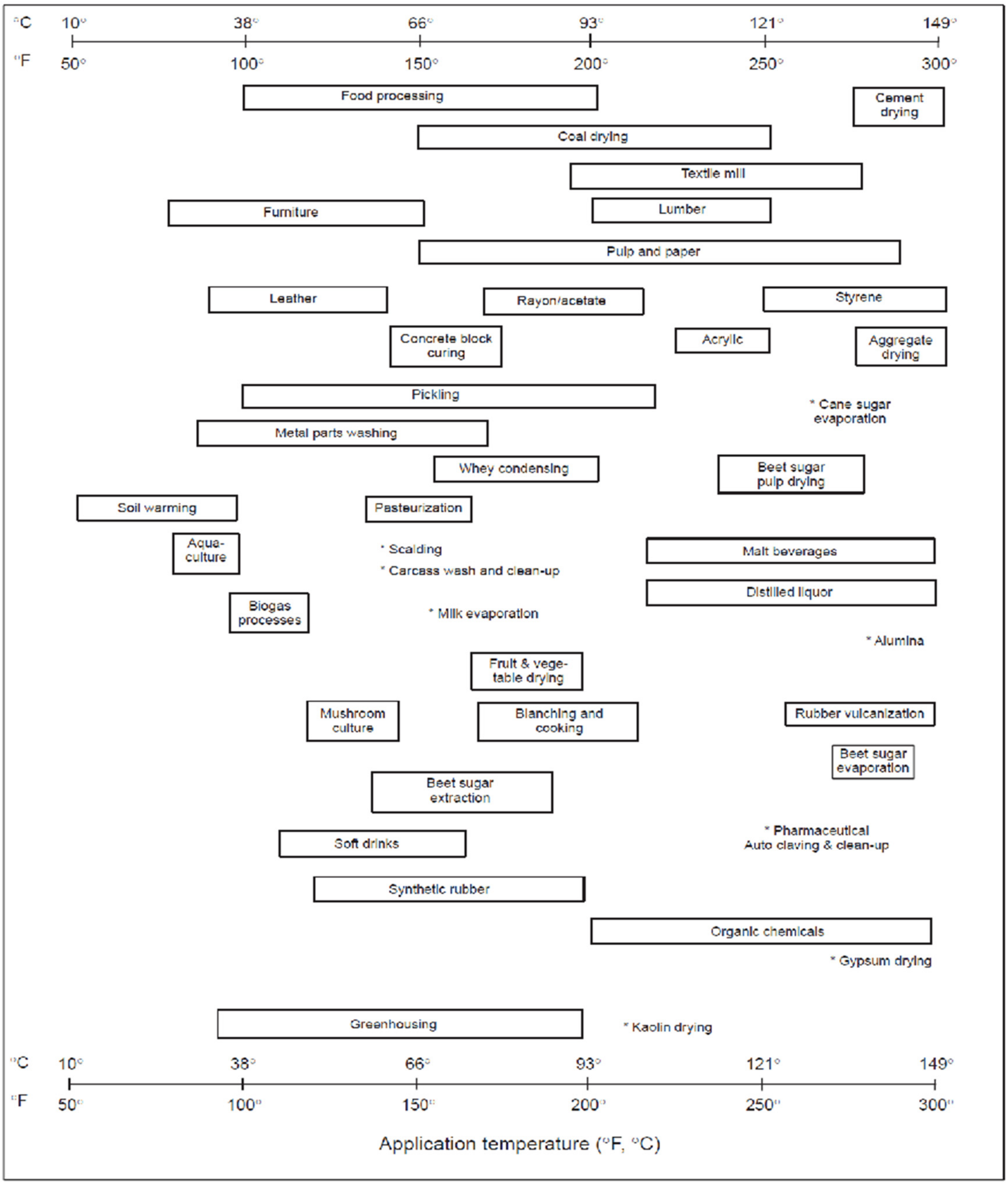

FIGURE 6: Application temperature range for selected industrial processes and agricultural applications (Lineau, 1978)

4. ADAPTED LINDAL DIAGRAM APPLIED TO WOTTEN WAVEN GEOTHERMAL FIELD

4.1 Proposed utilisation streams

It is yet unknown whether the geothermal power plant to be built at Wotten Waven, will be a binary plant or a flash steam plant. The current bid documents for an EPC (engineering, procurement and construction) contractor have been drafted in a way to let the market decide. The configuration proposed by DGDC is as follows: Production well P1 will be utilised, WW-3 located on the same well pad will be used for condensate reinjection and WW-01 and R1 will be used for reinjection of geothermal brine. The following specifications have been included in the bid documents:

- Reinjection at no more than 155°C;
- Temperature of condensate 40°C.

The following assumptions have been made:

i. The temperature of the fluid for direct use is 90°C;
ii. There is no cost for heat which is not being used by the power plant;
iii. All lands identified for structures are within 1 km radius of the resource;
iv. The flow rate of the production well is 80 kg/s with an enthalpy of 3300 kJ/kg.

The temperature and other weather data shown in Table 3 are derived from a weather station erected on the proposed power plant site and are assumed to apply for the entire Roseau Valley. Primary waters with Na-Cl and secondary waters (acid sulphate type, Ca-Na-HCO3 type and Na-HCO3-SO4 type) have been identified in the Wotten Waven area and near the Boiling Lake / Valley of Desolation. Ca-Na-Cl mineralised water discharged from the Valley of Desolation does not contain seawater which has been interpreted as evidence of the fluid having a distinct origin (Traineau and Lasne, 2008).

TABLE 3: Temperature and wind data from the power plant site in 2018

Month	**Average minimum temp.**	**Average wind speed**	**Maximum wind speed**
January	16.78	6.56	19.40
February	18.28	2.89	6.12
March	16.78	6.69	18.28
April	18.28	8.76	22.00
May	18.67	9.61	20.86
June	19.39	10.00	22.44
July	19.39	10.61	22.18
August	18.56	8.92	21.84
September	18.78	7.84	24.89
October	18.06	7.45	22.31
November	19.17	9.02	23.31
December	19.00	9.22	21.92

Considering the environment and the characteristics of the geothermal resource to be used for the proposed power plant, the following options are being proposed for the Laudat / Wotten Waven / Trafalgar communities. The list is by no means exhaustive and expansion is likely, particularly if further wells are drilled and a larger power plant for export of electricity to the neighbouring island is constructed, thereby increasing the amount of geothermal brine available.

1. *Greenhouses* – tomato and cucumber production for the local market. Exotic flower production should also be considered for the future.
2. *Fish farming* – production for the local market, particularly to supply the five new resorts under construction. Tilapia and Black Tiger prawns have been considered.
3. *Spas* - Supply of geothermal water to new and existing spas.

Dominica, despite its vast land and ocean resources, is a net importer of vegetables, flowers and fish. Table 4 below provides the quantities and value of imports for commodities from 2016 to August 2019. The Ministry of Trade expects an increase in demand in 2020 which cannot be supplied locally until four resorts currently under construction will be opened.

TABLE 4: Imports of selected commodities (Ministry of Trade, 2019)

Commodity / Indicators	2016 Value (ECS)	2016 NetMass (kg)	2017 Value (ECS)	2017 NetMass (kg)	2018 Value (ECS)	2018 NetMass (kg)	2019 Jan-Aug Value (ECS)	2019 Jan-Aug NetMass (kg)
Cucumbers and Gherkins	0	0	0	0	0	0	0	0
Tomatoes, fresh or chilled	58,362	8,562	47,936	7,778	19,561	3,482	25,873	4,218
Fish, frozen, excluding fish fillets & other fish meat	43,968	8,584	61,793	15,005	48,043	5,387	5,105	2,249
Fish fillets and other fish meat (whether or not minced) fresh chilled or frozen	20,826	8,641	15,665	3,716	54,721	10.624	37,286	6,903
Cut flowers and flower buds of a kind suitable for bouquets or for ornament	16,810	642	16782	840	17,507	684	45,933	362

Each utilization will be considered depending on its thermal demand. The thermal demand is estimated based on the amount of heat required to produce X amount of that utilization's product. This is, for example, the amount of thermal energy required to heat a square meter of a greenhouse in the climatic conditions in the Roseau Valley. The thermal energy is calculated using the mass flow from the power plant and temperature inputs. The temperature, mass flow and the assumption that the geothermal brine will be treated as freshwater are important because of how the amount of energy that can be provided is calculated (Equation 1):

$$Q = mc\Delta T \tag{1}$$

Q is the total power (W), m is the mass flow of the water (kg/s), c is the specific heat of water (J/kg°C) (in this report 4200 J/kg°C is used), and ΔT is temperature difference (°C), i.e. the input temperature (T_{input}) minus output temperature (T_{output}). The input temperature is the temperature of the hot geothermal water entering the system, while the output temperature is the temperature of the water when it leaves the system.

This formula can be used to calculate the amount of energy that can be supplied to meet the heat demands of each utilization. According to our assumptions above, the mass flow (m) is 80 kg/s, T_{input} is 90°C, and T_{output} is 30°C (approx. temperature of fish ponds). Hence, the available total heat power is:

$$Q_{total} \cong 20{,}000 \text{ kW}$$

4.2 Greenhouses for cultivation of tomatoes and cucumbers

Greenhouses are used to provide and maintain conditions for optimum yield. A geothermal greenhouse differs from greenhouse using conventional fuels or electricity for heating only by the source of heat. The principles of heat flow and loss remain the same. The main climate parameters which determine the layout, structural material, shape, orientation and heating systems are the sun, outside temperature and wind. The maximum and minimum temperatures and their durations are highly important for the design of the greenhouse.

The sun influences the greenhouse climate via radiation. Sun light is a vital determinant for plant life and development. It has been shown that only the part of the solar spectrum between 400 and 700 nm significantly influences plant life (Popovski, 1993). The periodicity, the velocity and the direction of the wind are the most notable wind characteristics but it is mainly velocity and direction that will influence the choice of material, the orientation of the greenhouse, the selection of the heating system and the positioning of windows.

The wind speed strongly influences the heat transfer coefficient which controls trans-mission heat losses. In this section, the focus is on whether the geothermal fluid from the power plant can be used to provide heat for greenhouses to produce vegetables. The overall principle is demonstrated in Figure 7. The geothermal fluid comes from a geothermal well and is sent to a storage tank to be used by the greenhouse. It is then pumped through pipes laid within the greenhouse. These pipes are used to transfer heat to either the air inside the greenhouse if the pipes are left exposed for aerial heating, or, if buried, to transfer heat to the soil in which the plants grow. Once the heat transfer has been completed, the water is pumped out of the system and to the site of the next cascading use (Ragnarsson, 2019).

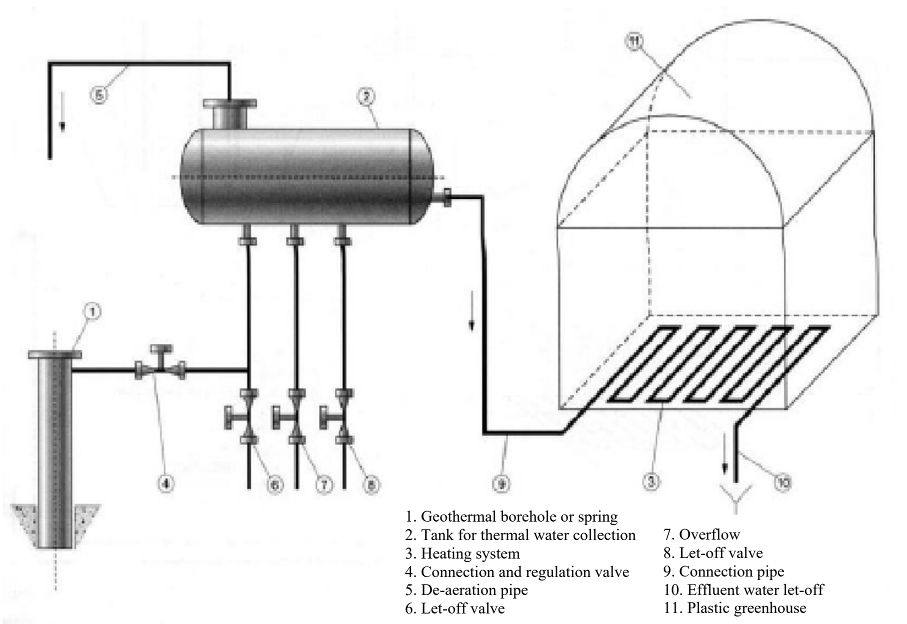

FIGURE 7: Common geothermal greenhouse heating system (Ragnarsson, 2019)

The final element in the greenhouse discussion is the material used to cover the greenhouse as this influences the heat transfer. Four commonly used covering materials were considered namely glass, fiberglass, single polyethylene, and double polyethylene. Despite polyethylene being the most commonly used material for greenhouses in Dominica due to its low cost and ease during construction, it is not recommended. With the high wind speeds and increasingly volatile weather particularly during the hurricane season, only glass greenhouse constructions will be considered. The above-mentioned inputs make it possible to calculate total transmission and infiltration losses and the maximum total of these values will be the estimate of total heat loss per m^2 for this specific type of greenhouse and plant. As design parameters for the system, the calculated maximum monthly heat loss in W/m^2 will be used.

When the total power needed per m^2 has been calculated, the total power available within a given temperature range can be divided by the total heat requirement per m^2. The result shows how many m^2 of this type of greenhouse can be effectively heated using the available temperature range. Additionally, having calculated the total amount of heat required, the piping system can be designed.

Dimensions of a typical greenhouse are taken from a study conducted by Emeish (1999) on geothermal heating in greenhouses (Table 5). Calculations are done for transmission and filtration heat losses, surface area and volume.

TABLE 5: Model greenhouse, volume and surface area (Emeish, 1999)

Parameter	Dimension
Greenhouse area (m^2)	2520
Greenhouse length (m)	45
Greenhouse width (m)	56
Greenhouse volume (m^3)	6720
Greenhouse surface area (m^2)	3690

This greenhouse design has a surface area of 1.46 m^2 off glazing material per m^2 of floor surface area. The volume is approximately 2.7 m^3 for each m^2 of greenhouse floor area. Each crop type has an optimum growing temperature which will be the design temperature of the greenhouse and used as the indoor temperature in the thermodynamic equations.

In this report, two vegetable types are considered, tomatoes and cucumbers. Other vegetables could be added in further studies. The optimum growing temperatures were chosen based on a study of Barbier et al. (1977) (Figure 8).

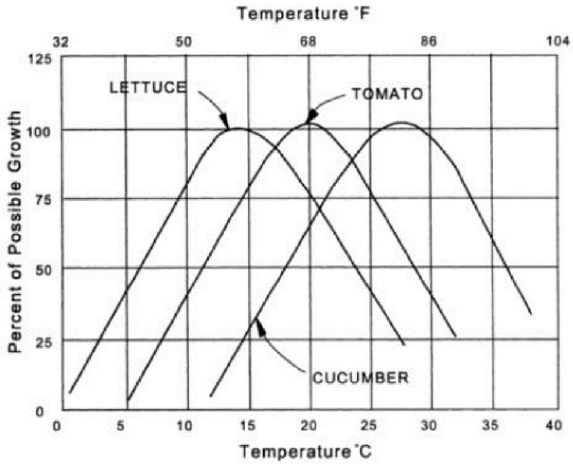

FIGURE 8: Optimum growing temperatures for lettuce, tomato, and cucumber (Barbier et al., 1977)

The optimum temperature for tomatoes and cucumbers are 20 and 27°C, respectively. Here it is assumed that the available input temperature T_{in} is 90°C and the output temperature T_{out} is 50°C. Based on that and calculations in the tables presented in Appendix I, the following can be stated, for a 2,520 m^2 greenhouse:

- ✓ *The maximum heat demand of the greenhouses for cucumbers and tomatoes is 113.5 and 36.6 W/m^2, respectively.*
- ✓ *The total number of greenhouses which can be heated, using the heat energy available according to our model, is 31 for cucumbers or 99 for tomatoes.*

Other factors such as material and piping cost also influence the optimum number of greenhouses for this utilisation. This should be the subject of further work before implementation.

4.3 Fish farming/aquaculture – tilapia and black tiger shrimp

Aquaculture is a form of fish production in which fish are raised and bred on-site. With increasing pressure on the oceans due to overfishing and climate change, fish farming is becoming increasingly popular. In Dominica, fishing is predominantly done using traditional canoes, the industry has not been modernised, the supply is seasonal and serves almost exclusively the domestic market. In 2000, the catch was 1,150 tons (552 tons in 1991) (Ministry of Agriculture, 2019).

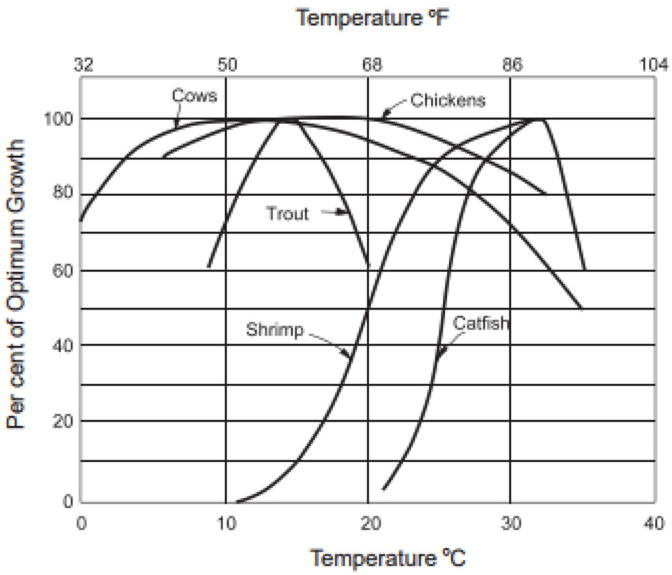

FIGURE 9: Optimum growth curves of aquatic and land animals (mod. from Beall and Samuels, 1971)

A successful experiment in fresh-water prawn farming, realized with Taiwanese aid, has produced substantial amounts of prawns for the domestic and local market. Geothermal energy is not mandatory for aquaculture which is generally considered to have a low heat demand. Depending on the fish species, temperatures are typically in the range of 10-30°C. In tropical locations, the sunrays can provide the heating required. However, even in warm climates, daily temperature fluctuations can be harmful to the growing fish population. In the Roseau Valley, average daily temperatures are approximately 20°C while night-time lows can reach 16.8°C. Aquatic species have much steeper optimum growth curves than cows and chickens (Figure 9), therefore it is much more critical to keep the fish population close to the optimal temperature.

Similar to the greenhouses, the heat required per pond can be calculated. There are four primary forms of heat loss acting in an outdoor pond, namely *evaporative, convective, radiant, and conductive* heat losses. The design values for these losses are calculated using a worst-case scenario as design conditions since an abrupt temperature change can greatly harm the fish population. The total heat loss can be calculated using the following formula (Dickson and Fanelli, 2013):

$$q_{total} = q_{ev} + q_{cv} + q_{rd} + q_{CD} \tag{2}$$

where q_{ev} is the evaporative heat loss, q_{cv} the convective heat loss, q_{rd} the radiant heat loss and q_{CD} the conductive heat loss. In this formula, q_{total} is the total heat loss and is given in kJ/h in Appendix II.

The values are converted to J/s, or W, to calculate the total heating power required (dividing by the volume of the pool). Values and calculations for typical ponds for each fish type are shown in the Appendix II. Here it is assumed that the resource temperature is 40°C, and the temperature of the fish ponds 32 and 29°C for tilapia and black tiger shrimp, respectively. Hence, for a 75 m^3 rectangular fish pond (50 m^2 ×1.5 m), the following can be stated:

- ✓ *The maximum heat demand for the model fish ponds for tilapia and black tiger shrimp is 548 and 440 W/m^3, respectively.*
- ✓ *The total number of model fish ponds, which can be heated using the heat energy available according to the model, is 65 for tilapia or 111 for black tiger shrimp.*

Tilapia and Black Tiger shrimp have been considered in this paper due to their optimum growth temperatures and known local demand, particularly for the restaurant sector and for their use as a substitute for current import of fish products.

4.4 Supply of geothermal water to spas and the construction of a swimming pool in Laudat

Balneotherapy has been practised all over the world from early history. In Iceland bathing in geothermal pools has been popular for recreation since the settlement some 1100 years ago. The famous Blue Lagoon in Iceland and other fewer renown attractions and similar concepts in Kenya have become attractive to visitors both for their contribution to leisure and for the touted health benefits in the treatment of skin diseases and rheumatism. A correlation between chemical classification and balneological properties is not always a straightforward task and different water types have been used for the treatment of various diseases (Kristmannsdóttir and Björnsson, 2003).

The mineral composition of geothermal brine from the Wotten Waven field is described in the report: "*Dominica geothermal development - environmental and social impact assessment, vol. 2: Environmental Impact Assessment*" (Jacobs N.Z., Ltd., 2018) and it is suitable for bathing at appropriate temperatures.

Temperature ranges used for bathing vary by country and in Iceland regulations state that the temperature of pools used for swimming should be in the range of 27-29°C, while the temperature of small thermal pools including children's pools should be 30-34°C, and relaxation pools and hot tubs can have temperatures of 34-44°C (MENR, 2010). A typical set up is shown in Figure 10.

Laudat, the only village in the project area which does not offer any public hot spas, is the one closest to the Morne Trois Pitons National Park, and the gateway to the Boiling Lake. Segment 4 of the Waitukubuli National Trail (WNT) passes through the village and most of the tourists to the village are avid hikers. Temperatures in Laudat range from 16.8 to 19.5°C (Table 3), and it is generally the coolest part of the island on any given day, making it attractive not just to hikers but also pleasure seekers.

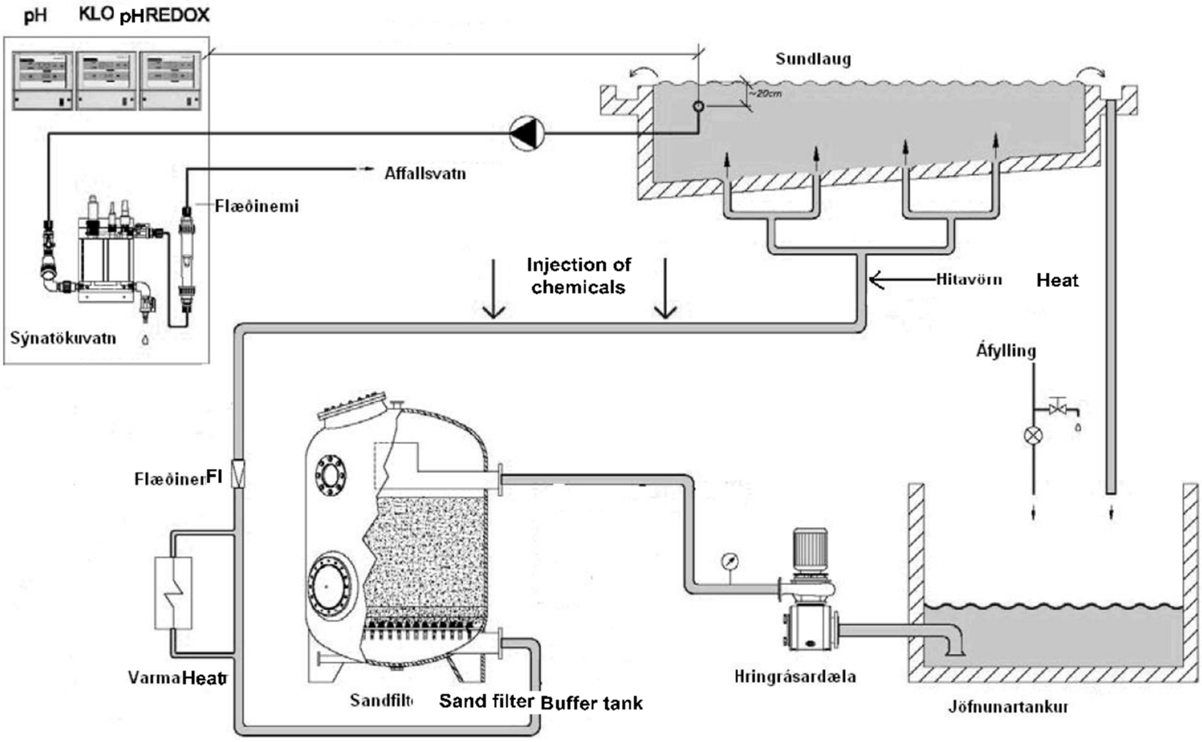

FIGURE 10: Typical setup for a modern-day closed circulation swimming pool
(mod. from Haraldsson and Ketilsson, 2010; courtesy of
Ólafur Gunnarsson, Dir., Vesturbaer Swimming Pool, Reykjavik)

A community managed rectangular pool measuring 20 × 40 m^2 is proposed for Laudat, to be located on land already acquired for the project, requiring little additional investment. Additional provision would, however, have to be made in the power plant design for sufficient cooling of the brine if the spa is to be utilized for bathing at temperatures in the range 38-40°C. Alternatively, provisions could be made for heating of surface waters for the spa.

5. SOCIAL AND ECONOMIC IMPACT OF PROPOSED UTILISATION STREAMS

In an economic analysis the amount of thermal energy is used to scale the production of each utilisation which is then used to calculate cost and revenue values. A further, more detailed economic analysis has to be conducted to calculate the optimum number of each type of greenhouse as well as the number of ponds and spas which could be constructed to make maximum use of the heat available. Factors to be considered in the analysis should include:

- Cost of construction material for various utilisations in Dominica;
- Labour costs for construction, operations and maintenance of the utilisations;
- Input costs including cost of the steam/brine;
- Location of utilisations and additional environmental impact assessment, considering the proximity to the Morne Trois Pitons National Park, a World Heritage site.

Critical to the viability after implementation is a management structure/framework which optimises the resources already existing in the Roseau Valley and empowers the local communities by utilising skillsets in management and agriculture already being used at the subsistence level. The discussions with focal groups such as women and the unemployed undertaken during the social impact assessment for the powerplant have revealed that 49% of the population are women who historically earn a living by vending to tourists during the tourist season and by engaging in farming activities in the off-season.

If the Government of Dominica, who owns the lands, and the DGDC, which would have a 40-year concession on the use of the lands and the resource, were inclined to facilitate such an undertaking at minimal cost within a cooperative framework, maximum benefits would accrue directly to the communities.

Consideration should also be given to include projects for direct utilisation in the proposal for the large power plant project (for export) and the possibility of de-risking implementation by using grant funding for construction and initial operating capital. Expected benefits would include:

- Additional revenue generating streams for the communities around the geothermal power plant;
- Additional offerings for tourists who visit the area;
- Employment;
- Knowledge transfer to subsistence farmers;
- Food security.

Given the relatively large number of greenhouses for crops and ponds for aquaculture which can theoretically be accommodated by using the expected heat available from the plant, the large amount of unused land available and the small population of the communities, the impact on the livelihoods could be significant. Here the focus should be on the Project Affected People (PAPs), whose lands have been acquired and who now find themselves without the benefit of land to *leave a legacy* (which is traditional in Dominica). Through the project, an opportunity exists to invest in long-term employment and income generating activity for these people. This would could lessen potential negative impacts of the project within the communities.

National food security was also brought into sharp focus after the destruction of hurricane Maria in 2017. Basic food items had to be airlifted to most communities as ports and roadways were compromised. A strong local food industry based on geothermal utilization could aid in counteracting repetition of such things in the future.

6. CONCLUSIONS

- The work carried out in this project serves as a theoretical confirmation that the heat emanating from the proposed power plant can be further utilised in the surrounding community through existing technologies to improve economic wellbeing. Ideally, all components i.e. greenhouses, aquaculture and the construction of spas can be implemented thereby making full use of the resource and maximizing the returns. However, various constraints exist which require further work.

- The report is also intended to serve as a starting point in a conversation between the GoCD, the DGDC and the communities of the Roseau Valley on alternatives, which may be explored, to use the proposed power plant construction and operation to raise the socio-economic profile of the affected communities and to provide opportunities beyond the reduction in the cost of electricity.

- Cascading utilization of the geothermal resource in the Roseau Valley through the options presented here, including greenhouse growing, aquaculture and a spa at Laudat is aligned with national needs and stated development goals. Adding value through each utilization, fosters new economic options and paves the way for further development.

- Paramount would be specific consultation between the stakeholders, particularly the DGDC, which owns the concession for the use of the reservoir, the lands and is also expected to own the proposed power plant, and the community to determine how the particular interventions could become a reality. Section 4 details the maximum number of greenhouses and ponds for fish which could be developed using the available resource; However, consideration for the proximity to the

National Park and maintaining the rustic appeal of Laudat would be a prime consideration as to the actual number constructed over a period.

- A continuation of work on the proposals is recommended.

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This programme provides an amazing pathway to development and poverty elimination through the transfer of knowledge and forging of personal relationships in cohorts of fellows from diverse countries.

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APPENDIX I: Data for building greenhouses and material need

TABLE 1: Greenhouse data for cucumber growing

					Greenhouse area [m²]	**2520**
Indoor design temp [°C]	**27**	**ACH**	3		**Greenhouse length [m]**	45
Surface area [m²]	1.4643	**Spec.heat of air [J/kg°C]**	1006		**Greenhouse width [m]**	56
Volume/m²	2.6667	**Density of air [kg/m³]**	1.29		**Greenhouse volume [m³]**	**6720**
Price of hot water [USD/kWh]	0.0075	**Lifespan [years]**	**20**		**Greenhouse surface area [m²]**	**3690**

Month	**Av. temp (°C)**	**Av. wind speed (m/s)**	**U**	**Q_t/m^2 [W/m²]**	**Q_i/m^2 [W/m²]**	**Q_{total}/m^2 [W/m²]**
January	16.78	6.56	5.521	82.6	29.48	112.1
February	18.28	2.89	5.037	64.3	25.15	89.5
March	16.67	6.69	5.533	83.7	29.78	113.5
April	18.28	8.76	5.692	72.7	25.15	97.9
May	18.67	9.61	5.747	70.1	24.03	94.2
June	19.39	10.00	5.770	64.3	21.95	86.3
July	19.39	10.61	5.805	64.7	21.95	86.6
August	18.56	8.92	5.703	70.5	24.35	94.9
September	18.78	7.84	5.626	67.7	23.71	91.5
October	18.06	7.45	5.597	73.3	25.79	99.1
November	19.17	9.02	5.709	65.5	22.59	88.1
December	19.00	9.22	5.722	67.0	23.07	90.1
				Max heat demand	**113.5**	**W/m²**
					Potential m²	**118,000**
					Number of greenhouses	**31**

TABLE 2: Greenhouse data for tomato growing

					Greenhouse Area [m^2]	2520	
Indoor Design Temp	20	ACH	3		Greenhouse length [m]	45	
Surface Area/m^2	1.464285714	specific heat of air [J/kg °C]	1006		Greenhouse Width [m]	56	
Volume/m^2	2.666666667	density of air [kg/m^3]	1.29		Greenhouse Volume [m^3]	6720	
Price of hot water [$/kWh]	0.0075	Lifespan	20		Greenhouse Surface Area [m^2]	3690	
	Average Temp	Average Wind Speed					
Month	Temp (C)	Wind (m/s)	U	Qt/m^2	Qi/m^2	Qtotal/m^2 [W/m^2]	
Jan	16.78	6.56	5.521	26.0	9.292459253	35.3	
Feb	18.28	2.89	5.037	12.7	4.966659253	17.7	
Mar	16.67	6.69	5.533	27.0	9.612888879	36.6	
Apr	18.28	8.76	5.692	14.4	4.966659253	19.3	
May	18.67	9.61	5.747	11.2	3.845155546	15.1	
Jun	19.39	10.00	5.770	5.2	1.76236296	6.9	
Jul	19.39	10.61	5.805	5.2	1.76236296	7.0	
Aug	18.56	8.92	5.703	12.1	4.165585172	16.2	
Sep	18.78	7.84	5.626	10.1	3.52472592	13.6	
Oct	18.06	7.45	5.597	15.9	5.607518506	21.5	
Nov	19.17	9.02	5.709	7.0	2.403222213	9.4	
Dec	19.00	9.22	5.722	8.4	2.883866667	11.3	
				Max heat Demand		36.6	W/m^2
					m^2 potential	365801	
					# of greenhouses	99	

TABLE 3: Greenhouse material

	U value	Wind Speed [m/s]								
ACH	Material	0	2.24	4.47	8.94	11.18	13.41		ln X	b
3	Glass	4.34	5.4	5.91	6.47	6.59	6.7	y = 1.3608ln(x) + 4.4095	1.3608	4.4095
2.6	Fiberglass	3.95	4.91	5.39	5.87	6.01	6.12	y = 1.2468ln(x) + 4.0079	1.2468	4.0079
0.75	Single poly	4.6	5.68	6.19	6.76	6.87	6.98	y = 1.3721ln(x) + 4.6755	1.3721	4.6755
0.5	Double poly	3.04	3.58	3.83	4.07	4.13	4.18	y = 0.6531ln(x) + 3.0889	0.6531	3.0889

APPENDIX II: Material need and data for tilapia ponds and black tiger shrimp ponds

TABLE 1: Data for a rectangular Tilapia pond (using optimum temperature 32°C)

Aquaculture											Fish farming m^3 potenti	18320	
	Fish farming m^3 potential	4,885									# of pools	244.3	
	# of pools max potential	65										300.0	
	Fish	Tilapia	**Optimum Temp**	32	**Pond Type**	Rectangular				**Hot Water needed**			
	Geo Temp	50	**Outside Temp**	16.67	**Indoor/Outdoor**	Outdoor				Q needed	Q	548.39	W/m^3
										Volume	V	75.00	m^3
Pond Dimensions	Rectangular				**Pond Dimension**	Circular				Resource Flow Requirement	m	0.0163756	l/s/m^3
L	25	meters			Diamter	20	meters	29.24		Total Heat Loss	Qtot	147,773.35	kJ/h
W	2	meters			Depth	1.5	meters	29.24		Pond Temp	Tw	32	C
h	1.5	m			(Surface) Area	314	m^2	29.243		Resource Temp	Tr	40	C
(Surface) Area	50	m^2			Volume	471	m^3						
Volume	75	m^3						25002.11					
Outdoor					*Indoor*								
Total Heat Loss	Qtot	**147,773.35**	**kJ/h**		**Total Heat Loss**	Qtot	**53,780.81**	**kJ/h**					
Evaporative Heat Loss (worst case scenario heat loss - design heat loss)					*Evaporative Heat Loss (worst case scenario heat loss - design heat loss)*								
Evaporative Heat Loss	Qev	112,348.6	kJ/h		Evaporative Hea	Qev	1,411.3	kJ/h					
Rate of Evaporation	Wp	46.04451257	kg/h		Rate of Evapora	Wp	0.5784	kg/h					
Air velocity	v	2.5	m/s		Saturation Wate	Pw	0.0069	bar					
Saturation Water Vapor Pressue	Pw	0.048439782	bar		Saturation press	Pa	0.0061	bar					
Saturation pressure at dew point	Pa	0.0061	bar		specific heat of	hev	2440	kJ/kg					
specific heat of water evap at Temp Ts	hev	2440	kJ/kg										
					Convective heat loss								
Convective heat loss					Convective heat	Qcv	34277.26303	kJ/h					
Convective heat loss	Qcv	17332.48125	kJ/h		Water Tempera	Tw	32	C					
air velocity	v	2.5	m/s		Air Temperature	Ts	16.67	C					
Water Temperature	Tw	32	C										
Air Temperature	Ts	16.67	C		*Radiant Heat Losses*								
					Radiant heat los	Qrd	15596.26577	kJ/h					
Radiant Heat Losses					Water Temp	Tw	32	C					
Radiant heat loss	Qrd	15596.26577	kJ/h		Air Temp	Ta	16.67	C					
Water Temp	Tw	32	C										
Air Temp	Ta	16.67	C		*Conductive heat loss*								
					Conductive heat	Qcd	2495.99	kJ/h					
Conductive heat loss					Length	L	25	m					
Conductive heat loss	Qcd	2495.99	kJ/h		Width	W	2	m					
Length	L	25	m		Water Temp	Tw	32	C					
Width	W	2	m		Air Temp	Ta	16.67	C					
Water Temp	Tw	32	C										
Air Temp	Ta	16.67	C										

TABLE 2: Data for a pond for Black Tiger shrimps (average of optimum temperatures is 28-30°C)

Aquaculture											Fish farmi	22825	
	Fish farming m^3 potential	8,369									# of pools	304.3	
	# of pools max potential	111										218.2	
	Fish	Tiger Shrimp	Optimum Temp	29	Pond Type	Rectangular				Hot Water needed			
	Geo Temp	50	Outside Temp	16.67	Indoor/Ou	Outdoor				Q needed	Q	440.14	W/m^3
										Volume	V	75.00	m^3
Pond Dimensions	Rectangular				Pond Dim	Circular				Resource Flow Requirement	m	0.0095588	l/s/m^3
L	25	meters			Diamter	20	meters	29.24		Total Heat Loss	Qtot	118,605.11	kJ/h
W	2	meters			Depth	1.5	meters	29.24		Pond Temp	Tw	29	C
h	1.5	m			(Surface)	314	m^2	29.243		Resource Temp	Tr	40	C
(Surface) Area	50	m^2			Volume	471	m^3						
Volume	75	m^3						25002.11					
Outdoor					*Indoor*								
Total Heat Loss	Qtot	118,605.11	kJ/h		Total Heat	Qtot	41,298.74	kJ/h					
Evaporative Heat Loss (worst case scenario heat loss - design heat loss)					*Evaporative Heat Loss (worst case scenario heat loss - design heat loss)*								
Evaporative Heat Loss	Qev	90,885.6	kJ/h		Evaporati	Qev	1,411.3	kJ/h					
Rate of Evaporation	Wp	37.24819218	kg/h		Rate of Ev	Wp	0.5784	kg/h					
Air velocity	v	2.5	m/s		Saturation	Pw	0.0069	bar					
Saturation Water Vapor Pressue	Pw	0.040351211	bar		Saturation	Pa	0.0061	bar					
Saturation pressure at dew point	Pa	0.0061	bar		specific h	hev	2440	kJ/kg					
specific heat of water evap at Temp Ts	hev	2440	kJ/kg										
					Convective heat loss								
Convective heat loss					Convectiv	Qcv	26108.52212	kJ/h					
Convective heat loss	Qcv	13940.60625	kJ/h		Water Te	Tw	29	C					
air velocity	v	2.5	m/s		Air Tempe	Ts	16.67	C					
Water Temperature	Tw	29	C										
Air Temperature	Ts	16.67	C		*Radiant Heat Losses*								
					Radiant h	Qrd	12352.63966	kJ/h					
Radiant Heat Losses					Water Te	Tw	29	C					
Radiant heat loss	Qrd	12352.63966	kJ/h		Air Temp	Ta	16.67	C					
Water Temp	Tw	29	C										
Air Temp	Ta	16.67	C		*Conductive heat loss*								
					Conductiv	Qcd	1426.28	kJ/h					
Conductive heat loss					Length	L	25	m					
Conductive heat loss	Qcd	1426.28	kJ/h		Width	W	2	m					
Length	L	25	m		Water Te	Tw	29	C					
Width	W	2	m		Air Temp	Ta	16.67	C					
Water Temp	Tw	29	C										
Air Temp	Ta	16.67	C										