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**RESOURCE STUDY FOR THE DIRECT USE  
OF LOW TEMPERATURE GEOTHERMAL  
HEAT IN UGANDA**

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**RESOURCE STUDY FOR THE DIRECT USE OF  
LOW TEMPERATURE GEOTHERMAL HEAT IN  
UGANDA**

By Faith Natukunda

This thesis is submitted in partial fulfillment for the requirements of the award of a Master of Energy (Engineering Track).

## DECLARATION

I declare that this thesis, which I submit in partial fulfillment for the award of a Master in Energy (Engineering track) is my personal work. Wherever the contributions of others are involved, it has been duly referenced in the literature and in other instances where it has appeared.



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28<sup>th</sup> August, 2016.

In my capacity as supervisor to Ms. Faith Natukunda, I certify that the above mentioned statements are true to the best of my knowledge.

(Signature)

Prof. Dr. Pall Valdimarsson

(Date)

## **DEDICATION**

*To my Beloved Zambian Babies; Mary, Bidotse, Irene, Ruth, Franchesca, Yvonne, Carol, Emmanuella, Muchimba, Mumbi, Cecilia, Natasha and Elizabeth. May you not fall short in fulfilling your dreams.*

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## ABSTRACT

The use of geothermal energy is a rapidly growing sector around the world. The need to explore less popularly known renewable energy sources, as well as the necessity to curb the currently soaring effects of the emission of greenhouse gases into the atmosphere are key drivers for this growth. Geothermal energy utilizes heat harnessed for within the earth to supply required heat for various processes, these processes range from electricity production to direct use of the heat in domestic and industrial applications. The advantages of using geothermal energy are diverse and include; minimal greenhouse gas emissions, high capacity factor, and a reliable heat supply, to mention but a few. However, the development of a geothermal project until its actual implementation and running is a costly venture.

Uganda has potential for geothermal exploitation especially in the field of direct use. Many agro-based industries exist and could use this energy to supply heat to their processes in the stead of burning biomass, which has resulted in high rates of deforestation and land degradation. This study was done to assess the geothermal resource available within the country, and then follow through with a prefeasibility study for the implementation of low temperature geothermal heat for direct uses in Uganda.

Geothermal fields from different locations of the country have been considered under this study. Each field was assessed on the basis of fluid temperature, geochemistry and status of market for the heat. Fluid temperature was obtained from available data for the different regions, whereas the geochemical assessment was included aspects such as; potential for scaling and corrosion. Results showed that the geothermal waters of most regions did not pose a threat of silica or calcite scaling except for Kanangorok that exhibited possibility for calcite scaling. The market status was focused on prevailing economic activities and the products and services they yield, and was used as a key parameter in the selection of a field for further study.

Direct use applications were selected based on the fluid temperature and possible uses as per the market status. The selected uses included; agricultural drying, aquaculture, greenhouses, geo-bio energy synergy, apiculture, milk pasteurization, balneology and salt extraction. The selection of a geothermal field for further assessment was done using screening and scoring methods. Screening was based on the number of possible direct use applications that could possibly be carried out for a given geothermal field, whereas scoring

was done on the basis of weights and ranks for criteria such as market status, fluid temperature, scaling and corrosion potentials and the field with the highest weights chosen.

The Buranga geothermal prospect was assessed under three scenarios. Scenario A used brine from a binary power plant for cascade application with direct uses. Scenario B used brine directly from a drilled well, and scenario C used hot water from a geothermal hot spring. The direct uses analyzed were agricultural drying of cocoa and a geothermal spa in a multiple system arrangement where all cases showed profitability, and hence feasibility of the projects. Scenario A exhibited the lowest costs related to investment and operation and hence a lower levelized cost of energy (LCOE) compared to the other two scenarios which only had slightly higher values for the case of agricultural drying. LCOE is however differing considerably in the case of the geothermal spa.

**Keywords:** Fluid temperature, geochemistry, market status, agricultural dryer, geothermal spa.

## PREFACE

**Mots clé :** Température de fluide, géochimie, statut du Marché, séchoir agricole, spa géothermique

L'utilisation de l'énergie géothermique est un secteur encouru de développement rapide à travers le monde. Le besoin d'explorer des ressources d'énergie renouvelables qui sont moins connus et aussi la nécessité de réduire les effets nocifs des gaz à effet de serre dans l'atmosphère sont des causes importantes pour le développement. L'énergie géothermique utilise la chaleur existante à travers la terre pour fournir la chaleur exigée par différents processus, ces processus varient de la production d'électricité jusqu'au besoin domestique de chaleur et aussi des applications domestiques. L'utilisation de l'énergie géothermique a plusieurs avantages, en citant quelques-uns ; moins d'émission des gaz à effet de serre, facteur de capacité élevé et aussi une source fiable pour l'approvisionnement de chaleur. Mais, le développement d'un projet d'énergie géothermique jusqu'à sa mise en œuvre et sa mise en marche n'est pas faisable financièrement.

L'Ouganda a un potentiel d'exploitation d'énergie géothermique spécialement dans sa directe utilisation. Plusieurs agroalimentaires industries existent et peuvent utiliser cette énergie pour fournir la chaleur pour leur processus à la place de brûler biomasse, qui résulte en un haut débit de déforestation et aussi la dégradation des terres. Cette étude était faite pour évaluer les ressources géothermiques disponibles dans le pays, puis après une étude de faisabilité pour la mise en œuvre de l'utilisation directe de géothermie à basse température.

Des champs géothermiques des différents endroits du pays ont été examinés dans cette étude. Chaque champ a été évalué à base de la température des fluides, la géochimie et le statut de marché pour la chaleur. La température du fluide a été obtenue à partir des données disponibles pour les différentes régions, alors que l'évaluation géochimique a inclus des aspects tels que : le potentiel d'entartrage et à la corrosion. Les résultats ont montré que les eaux géothermiques de la plupart des régions ne constituaient pas une menace d'entartrage de silice ou calcite sauf pour Kanangorok qui présente une possibilité d'entartrage de la calcite. Le statut du marché était axé sur les activités économiques dominantes et les produits et services qu'ils cèdent. Et a été utilisé comme un paramètre essentiel dans la sélection d'un champ pour une étude plus approfondie.

L'utilisation directe des applications ont été choisies en fonction de la température du fluide et l'utilisation possible comme par l'état du marché. Les utilisations sélectionnées incluses : séchage agricole, l'aquaculture, les serres, Géo-Bio énergie synergie, l'apiculture, la pasteurisation du lait, balnéologie et l'extraction de sel. La sélection d'un champ géothermique pour une évaluation plus poussée a été effectuée à l'aide des méthodes de dépistage et notation. Le dépistage était fondé sur le nombre des possibilités d'utilisation directe des applications qui pourraient être éventuellement effectuée pour un champ géothermique, tandis que la notation a été effectuée sur la base de poids et grades des critères tels que l'état du marché, Température du fluide, le potentiel d'entartrage et de la corrosion et le domaine ayant le plus fort poids sélectionnés.

La perspective géothermique du Buranga a été évaluée selon trois scénarios. LE scénario A utilisé la saumure à partir d'une centrale électrique binaire pour une application en cascade avec des usages directs. Le scénario B utilise la saumure directement à partir d'un puits foré, et le scénario C utilisé l'eau chaude à partir d'une source d'eau chaude géothermique. Les utilisations directes analysées étaient le séchage agricole du cacao et un spa géothermique dans un système de multiple arrangement où tous les cas ont montré les rentabilités, Et donc la faisabilité des projets. Le scénario A présentait les plus faibles coûts liés à l'investissement et le fonctionnement d'où un coût d'énergie plus faible (LCOE) comparativement aux deux autres scénarios qui n'avaient que des valeurs légèrement plus élevées dans le cas de séchage agricole. LCOE est toutefois considérablement différentes dans le cas d'un spa géothermique.

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# 1 INTRODUCTION

## Outline

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## **1.1 Background**

Uganda is endowed with a broad range of natural energy resources. The country boasts of abundant supplies of biomass and water, and exhibits propitious conditions for solar, wind and geothermal power generation. Hydropower and biomass make the greatest contribution to meeting the electricity and general energy needs of the population, with hydro power accounting for over 80 percent of the total installed capacity of 895.5 MW [1]; whereas over 90 percent of all the energy consumed in the country derives from biomass. The current unpredictable trends in climate change are having a substantial impact on the availability of water for power generation and biomass for domestic and industrial heating needs.

Geothermal energy is derived from the heat of the earth and has the capacity to serve as an additional and/or alternative source of energy to cope with the rapidly growing energy demand in the country. The geothermal resource in Uganda is estimated to be 450 MW [2]. This resource is concentrated within the East African Rift Valley (EARV) system whose western arm traverses the western part of Uganda, descending into Rwanda, Tanzania, Malawi and then to Mozambique. Geothermal energy as a resource can be harnessed both for electricity production and direct applications through the provision of heat. The direct use of geothermal heat serves as an efficient use of energy because it minimizes on the losses experienced from multiple energy conversions, thereby presenting attractive financial benefits to industries. Additionally, geothermal energy has a high availability and capacity factor and yet is a low polluting energy source. The initial investment may nonetheless require a considerable financial input.

Over the years, there has been a growing popularity in direct applications of geothermal energy across the globe. Estimates on the global distribution of geothermal energy use by category is approximated at “55.3% for ground-source heat pumps, 20.3% for bathing and swimming (balneology inclusive), 15.0% for space heating of which 89% is for district heating), 4.5% for greenhouses and open ground heating, 2.0% for aquaculture pond and raceway heating, 1.8% for industrial process heating, 0.4% for snow melting and cooling, 0.4% for agricultural drying, and 0.3% for other uses” [3].

Uganda has the capacity to take advantage of the technology improvements in the field of direct utilization of geothermal energy to meet the growing energy demand. This

will not only be beneficial in diversifying the country's energy mix, but will be a tool for improved access to clean energy, serve as a mitigation strategy to climate change effects, boost industrialization and drive the country towards a better economy.

## **1.2 Problem Statement**

The economy of Uganda is dependent on agriculture. There exist a number of agro-based industries for value addition to agricultural produce spread across the country. Many of these industries are rural based; and the few that receive electricity from the grid find the supply insufficient and unreliable for their operations, others are heavily dependent on biomass as a source of heat for their processes because of its availability and financial affordability, the environmental cost oftentimes neglected. This dependency has however placed a great strain on the country's forest cover thereby increasing the effect of greenhouse gases (GHG) on climate change from massive destruction of carbon dioxide sinks.

The rampant felling of trees to provide fuelwood as an energy source for heat to run industrial processes has led to an increased rate of deforestation and is serving as a high contributor to climate change. A report from Uganda's Ministry of Water and the Environment stated that, "At the present rate of deforestation, it is predicted that Uganda is likely to be importing fuel wood by 2020." [4]. As of 2014, the estimated biomass energy consumed totalled to 33.3 million tons with wood accounting for 28 million tons. This energy had an estimated monetary value of about 4.6 billion Uganda shillings (approximately USD 1, 850 million) as shown in Table 1.1 below. Of this total, the industrial sector, second only to the household sector accounted for a total wood equivalent of 6.4 million ton as can be seen in Table 1.2 below [5]. The area of natural forests and woodlands is quickly reducing in Uganda as a result of high demand for timber, fuel wood, and other land uses. By 2009, Uganda's forest cover was 18%, having declined from 24% in 1990 [6].

**Table 1.1: Estimated value of biomass energy reserves**

Fuel type	Mill. Tons consumed	Conservative cost/ton in USD	Biomass value in million USD	Value in Billion UgX
Wood	28	50	1,400	3,500
Charcoal	1.8	200	360	900
Agro-residues	3.5	25	88	218
Total			1,848	4,618

*Source: Ministry of Energy and Mineral Development (2014)*

**Table 1.2: Biomass demand in 2014**

Sector	Firewood Mill. Tons	Agro residues mill. Ton	Charcoal mill. Tons	Charcoal wood equivalent	Total wood equivalent
Household	20.9	1.7	1.5	13.2	34.5
Industrial	4.8	1.8			6.4
Commercial	0.54		0.3	2.6	2.8
Institutions	1.8				1.7

*Source: Ministry of Energy and Mineral Development (2014)*

Geothermal projects are rather expensive to implement although they eventually give an economical source of energy after establishment. A geothermal project usually requires 6-10 years before it is up and running and capable of supplying the desired energy. This time lag owes itself to the processes first of surface exploration, then subsurface exploration, then exploration drilling and eventually establishment of the plant. Each of these processes is time consuming and hence financially demanding. The initial investment on the preliminary stages of exploration are costly and before actual commitment is made to the final phases of development, it is important to carry out prefeasibility studies in order to enable investors to take on informed risk.

### 1.3 Project Objectives

The overall objective of the project is stated in this section, and further split into definable milestones.

#### 1.3.1 Main Objective

To carry out a resource study for direct use of low temperature geothermal heat in Uganda and carry out a prefeasibility study on a selected resource.

### **1.3.2 Specific objectives**

The project will seek to achieve the following objectives:

1. To identify candidate fields with potential for direct use based on fluid temperature, chemistry and market for the heat
2. To identify possible direct use applications to the resources under study
3. To analyze and rank candidate fields based on ability to meet selected criteria
4. To carry out a prefeasibility study on the selected geothermal field

### **1.4 Project Significance**

1. This project will be an incentive to Uganda towards boosting further exploration and drilling of geothermal projects so as to diversify the country's energy mix and encourage industrialization.
2. Geothermal energy presents a high priority alternative to hydropower and other energy sources, and therefore, findings and recommendations from the geothermal project will be an important input to meeting the energy needs of the country.
3. Geothermal energy is available when required; this implies that it minimizes the dependence on biomass and hydro power whose availability is affected by seasonal changes.
4. Because geothermal energy is a clean source of energy, its use in direct applications will serve as a measure to minimize greenhouse gas emissions from the burning of biomass in traditional ways, a practice employed by most rural industries.
5. Furthermore, developing of direct use of geothermal heat will help in overcoming issues related to local deforestation and land degradation.
6. Data compiled and assessed from this project will add to the body of knowledge thereby becoming a reference for further work.

### **1.5 Project Scope**

This project is limited to the use of already analyzed geochemical data to assess the suitability for the direct use of geothermal fluid from the candidate fields chosen. It does not involve the primary sampling and collection of geochemical data or assessment of geophysical data.

## **1.6 Methodology**

A summary into the method used to achieve each milestone in section 1.3.2 above is given in this section.

### **1.6.1 Identification of candidate fields**

Candidate fields were identified based on the literature available in relation to the characteristics they exhibit. These characteristics include but are not limited to: fluid temperature, chemistry of the field as well as availability of market for the heat to be extracted. The market status was assessed based on the population of the area, main economic activities carried out and possibility of product marketing outside the region.

### **1.6.2 Identification of possible direct use applications**

Geothermal heat can be used in a wide range of applications, however, difference in temperature requirements of different processes present a limiting factor in choice of process. Therefore, following characteristics presented in section 1.6.1 above, possible direct use applications were selected and their use and key design parameters discussed for consideration in the next phase.

### **1.6.3 Analysis and ranking of candidate fields**

The candidate fields considered in section 1.6.1 above were then assessed based on criteria given in sections 1.6.1 and 1.6.2 above. A screening process was first used for preliminary elimination of fields. The surviving fields then undergo further assessment through a scoring process where weights were given to different criteria according to their importance. This process yielded a candidate field for a prefeasibility study.

### **1.6.4 Prefeasibility study**

For the field selected from the process in section 1.6.3 above, a prefeasibility study was carried out. This study included a detailed analysis of the need for heat, description of the proposed processes, their technologies and possible mode of implementation (stand-alone or cascade models), the cost associated with each model considered as well as the environmental and social impact assessment of a geothermal low temperature direct use project in the area.

## 2 LITERATURE REVIEW

### Outline

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## **2.1 Energy in Uganda**

Uganda has one of the lowest electrification rates in Africa, 15% in 2014 [7]. Uganda has an installed capacity of 895.5 MW and peak demand of about 509.4MW [8] mainly because of the low grid coverage. The installed capacity is dominated by hydropower (approximately 80 per cent) and backed by heavy fuel oil and biomass cogeneration power plants. Only about 17% of the installed capacity comes from renewable sources excluding large hydro [7]. Electricity supply from hydropower in recent years has been affected by erratic rainfall and droughts leading to load shedding. Although an increase in the capacity and existence of two 50 MW heavy fuel oil (HFO) powered plants has seen a drop in incidences of load shedding, it comes at a cost of increased emission of greenhouse gases. Aside from electricity, over 90 per cent of energy consumption is biomass; principally firewood or charcoal [8]. Uganda's recently discovered oil reserves are currently estimated at 6.5 billion barrels.

Although there exists a surplus when the installed capacity is compared with the peak demand, the Uganda Electricity Transmission Company Limited [9] submits that an increasing energy demand at a rate of 10% per annum, will eventually result in a flip in status if no new power generation projects are commissioned. Uganda has a target to increase the share of modern renewables in total energy consumption from 4% in 2007 to 61% by 2017 to which it has been making progress, with a share of 25% in 2014 [7]. The country government is promoting development of small hydropower projects such as: Kikagati - 16 MW, Muzizi - 46 MW, Rwimi - 10.4 MW, Siti 1 & 2 - 21.5 MW, Mitano - 2.9 MW, Lubilia – 4 MW, Nyagak III - 4.5 MW, to mention but a few. Plans are also underway to develop small scale wind power in the regions of Kabale, Ntungamo, Kisoro mountainous areas bordering Rwanda and the area around Mount Elgon which experience wind speeds averaging to four meters per second. A study is also currently being carried out for large scale establishment of wind farms in the Karamoja region [8]. Geothermal prospects and some solar prospects are also being considered in parts of the country.

### **2.1.1 Geothermal Utilization in Uganda**

Uganda has an estimated geothermal potential of 450 MW [2]. Although the actual use of this potential has not yet been realized, plans are underway to use this energy for electricity generation and direct use applications in some locations. Presently, electricity

generation is an important motivation for geothermal exploitation owing to the low rate of electrification in the country as well as the need to minimize the country's dependency on hydro power. The country however has a broad range of areas that require not only electricity, but process heat as well. As an agro-based economy, the country has numerous agro-based industries that require process heat for value addition to products; this opens a broad range of possibilities on the future use of geothermal energy, not only for economic growth but also for social development.

Direct use of geothermal heat in Uganda is currently limited to the use of hot springs in their various locations. The local inhabitants utilize the hot spring waters for bathing for therapeutic values, watering animals and as tourist attractions. However, the Kisiizi spring which has clear warm waters at about 30 °C is being used at a different scale. Kisiizi hospital in Rukungiri makes use of the warm waters from the spring to supply water for bathing and other domestic uses. This is one of the major direct applications of geothermal heat in Uganda [10]. Geothermal waters have also found application in Katwe and Kibiro, where they are used for salt production especially in the warmer seasons [11].

## **2.2 Classification of geothermal resources**

The classification of an energy resource has a key role in the characterization, assessment and development of the resource. Geothermal energy resources are not excluded from this. There exist a broad range of classifications for geothermal resources, each rooted on an aspect of geothermal systems. The aspects include; the geological setting, the reservoir temperature, heat transfer, heat source, physical state and commercial utilization [12]. The section focus however, is on classification of geothermal systems based on their reservoir temperatures.

The classification of geothermal systems based on reservoir temperatures is economically important especially in aspects where the final target is to extract heat from the reservoir. Many classifications have been put forward by different authors, founded on either a thermodynamic or economic utilization context. [13] and [14] put forward a categorization based on whether or not the reservoir can be used for electricity generation, and [15], based on whether a reservoir is of high- or low-enthalpy (Table 2.1 below). More recent classifications follow the basis of possible utilization processes a given temperature range can economically service.

**Table 2.1: Classification of geothermal resources based on the relation between enthalpy and temperature (°C)**

Category <sup>1</sup>	(a)	(b)	(c)	(d)	(e)
Low temperature	< 90	< 125	<100	≤ 150	≤ 190
Intermediate enthalpy resources	90 – 150	125 – 225	100 – 200	-	.-
High enthalpy resources	> 150	>225	>200	> 150	> 190

**Sources:** *Fanelli and Dickson (1995); Mburu (2009)*

Each temperature class implies a different range of opportunities in pragmatic utilization of geothermal resources. The utilization of geothermal fluid for either electricity generation or direct applications is contingent upon the enthalpy of the fluid. Electricity generation is the most significant form of utilization of high-temperature geothermal resources while intermediate and low temperature resources are better suited for direct applications [17].

The classification according to [14] does not however only entail the capacity of a source to be used for electricity generation, but also uses aspects such as mobility phase of the reservoir, fluid state at wellhead, production mechanism, as well as well productivity thereby making the temperature intervals smaller and the selection of a utilization mode easier. Table 2.2 below shows this classification system.

In this study, low temperature geothermal heat sources will be considered to be those that fall within the temperature range of 30 °C to 150 °C. Therefore, only direct use applications falling within this range will be considered.

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<sup>1</sup> (a) Muffler and Cataldi (1978); (b) Hochstein (1990); (c) Benderitter and Cormy (1990); (d) Nicholson (1993) and (e) Axelsson and Gunnlaugsson (2000)

Table 2.2: Classification of geothermal resources

Resource category	Reservoir temperature (°C)	Mobile fluid phase in reservoir	Production mechanism	Well productivity and other controlling factors excluding temperature	Potential power conversion technology
Non electrical grade	<100	Liquid water	Artesia self-flowing wells; pumped wells	Productivity depends on reservoir flow capacity and static water level	Direct use
Very low temperature	100 – 150	Liquid water	Pumped wells	Well capacity 2 to 4 MWe; depends on reservoir flow capacity and gas content in water	Binary
Low temperature	150 – 190	Liquid water	Pumped wells; self-flowing wells (only at the higher temperatures)	Well capacity 3 to 5 MWe; depends on reservoir flow capacity and gas content in water	Binary; Two stage flash; Hybrid
Moderate temperature	190 to <230	Liquid water	Self-flowing wells	Productivity highly variable (3 to 12 MWe); strongly dependent on reservoir flow capacity	Single-stage flash; Two stage flash; Hybrid
High temperature	230 to < 300	Liquid water; Liquid dominated; Two phase	Self-flowing wells	Productivity extremely variable (up to 25 MWe); dependent on reservoir flow capacity and steam saturation	Single stage flash
Ultra-high temperature	≥ 300	Liquid dominated, Two phase	Self-flowing wells	Productivity extremely variable (up to 50 MWe); dependent on reservoir flow capacity and steam saturation	Single stage flash
Steam field	240 (33.5 bar; 2, 800 kJ/kg)	Steam	Self-flowing wells	Productivity extremely variable (up to 50 MWe); dependent on reservoir flow capacity	Direct steam

Source: Sanyal (2005)

## 2.3 Geochemistry

Geochemical exploration is a critical aspect in geothermal resource development. It comprises sampling, analysis and interpretation of discharge of thermal fluids from fumaroles, hot springs and steaming grounds [18]. Understanding of geothermal fluids before utilization is of necessity by reason of its direct impact on the costs of a geothermal system. Geochemical studies meet this need through the characterization of the thermal fluids, establishment of their origin, flow direction (upflow, outflow), evaluation of mixing scenarios, estimation of the equilibrium reservoir temperature and determination of the suitability of the fluids for the intended use [18].

### 2.3.1 Water chemistry

The chemistry of geothermal waters is influenced by several factors including the geology of the resource, temperature, pressure and the source of water. This, therefore, makes the understanding of the chemistry of the waters critical for successful utilization [10].

Anion and cation content of geothermal waters has been used to classify geothermal waters into the categories; alkali-chloride water, acid sulphate water, acid sulphate-chloride water and bicarbonate water [18]. Geothermal waters in-land areas are mainly of meteoric origin, however, oceanic waters are found in geothermal systems in coastal areas and in systems under the oceanic floor. Magmatic waters have often been detected in geothermal waters in volcanic systems [19]:

- **Alkali-chloride waters** have a pH ranging from 4 to 11. These are mostly sodium (Na) and potassium (K) chloride waters although in brines calcium (Ca) concentration is often significant.
- **Acid sulphate water** arise from the oxidation  $\text{H}_2\text{S} \rightarrow \text{SO}_4$  near the surface and most of its constituents are dissolved from surface rock. Thus such water is generally not useful for prediction of subsurface properties.
- **Acid sulphate-chloride waters** are often a mixture of alkali chloride water and acid sulphate water. Alternatively, that may arise as a result of the oxidation of  $\text{H}_2\text{S}$  to  $\text{SO}_4$  in alkali-chloride water or dissolution and then oxidation of Sulphur from rock. Sulphate-chloride waters may or may not be very acidic, however, they

reflect subsurface equilibria and can be used for prediction of subsurface properties.

- **Bicarbonate waters** may derive from CO<sub>2</sub> rich steam condensing or mixing with water. It is common in old geothermal waters or on the peripheries of geothermal areas in outflows. They are commonly at equilibrium and may be used to predict subsurface properties.

### 2.3.2 Solute geothermometers

Geothermometers are valuable tools in estimation of the temperature of reservoir fluid. They are based on mineral solubility (silica) and exchange reactions (Na-K, Na-K-Ca, and others). Solute geothermometers are based on temperature dependent minerals-fluid equilibria and their successful application is dependent on five basic assumptions as stated in [13]. Some of the commonly used solute geothermometers are: silica, Na-K, Na-K-Ca, Na-Li, K-Mg and Li-Mg, Na-K-Mg and Ca-Mg and  $SO_4/F$  [13].

- **Silica:** the limiting temperature used in silica geothermometry is 250 °C because above this temperature, silica dissolves and precipitates very rapidly. The geothermometry is dependent on absolute concentrations and not ratio of concentrations, hence is affected by boiling and dilution. It is possible for silica to be added by mixing with acidic near surface fluids and this can give misleading geothermometry temperatures [13].
- **Na-K:** The  $\frac{Na}{K}$  ratio is a useful guide to high temperature zones; a lower ratio implies higher temperature. Lower  $\frac{Na}{K}$  ratios (<15) tend to occur in waters which have reached the surface rapidly hence are often associated with upflow structures or more permeable zones [13]. The temperature dependent variation of sodium and potassium in geothermal waters of high temperature systems is due to ion exchange of these elements between co-existing alkali feldspars. Various equations for this have been derived and can be found in [13]; all give similar results above 300 °C. The slow rate of re-equilibration of Na-K makes it a good geothermometer for indication of high temperatures from deeper levels because it has the ability to “remember” these temperatures. However, this geothermometer

gives anomalously high results for waters rich in ammonia that have reacted with organic rich sedimentary horizons.

- *Na-K-Ca*: In waters rich in Ca (usually lower temperature systems), the Na-K geothermometer gave very high temperatures, this is tied to the competition of Na, K and Ca in ion exchange reactions with silicate minerals, hence upsetting the Na-K feldspar equilibrium. An empirical Na-K-Ca geothermometer was therefore developed to supplement the Na-K geothermometer in cases where  $[Ca^{1/2} / Na] > 1$  (with concentration in molar units).

### **2.3.3 Gas chemistry**

The most common gases present with steam in geothermal discharge either from natural features or wells are; CO<sub>2</sub>, H<sub>2</sub>S, NH<sub>3</sub>, N<sub>2</sub>, H<sub>2</sub>, CH<sub>4</sub>. These gases are commonly referred to as “non-condensable gases”.

### **2.3.4 Gas geothermometers**

Most of the geothermometers require that the gas/steam, and for hot reservoirs, the steam/water ratios are known. This aspect limits the use of gas geothermometers except CO<sub>2</sub>-H<sub>2</sub>S-H<sub>2</sub>-CH<sub>4</sub> system and the CO<sub>2</sub>, CO and H-Ar geothermometers. The details on how the properties exhibited by different combinations for geothermometry can be found in [13].

## **2.4 Materials Selection**

Geothermal fluids are rich in minerals compares with cold ground water, and therefore, their fluid chemistry becomes an important factor in their applications for direct use. The material of the equipment to be used therefore has to be tailored to suit the concentrations of components such as; chloride, silica, oxygen, magnesium, calcium, hydrogen sulphide as well as the pH of the fluid. The materials selected for the equipment could be mild steel, stainless steel, fiberglass or even titanium, depending on the fluid composition and temperature, as well as the application being considered.

The water chemistry of a geothermal system varies with location and factors such as; inflow of cold groundwater, or sea water into the geothermal system which could result into issues such as deposition and corrosion. Although deposition is not expected to be a critical problem in low temperature utilization compared to high-temperature utilization,

(calcite, sulphide and silica), the mixing of geothermal water with cold groundwater is not desirable due to the potential risk for magnesium silicate scaling [19].

#### **2.4.1 Piping materials**

Carbon steel is the most commonly used material for geothermal transmission and distribution networks. It is manufactured in sizes ranging from 10 to 1,500 mm and can be joined by threading for small sizes of (< 50 – 15 mm) and welding for sizes > 50 mm. Carbon steel is however susceptible to corrosion and should therefore be carefully selected.

Stainless steels differ from carbon steels by the amount of chromium present, which gives them better resistance to corrosion. Duplex stainless steels offer a higher mechanical strength with less weight, and are therefore able to withstand high pressure environments. They have a superior corrosion resistance (to pitting, crevice corrosion and stress corrosion cracking) to that of ordinary stainless steels.

Fiberglass often referred to as FRP (fiber glass reinforced plastic) can be used to temperatures of up to 140 °C. However, they are susceptible to damage at high temperatures where flashing of the fluid occurs; care must therefore be taken to maintain operating pressures high enough to prevent flashing of the hot fluid. FRP pipes are usually available in sizes larger than 50 mm, this implies that for smaller pipe diameters, another material ought to be used.

Poly-vinyl chloride (PVC) is a rigid thermoplastic material, and comes second only to steel in most commonly used piping materials. It is manufactured in diameters in the range of 15 to over 400 mm, and is capable of withstanding temperatures up to about 60 °C.

Polyethylene (PE) is a flexible material capable of withstanding service temperatures 40 to 50 °C. It is available in sizes from 15 to 1,000 mm. PE with a very high molecular weight/high density can be used in low pressure applications to temperatures as high as 80 °C.

[20].

## 2.5 Scaling

Geothermal fluids contain dissolved solids in varying measures even amongst wells of the same geothermal field. Under certain conditions of temperature and pressure, the chemicals remain dissolved in water, however, during exploitation, geothermal fluid is brought to the surface to allow for the extraction of heat. Heat can be extracted either by removal of steam from the water or by heat transfer to a second working fluid in a heat exchanger. Whichever the process used, the water will be subjected to this new equilibrium usually leads to deposition of some minerals, hence the beginning of scaling.

### 2.5.1 Types of scales

Scaling of different types and in differing measures can be found in various geothermal areas. The most common mineral scales found in geothermal systems are calcium carbonate minerals, amorphous silica and sulphide compounds. Calcite scaling is common in geothermal production wells, while silica deposition is of concern if geothermal water cools sufficiently through boiling to make it amorphous silica supersaturated [21].

#### *Silica scaling*

Silica scales are found to some extent in all high temperature geothermal installations. However, if the temperatures are maintained above the solubility level for amorphous silica (the non-crystalline form of silica), the scaling should not occur [18]. The application of this principle is key in the design criteria for geothermal plants. The silica concentration in water begins to increase when the water starts to boil, this is often due to a steam loss which makes less water available for dissolution of silica. The water therefore immediately becomes quartz supersaturated, but quartz precipitates are not formed when the amorphous silica solubility curve is passed (Figure 2.1 below). In low temperature geothermal systems, the silica content is governed by the solubility of the silica mineral chalcedony at low temperature and quartz at higher temperature.

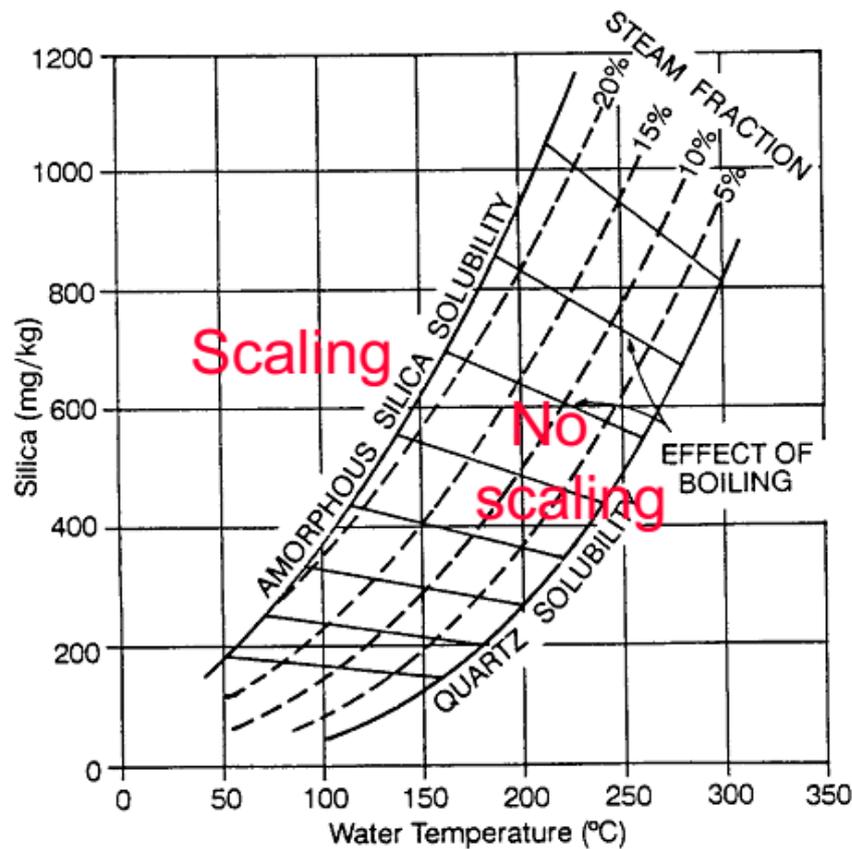
In the absence of data, analysis of amorphous silica solubility is done using the equation given below, with respect to temperature and is true for temperatures in the range of 0 to 250 °C.

$$\log C = \left( -\frac{731}{T} + 4.52 \right) \quad (2.1)$$

Where:

C = the amorphous silica concentration (mg/L)

T = the absolute temperature (K)



**Figure 2.1: The solubility of silica in water showing the curve (amorphous silica curve) across which scaling begins to occur**

*Source: Gunnlaugsson, et al, 2014*

According to [23], the quartz solubility estimate with respect to the temperature is given by:

$$Q(T) = 41.598 + 0.23932T - 0.011172T^2 + 1.1713 \times 10^{-4}T^3 - 1.9708 \times 10^{-7}T^4 \quad (2.2)$$

Where:

Q (t) = the silica concentration (mg/kg)

T = the reservoir temperature (°C)

The equation gives the Silica Saturation Temperature (SST) for a given resource temperature. The SST is defined as the temperature of the geothermal fluid at the exit of the heat exchanger before the fluid reaches saturation with respect to the amorphous silica. The SST is a temperature that allows the geothermal to be exploited without the possibility of silica scaling.

### ***Calcium carbonate scales***

Calcium carbonate scales, often in the crystalline forms calcite or aragonite, are common in wells with reservoir temperatures of 140-240°C, and are primarily found at the depth where the water starts to boil in the well. The solubility of calcite increases with decreasing temperature, therefore cooling of geothermal water does not cause scaling of calcite. Calcite scaling is however not dependent on only temperature, other factors such as; partial pressure of carbon dioxide, pH, salinity and calcium ion concentration in the geothermal fluid [23]. During flashing, the steam released carries with it most of the CO<sub>2</sub> resulting in a drastic increase in pH. The geothermal fluid becomes supersaturated with respect to calcite which begins to precipitate and deposit on the walls of the wellbore according to the equation below:



Geothermal water is saturated with respect to calcite at temperatures below 240°C in the reservoir, however, at temperatures greater than 260 °C, calcite deposition is usually not a problem [19]. Prevention of calcite scaling in wells is mostly done by using various chemical inhibitors such as sodium polyacrylate. A capillary tube is inserted into a production well to the depth of the flashing point and the chemical inhibitor is directly injected for so as to prevent scaling.

### **Prediction of calcite scaling**

#### **a. Langelier Saturation Index (LSI)**

This method is probably the most widely used indicator of calcite scaling in cooling water. The LSI is an equilibrium model derived from the theoretical concept of saturation and provides an indicator for the degree of saturation of water with respect to calcium carbonate [24]. The index indicates the driving force for scale formation and growth in terms of pH as the main variable. LSI can be interpreted as the pH change required to bring water to equilibrium.



The LSI however does not provide an indication of how much scale or calcium carbonate will actually precipitate to bring water to equilibrium. LSI is defined as:

$$\text{LSI} = \text{pH} - \text{pH}_s$$

Where pH is the measured water pH, and  $\text{pH}_s$  is the pH at saturation in calcite or calcium carbonate and is defined as:

$$\text{pH}_s = (9.3 + \text{A} + \text{B}) - (\text{C} + \text{D}) \quad (2.3)$$

Where:

$$\text{A} = (\log_{10}[\text{TDS}] - 1)/10;$$

$$\text{B} = -13.12 \times \log_{10}(\text{°C} + 273) + 34.55;$$

$$\text{C} = \log_{10}[\text{Ca}^{2+} \text{ as CaCO}_3] - 0.4;$$

$$\text{D} = \log_{10}[\text{alkalinity as CaCO}_3]$$

The potential for the occurrence of calcite scaling can therefore be compared on the basis of LSI values. A negative values implies that there is no potential to scale because the water will dissolve  $\text{CaCO}_3$ , a positive value implies that calcite scale can form from the precipitation of  $\text{CaCO}_3$ , while a zero value shows that the water is at the scaling borderline, and any changes in water quality of temperature, or evaporation could change the index.

#### a. Saturation Index (SI) method

The saturation index (SI) is the degree of saturation of minerals in aqueous solutions. It involves a comparison between ionic activity products and the thermodynamic activity product. This method involves the comparison of the calcium and carbonate ion activity product to the thermodynamic activity product [24]. The saturation index, SI is sometimes used to predict scales formation, and is given by;

$$\text{SI} = \log\left(\frac{Q}{K}\right) \quad (2.4)$$

Where:

Q is the calculated ion activity product, and

K is the equilibrium constant.

If SI is:

- Negative: under saturated water, no potential to scale, the water will dissolve  $\text{CaCO}_3$ ,
- Positive: supersaturated water, scale can form and  $\text{CaCO}_3$ , precipitation may occur
- Zero: Equilibrium, Borderline scale potential

### ***Sulphide scales***

In saline geothermal fluids or in fluids disturbed by the effects of volcanic gas sulphide deposits are prone to form by reaction of metal(s) with  $\text{H}_2\text{S}$ . In saline solutions these tend to comprise PbS (galena), ZnS (wurtzite, sphalerite), CuS (covellite),  $\text{Cu}_2\text{S}$  (chalcocite),  $\text{CuFeS}_2$  (chalcopyrite) and bornite ( $\text{Cu}_5\text{FeS}_4$ ) [19].

## **2.6 WATCH Software**

WATCH is a computer program intended to serve as a tool for interpreting the chemical composition of geothermal fluids. It however, can also be applied to non-thermal waters. The program reads chemical analyses of water, gas and steam condensate samples collected at the surface and computes the chemical composition of downhole or aquifer fluids. The composition and characteristics include; pH, aqueous speciation, partial pressures of gases, redox potentials and activity products for mineral dissolution reactions [25].

The program outputs component and species concentrations at the reference temperature, as well as the activity coefficients. Additionally, geothermometer temperatures, ionic balance, partial pressures of gases, and redox potentials are also output. Computation and printing of the ion activity products and solubility products of selected minerals is done, to enable the retrieval of the corresponding saturation indices [24].

The WATCH program can also be used to compute the resulting species concentrations, activity coefficients, and activity products and solubility products when the equilibrated fluid is allowed to cool conductively or by adiabatic boiling from the reference temperature to some lower temperature. This is particularly useful in the study of scaling [25].

## **2.7 Corrosion**

Corrosion is the natural process of deterioration of metals and alloys in a corrosive environment. Corrosion attacks in geothermal systems can lead to severe equipment damage

and failure. Production wells, steam and brine gathering systems, injection lines and wells are all subject to the extreme corrosion tendencies of geothermal steam and brine. In brines, corrosion occurs based on various mechanisms. These mechanisms are associated with species such as; chloride, hydrogen ions, carbon dioxide, sulphide, ammonia and oxygen. Additional factors that play a role in the rate of corrosion are temperature and fluid flow rate. The corrosive environments that brines create necessitate for materials that are able to withstand these environments for an economically viable period.

Temperature increase almost always results in an increase in the rate of corrosion, and so does increasing oxygen concentration, flow velocity and suspended solids. An increase in temperature increases the rate of kinetic reactions and enhances the rate of diffusion of many corrosive by-products, thereby increased rate of corrosion. The increases in the concentration of oxygen or other oxidizing agents such as chloride, bromide and the hydrogen ion lead to increases their rate of diffusion into a metal, hence enhancing corrosion rate. Fluid velocity has a complex relationship with rate of corrosion. Although the general rule is that higher flow velocities result in higher rates of corrosion, it is important to keep in mind that very low fluid velocities can heighten diffusion effects. Decreasing fluid pH generally increases the rate of corrosion, owing to the increase in the concentration of the aggressive hydrogen ion [26].

In geothermal systems, corrosion occurs in a variety of forms, these include [26] [27] [28];

1. **Uniform or general corrosion** is the uniform loss of metals across the entire metal surface and is generally due to chloride, ammonium and hydrogen ions. This type of corrosion accounts for the greatest loss of material, although it may not necessarily lead to severe material failure.
2. **Pitting corrosion** where pits are formed locally through the metal surface and often deepen due to breakage of a passive film. The main cause of this form of corrosion is the presence of chloride. Pitting can cause very high metal loss rates and leads to unexpected material failure. The resistance of a material to pitting corrosion can be assessed by use of the pitting resistance equivalent number which is calculated based on the alloy content of the material.

3. **Crevice corrosion** is similar to pit corrosion, however, it is dependent on geometry. Corrosion materials build up in the space of the crevice creating highly localized corrosion environment. It is commonly as a result of the presence of anions such as chloride, which promote hydrolysis reactions. It can be avoided by sealing crevices with flexible sealant or by using a corrosion resistant grade.
4. **Stress corrosion cracking (SCC)** occurs due to chloride ions and stress in the metallic material. It is a notorious type of corrosion and has an increased rate in the presence of oxygen and with increasing temperatures. Some of the typical applications where SCC can occur are swimming pools and hot water tanks. Another form of stress corrosion cracking is the Sulphur Stress Corrosion Cracking (SSCC) which is associated with the presence of hydrogen sulphide in moist environments. High strength steels are most susceptible to this.
5. **Hydrogen bubbling** occurs by the formation of fractures that result from the insufficient movement of hydrogen caught in vacancies in a metal. It commonly occurs due to the presence of low strength steels in aqueous solutions containing hydrogen sulphide.
6. **Intergranular corrosion** is a regional corrosion that occurs around the grain boundaries or in the neighbor grains of metallic materials, without affecting the grains. It is usually caused by wrong heat treatment of alloys in contact with brines and at temperatures between 450 - 850 °C.
7. **Galvanic corrosion** occurs by electrical conduction of two different metals connected in an electrolytic solution under the proper conditions. The alloy highest in the galvanic series will corrode fastest
8. **Fatigue corrosion** is a result of fluctuating stress in a corrosive environment. Fatigue corrosion limit is the largest stress under given conditions. The combined effect of fluctuation, stress and corrosion is much larger than the other simple effects.
9. **Erosion corrosion** is the abrasion of the metallic material by the striking of high velocity fluids to the hanging solid materials or particles. Metals exposed to this kind of corrosion do not form corrosion products on their surfaces, however, pits can be seen with the naked eye along the flow direction of the fluid.

10. **Cavitation** is a fast and regional decomposition around the metal surface caused by the exploding of steam bubbles.

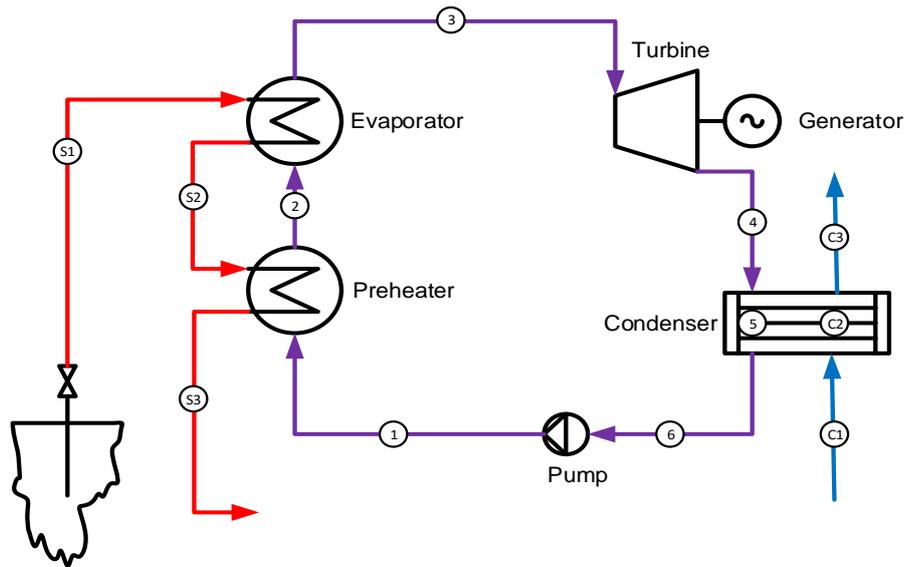
## **2.8 Binary Power Plants**

Geothermal fluid at temperatures of 150 °C and below are difficult to make use of both efficiently and economically in flash steam power plants. Binary power plants, however are widely used to generate power from these low to medium temperature sources.

### **2.8.1 The cycle**

In a binary cycle as illustrated in Figure 2.2, heat from the geothermal water is transferred to a secondary working fluid, usually an organic fluid with a low boiling point and high vapor pressure compared to water under the same temperature conditions. Such a system has the advantage of minimizing emissions to the atmosphere save for water vapor from cooling towers. Because there is no contact of the geothermal fluid with moving mechanical equipment of the plant, the equipment has longer life, and binary power plants can also be used where the chemistry of the geothermal fluid could pose utilization problems ([23]; [29]).

Brine specific consumption in geothermal binary plants is often higher than 50 kg/s per MW of electricity produced [29].



**Figure 2.2: Model of binary power plant showing location of the different components**

### 2.8.2 The working fluid

The choice of working fluid is a critical design decision and has great implications on the overall performance of a binary plant. Many working fluids exist giving the designer a range of choices. However, every working fluid has constraints relating to its thermodynamic properties and factors such as safety, health and environmental impacts.

Many of the suitable working fluids used in binary power plants have low boiling points, and critical temperatures and pressures lower than those of water. This makes them suitable as working fluids in geothermal systems, where the heat source is a saline mixture consisting majorly of water [23]. However, many such fluids that suit the thermodynamic requirement fall short in aspects of health, safety and environment. Some like fluorocarbons have a high ozone depletion potential, others like ammonia are toxic and generally, most of them are flammable making them capable of creating safety hazards. Care therefore has to be taken in the selection of a working fluid, with all the factors in mind.

The very low critical temperatures of some fluids allows them to work under supercritical conditions. This characteristic affects the appearance of the saturation curve which is one of the key parameters for determining a recovery cycle to match the working fluid. Two types of vapor saturation curves exist in the temperature-entropy (T-s) diagram fluids with negative slopes like isobutane and n-pentane, that can be termed as wet type fluids, and fluids like R134, propane and R152a with positive slopes. These fluids allow for

vapor expansion through the turbine along the sub-vertical line on the T-s diagram, the vapor remains saturated throughout the turbine and it is therefore not necessary to use a Rankine cycle with superheat [29]. Wet type fluids will however need a super heater so as to avoid excess moisture in the turbine exhaust.

## **2.9 Cocoa Drying**

Cocoa is majorly grown in developing countries, however, it is largely consumed in industrialized countries. Cocoa is usually sold as dried fermented beans for further processing. In some producing countries, however, cocoa is being processed as cocoa liquor, cocoa butter, cocoa cake or cocoa powder before exportation [30].

Cocoa fruits or pods weight on average 400g – 500g and each pod contains 30 – 60 beans ([31]; [32]). The cocoa bean (seed/cotyledon) contains approximately 32–39% water, 30–32% fat, 8–10% proteins, 2–3% cellulose, 4–6% starch, 4–6% pentosans, 2–3% sucrose, 5–6% polyphenols, 1% acids (mainly citric, oxalic, and malic acids), 1–3% theobromine, and 0.2–1% caffeine [33]. The size of the bean has been shown to vary among cocoa clones, with values ranging from around 0.5 to 2.0 g when dried beans were measured [31].

Cocoa pods are harvested and stored for a few days before they are split to extract the wet beans. The wet beans are then subjected to fermentation which varies depending on the variety and can last for about 5-8 days, with continuous turning after every three days [34]; [32]. Fermentation is done to kill the germ (embryo) of the bean and to develop the desired chocolate flavor. Fermentation plays a major role in the flavor of cocoa for the production of chocolates and other cocoa bean products. Oxidation processes during fermentation allow for the production of alcohol and acids which together with the increasing temperature create suitable conditions to kill the germs, cause breakdown of storage cells in the cotyledon and increase cell permeability [33]. The well fermented beans are then subjected to drying. A common method used is sun drying although artificial dryers are also used. The main two reasons for fermented beans are; to reduce the moisture content from about 40-65% to safe levels of between 4% and 8% for storage and shipment. The other reason is to allow the completion of the oxidation process that started during fermentation, hence reducing astringency, bitterness and acidity, while ensuring enhanced flavor and browning of the well fermented beans [33].

### **2.9.1 Theory of drying**

The simulation of various drying systems involves solving a set of heat and mass transfer equations which describe;

- a) Heat and moisture exchange between the seed and air,
- b) Adsorption and desorption rates of heat and moisture transfer,
- c) Equilibrium relations between seed and air, and
- d) Psychrometric properties of moist air.

Equations associated with group (a) are based on the governing laws of energy and mass conservation, and equations in group (d) are based on thermodynamic relations for mixing of dry air and water vapor. Equations in groups (b) and (c) are material dependent and their developments are based on experimental results [35].

The drying of cocoa beans is a function of two factors; transfer of heat into the cocoa bean to allow for the evaporation of moisture from the bean and the movement of vaporized moisture from some point within the bean to the surrounding air ( [35]; [36]). The drying rate is therefore determined by the slower of the two processes and has a great influence on the bearing on the flavor. The later process is often the slower one there by giving a rapid falling rate for beans freshly from the fermenter and later a lower rate with the same heat supplied and air flow conditions.

During drying, oxidative processes as well as loss of volatile acetic acid reduce acidity. Rapid drying at temperatures above 60°C may arrest the oxidative changes due to inhibition of enzymatic activities; hence this reduction in acidity is prevented. Rapid drying can also result in case/testa hardening of the bean surface thereby creating a semi-impermeable cap that prevents the outward migration of moisture and loss of acetic acid still trapped within the bean [35].

The drying rate also affects the browning of the cotyledons. This is done through the reactions of polyphenol oxidase which requires oxygen; very high drying temperatures result in adherence of the cotyledon to the testa which limits oxygen transport for the oxidation reactions for anthocyanins and catechins.

The most important factors that govern artificial drying of cocoa are the:

1. Difference in temperature between the drying air and the product,
2. Difference in vapor pressure between the air and that of the product,
3. Surface area of the product exposed to the air, and
4. Velocity of the drying air.

Using a temperature of about 60 °C and a high air volume are used, nib shrinkage during the early stages of drying is minimal. This gives structural support to the skin which does not collapse [33].

### **3 POTENTIAL GEOTHERMAL FIELDS**

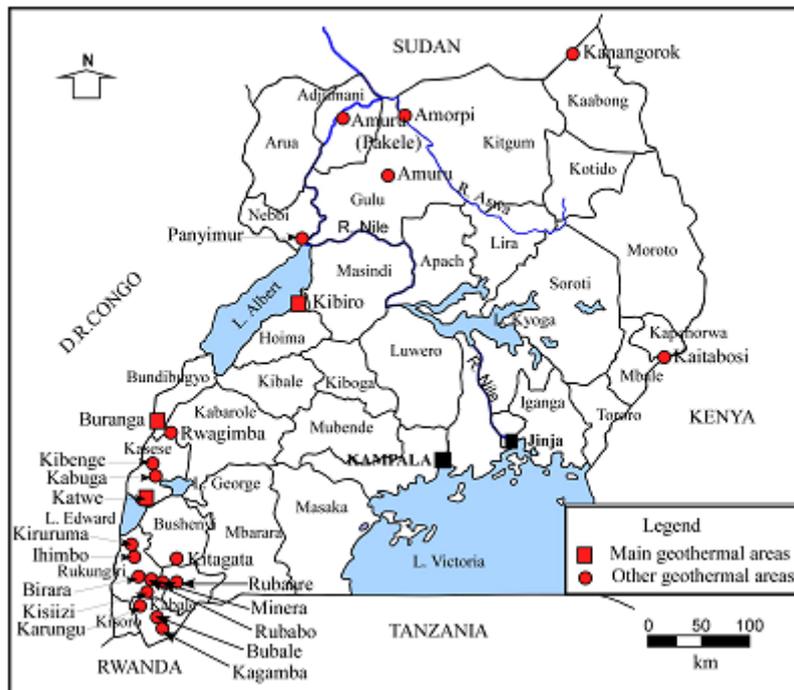
#### **Outline**

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### 3.0 Introduction

Geothermal potential has been observed in many parts of Uganda. Most of these lie within the western branch of the East African Rift System that runs for most of its length along the border of Uganda with the Democratic Republic of Congo (DRC). The Western Rift valley is marked by intensive faulting, often accompanied by volcanic and seismic activities [37].

Exploration of geothermal energy in Uganda has been ongoing since the 1950s. Some of the sites that have aroused interest include; Buranga in Bundibugyo, Kibiro in Hoima, Katwe in Kasese, Rubaane in Ntugamo, Panyimur in Nebbi, Kitagata in Bushenyi, Ihimbo in Rukungiri and Kanangorok on Kaabong and can be located in the Figure 3.1 below.



**Figure 3.1: Geothermal areas in Uganda**

*Source: Bahati, G. (2003)*

### 3.1 Buranga

The Buranga geothermal prospect is located in Bundibugyo and Ntoroko districts at the north-western base of the Rwenzori Mountains in the Western Rift Valley. The two districts lie at the border with the Democratic Republic of Congo. While Bundibugyo district is predominantly an agricultural area, Ntoroko district is dominated by pastoralism. The two

districts are also engaged in fishing on Lake Albert and River Semuliki [39]. Buranga field falls in the Semiliki National park which is an area of national importance for nature and landscape conservation and natural heritage preservation with ecologically viable units.

### **3.1.1 Fluid temperature**

Buranga has got a number of hot springs which served as some of the key features of the presence of geothermal activity, of these, three are of key note. Firstly, the Nyansimbe spring that has developed a carbonate cone with clear pool of hot water at a temperature of 86°C. The pool has a diameter of 30 m; depth is more than 5 m and a flow rate of 15 l/s. Secondly are the Mumbuga springs (Figure 3.2) in an area of 60 x 40 m, and have a flow rate of 6.5 l/s and temperatures reaching 98.4°C. All the springs deposit carbonates and one spring has built a 1.5 m tall travertine cone with terraces. Water here is bubbling and emanating gases. Lastly, the Kagoro springs which span an area of 50 x 15 m enclosed by rainforest and have water temperatures of 60 - 91° C. These springs have also built up to 1.5 m high travertine cones and have sulphur deposits at the base of the largest cone [40].



**Figure 3.2: Mumbuga erupting springs, Sempaya hot springs**

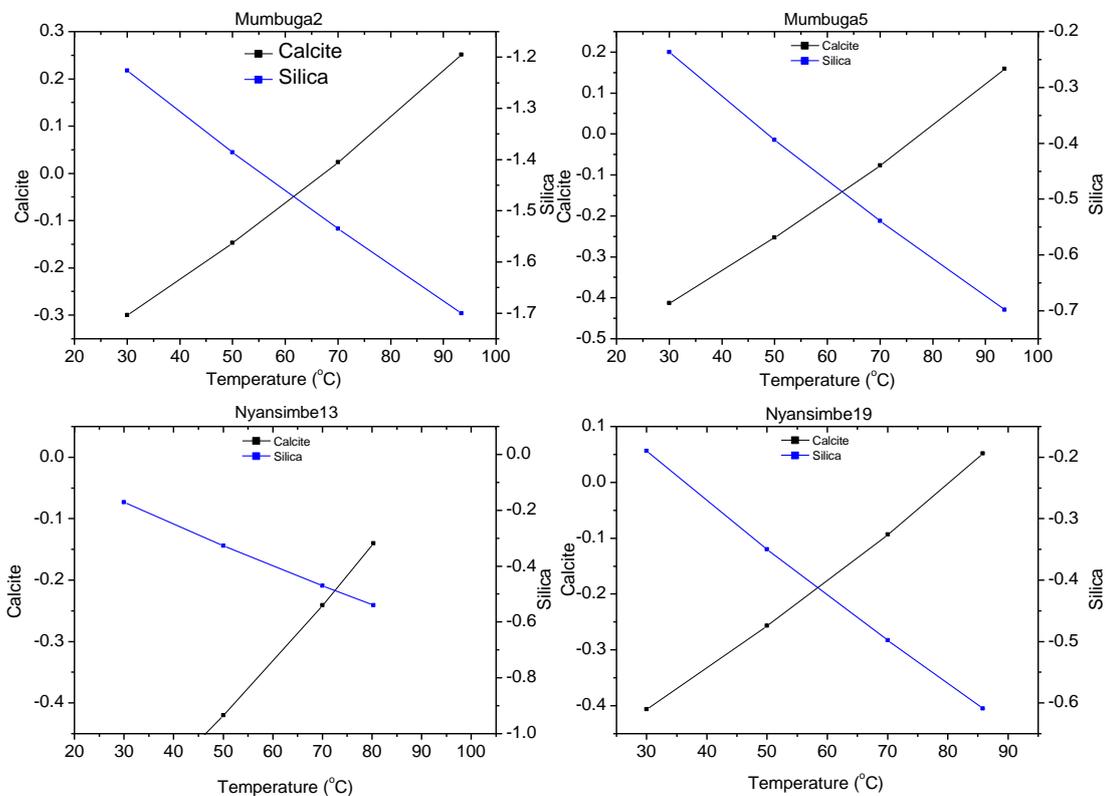
*Source: Unknown. (2011)*

Following the application of geology, geophysics, geochemistry and temperature gradient measurements at the site, the subsurface fluid temperatures have been estimated to be between 120 – 150 °C through geothermometry [39]. Isotope hydrology suggests that recharge of the thermal fluids is from high ground in the Rwenzori Mts. TEM and MT

geophysical surveys at Buranga geothermal prospect have located resistivity anomalous areas up to 3000 m below sea level with a major anomaly close to the hot springs [37]

### 3.1.2 Geochemistry

The pH of the fluids is almost neutral ranging from 7.5 – 8.6. There is plentiful supply of fluid, which is fairly saline with total dissolved solids of up to 14,000 - 17,000 mg/kg as shown in Table A.1 in Appendix A. Gas analysis of the samples did not show presence of hydrogen sulphide; this indicated that the subsurface temperature cannot exceed 200°C [37]. The chemistry also shows no indications of mixing of the geothermal and cold water. This fluid would be suitable for binary power production and industrial use.



**Figure 3.3 : Graphs showing the calcite and silca scaling potensions for select locations in the Buranga geothermal prospect**

The Buranga waters were assessed for scaling by assessing the available geochemical data using WATCH software. The highest value obtained was 0.251 for the SI for calcite with the Mumbuga2 sample and -0.171 for SI value for silicate with the Nyasimbe13 sample (Figure 3.3 above). These results therefore imply that there exists no threat of calcite scaling even with cooling to temperatures of as low as 30 °C.

Observation of the data was used to assess the potential for corrosion during use of the Buranga waters. It was observed that, although the pH of the fluid is considerably high and carbonate at considerably low levels, the presence of chloride in values above 1, 000 mg/kg raises some concern for corrosion and therefore, material selection should be done carefully to prevent corrosion occurrences.

### 3.1.3 Market status

The main economic activity in Ntoroko district is livestock rearing; cattle, goats, sheep and chickens are the major animals kept. Crop farming and fishing are also practiced in the region. Crops cultivated are mainly cassava, maize and cocoa. Fishing along the Semiliki River and from Lake Albert is a common practice. Livestock and crop farming is still under traditional practice in the district and marketing is still substandard due to a number of factors including poor roads, which hinder mobility. [41]. The area however faces floods in the rainy season and droughts in the dry season.

**Table 3.1: Status of crop production in Bundibugyo**

<b>Crop</b>	<b>Acreage (Ha) 2008/9</b>	<b>Yield (MT) 2008/9</b>	<b>Yield estimate 2012</b>	<b>Remarks</b>
Cocoa	4, 741	15, 000	18, 000	Increased 20%
Cassava	7, 784	23, 144	21, 040	Decreased 10%
Beans	2, 502	3, 650	3, 318	Decreased 10%
Banana (Eating)	4, 752	22, 092	11, 000	Decreased 57%
Banana (Beer)	386	1, 090	654	Decreased 40%
Banana (Sweet)	37	752	75	Decreased 70%
Sweet Potatoes	1, 168	3, 380	3, 314	Decreased 2%
Soya beans	568	440	440	Static
Rice	110	71	28	Decreased 60%

*Source: Lutheran World Relief (U) (2015)*

Bundibugyo district has a population of over 200, 000 people. The district has crop farming as the main economic activity with emphasis on food crops such as: sorghum, maize, finger millet, pigeon peas, groundnuts, sunflower, sweet potatoes and beans. Cash crops include: cocoa, vanilla and palm oil, whereas tomatoes, cabbages and onions make the biggest portion of the vegetables. Bundibugyo district is Uganda's largest producer of cocoa. Fishing is also practiced on lake Albert and tourism at the Semliki national park, the hot springs, the Semliki wild reserve and the pygmies near Ntandi. Table 3.1 above gives

the actual and estimated yields of different crops commonly grown in Bundibugyo district for the years 2009 and 2012 respectively.

Bundibugyo district is a major cocoa producing area with 85% of the farmers engaged in cocoa growing [42]. Cocoa can be harvested throughout the year and only the amount will rise or fall depending on the season [43]. Harvesting usually begins when there is a sufficient number of ripe pods to start fermentation. The frequency of harvesting depends on the crop and increases during the peak periods of pod production [44]. The bimodal rainfall pattern in Uganda allows for two major harvesting periods each year. The rainy seasons are the months of March to May and August to November, while the dry spells occur in the months of June to July and November to January. Harvesting commences 2 weeks after the on-set of rains and peaks one and a half months after. It is done over a period that overlaps part of the dry season, and goes on for approximately 3 months. [32]. The cocoa harvesting seasons are March, April, July and October to December [45].

**Table 3.2: Cocoa bean exports: 2003 – 2011**

Year	Volume (metric tons)	Value (USD)
2003	4, 328	7, 001, 000
2004	5, 155	6, 801, 000
2005	7, 600	9, 638, 000
2006	7, 632	10, 016, 000
2007	9, 404	15, 936, 000
2008	8, 982	22, 834, 000
2009	11, 882	27, 829, 000
2010	14, 529	35, 123, 000
2011	16, 478	52, 700, 000
2012	18, 000	55, 000, 000

*Source: Lutheran World Relief (U) (2015)*

Cocoa is an internationally traded commodity and nearly all cocoa beans produced in Uganda are exported. In the recent years, the world price of cocoa has fluctuated between USD 2, 500 to USD 3, 000 per metric ton. Although the price has currently dropped to about USD: 2,700 per metric ton as a result of exceptionally good weather in the major cocoa growing countries in the last 18 months, it is still considered profitable for cocoa growers. Local farm-gate prices in Uganda currently range from UGX 4,200 /kg – 7,000/ kg for dry cocoa with 7.5 -7.8 moisture content [30]. The Table 3.2 is a representation of the annual

production and income from the sale of cocoa over a period of 10 years. Ugandan cocoa is reputed to have special aromatic properties that are favored by chocolates manufacturers. This increases the demand of Ugandan cocoa by the large chocolate companies that manufacture special flavor chocolates and makes it a favorable economic venture.

Some of the probable geothermal uses in this region are; binary power plant, cocoa drying, fish drying, milk pasteurization and a geothermal spa.

## **3.2 Kibiro**

The Kibiro geothermal prospect is located on a small peninsula in Lake Albert under the Rift Valley escarpment in Hoima district [37].

### **3.2.1 Fluid temperature**

“The Kibiro prospect has a relatively simple geologic structure and waters indicative of subsurface temperatures of above 200°C suitable for conventional electricity production” [38]. The recharge of the thermal fluids in Kibiro is from Mukihani-Waisembe Ridge in Kitabo subcounty.

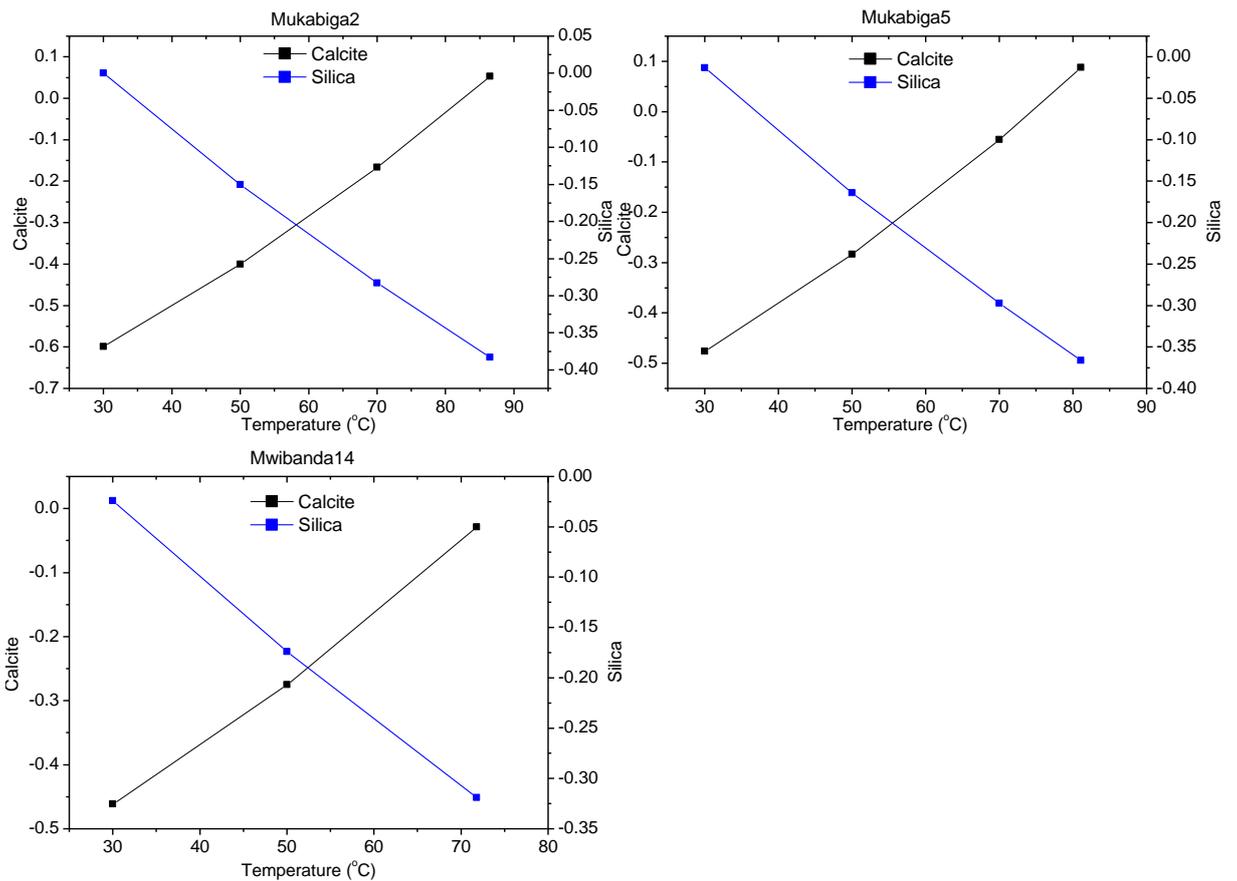
### **3.2.2 Geochemistry**

The chemistry of the surface fluids from Kibiro suggests a mixture of thermal and cold waters, this is likely to pose some challenges during utilization [37]. The pH of the fluids is in the range of 6 to 8, and salinity of up to 4,000 - 5,000 mg/kg total dissolved solids are exhibited. Geothermometry and mixing models predict a reservoir temperature of 200°C and above for Kibiro. Table A.2 in Appendix A shows the geochemical data used.

The potential for the occurrence of scaling owing to the chemistry of the waters at this prospect was assessed using WATCH software. All samples gave values of SI for calcite of less than 0.3 except Muntere15 and L.Albert with values of 0.401 and 0.864 in Table 3.3 below, whereas for silicate, the values were generally below zero. Values of SI for calcite above 0.3 for the mentioned samples do not however pose a threat for calcite scaling given the low sampling temperatures below 40 °C (Figure 3.4 below). Concerning corrosion however, careful consideration ought to be taken in material selection owing to the corrosion threat from the high concentrations of chloride especially in the higher temperature samples analyzed.

**Table 3.3 : Additional values for calcite and silica scaling potention for other locations in the Kibiro prospect**

Location	Temperature	Calcite	Silica
Muntere15	39.5	0.401	-0.064
	30	0.364	0.01
L. Albert	30	0.864	-2.457
Wantembo	29.8	-0.118	-0.151
Kiganja1	23.6	-2.047	-0.207
Ndalagi1	24.9	-0.346	-0.187



**Figure 3.4 : Graphs showing the calcite and silica scaling potentions for select locations in the Kibiro geothermal prospect**

### 3.2.3 Market status

Hoima district has a population of over 300, 000 inhabitants. It has agriculture as the main economic activity with emphasis on food crops such as: sorghum, maize, finger millet, pigeon peas, groundnuts, sunflower, sweet potatoes and beans. Cash crops include: cocoa, vanilla and palm oil. Vegetables include; tomatoes, cabbages and onions. Fishing is also practiced on lake Albert.

Although the prospect is not located in Masindi district, it has a very close proximity to it and the district is therefore also being considered within this section. The major economic activities carried out in high rainfall zones of the district include: pit-sawing especially in Budongo Forest, as well as the growing of crops such as maize, cassava, sugar cane, tobacco and bananas. This has contributed to increased household incomes enabling the population to sustain their livelihoods. Similar activities are carried out in areas receiving medium rainfall. The major activities carried out in low rainfall zones are pastoralism, fishing and cotton growing [46].

**Table 3.4: Showing Acreage and Productivity of some selected crop enterprises in Hoima district**

<b>Selected enterprise</b>	<b>Present productivity (kg/acre)</b>	<b>Mean productivity (kg/acre)</b>	<b>Ideal productivity (kg/acre)</b>	<b>Projected target in 5 yrs (kg/acre)</b>
Rice	1,646	1,275	2,550	2,000
Maize	681	800	1,600	1,500
Cassava	2,000	5,000	10,000	2,700
Pineapples	3145	3,145	10,000	4,423
Bananas	500	3,000	6,000	862
Beans	350	450	900	550
Groundnuts	450	500	1,000	700
Sweet potatoes	2,100	2,500	5,000	3,000
Millet	600	900	1,800	1,000
Coffee	1,500	1,000	2,000	2,000
Cocoa	400	450	900	550
Cotton	1,200	750	1,500	1,500

*Source: DDP2 (2015)*

The region has the capacity to apply a number direct use geothermal applications such as: coffee, cotton, cassava or pineapple drying, drying of timber, greenhouses and spa in addition to electricity generation from a single-stage flash or two stage flash or a binary power plant.

### 3.3 Katwe

The Katwe geothermal prospect is situated in the Katwe-Kikorongo Volcanic Field (KKVF), south of the Rwenzori massif in Kasese district. It is bordered by the Lake Edward and Kazinga Channel to the south and to the east by Lake George. The prospect stretches from Lake Katwe to Lake Kikorongo and is bordered to the south by Lake Edward and the Katwe – Katunguru road, to the west by River Nyamugasani, to the north by the Kikorongo – Bwera road and to the east by the Katunguru – Kasese road [37]. The prospect occupies an area of approximately 150 km<sup>2</sup> [47].

#### 3.3.1 Fluid temperature

Fluid temperature estimates from reliable geothermometry are between 160 – 220 °C [37]. Temperature gradients in the range of 30 – 36 °C/km were established through temperature gradient drilling and measurements. They also suggested that the geothermal reservoir is either deep seated or offset from the drilled area [37]. Thermal fluids recharge is from high ground in the Rwenzori Mts. for Katwe. According to [38], the size of the volcanic field at Katwe, the high subsurface temperature of about 160-200°C, as well as various geological observations and proximity to the national grid make the prospect attractive for electricity production.

#### 3.3.2 Geochemistry

The chemistry of the surface fluids from Katwe suggests pH in the range of 6 to 9, and very high salinity of up to 25,000 - 30,000 mg/kg total dissolved solids are exhibited (see Table A.3 in Appendix A). The waters are classified as mature waters owing to the higher concentrations of Cl compared to the SO<sub>4</sub> and HCO<sub>3</sub> concentration.

WATCH software was used to assess the potential for scaling over different cooling temperatures and the results showed no potential for silica scaling. However, some of the samples, specifically L. Kitagata1 and L. KitagataW show potential for calcite scaling with cooling.

Saturation index values for calcite are as high as 1.1, even with temperatures as high as 60 °C (Table 3.5 below and Figure 3.5 below). It should also be noted that for these samples, the concentrations of CO<sub>2</sub> in mg/kg are in the tune of 10, 000 mg/kg which give a good

correlation with the WATCH results. There exists a potential for corrosion owing to the considerably high chloride values. However, this threat is not as great as that for calcite scaling; and when compared with Buranga and Kibiro, the threat of corrosion is considerably lower.

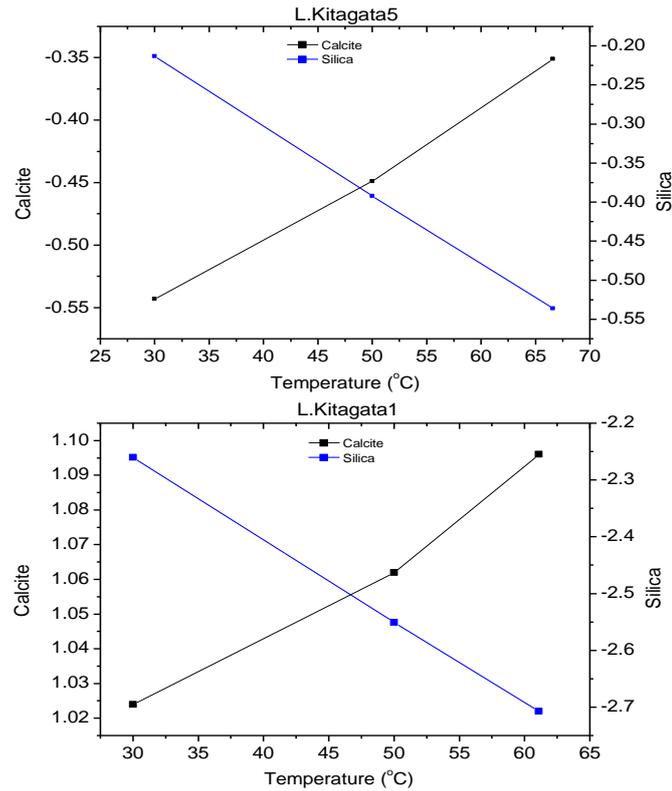
**Table 3.5 : Additional values for calcite and silica scaling potentio for other locations in the Katwe prospect**

Location	Temperature	Calcite	Silica
L.Katwe	28.6	-0.445	-0.633
L.Katwe6	28.5	-0.412	-0.93
L.Nyamunu1	27.5	-0.367	-0.978
L.Edward1	23.3	0.719	-0.812
Katunguru1	26.6	0.612	-0.353
	30	-0.543	-0.213
L.Kitagata2	56.6	-0.316	-0.325
	30	-0.491	-0.111
KazingaCh	26.2	0.365	-0.755
L.KitagataW	36	1.087	-0.606
	30	1.082	-0.512
L.KatweW	28	0.974	-0.777

### 3.3.3 Market status

The prospect is located in Kasese district in western Uganda. The district has a population of over 700, 000 people whose main economic activities are crop production, animal grazing, brick making, timber harvesting and charcoal making. The main cash crops grown include: coffee growing Robusta and Arabica, passion fruit, cotton, pineapple and mangoes while the major food crop grown is maize grown in the Kitwsamba-Hima area. Other food crops include beans, Irish potatoes, cassava, millet, groundnuts, sweet potatoes and soya beans.

Mining, tourism, fish farming and industry are the other areas of economic activity. Some of the mineral resources mined in the region include: copper, cobalt, cement and lime, and salt. Tourism is made possible by the presence of numerous wildlife species, national parks and bird sanctuaries, while industry includes cement production and agro processing. According to [48], there is one agro processing plant found in Kasese Town Council called Reco Industries Ltd and it deals in the production of fruit juice, chilli sauce, pepper, and other products.



**Figure 3.5 : Graphs showing the calcite and silca scaling potensions for select locations in the Katwe geothermal prospect**

Salt production is one of the major economic activities in Kasese district. [49] infers that Lake Katwe has the capacity to sustain a plant for over 30 years at 40,000 tons/annum NaCl production from its reserves of 22.5 million tons of crystalline salts. The lake contains the best salt reserves in Uganda which are believed to come from a salty volcanic rock and brought into the closed crater by saline springs around the edge of the lake which discharge water adding about 2,000 tons of salts to the lake each year. Although no comprehensive record keeping exists at the site, annual production at the lake is put at close to 15,000 tons/year.

A number of geothermal direct use applications can utilize the geothermal resource at Katwe, these include; salt extraction, geothermal spa, coffee drying, timber drying, waste water treatment in addition to electricity generation for a binary or two stage flash power plant.

### 3.4 Panyimur

Panyimur Geothermal Resource Area (PGRA) is one of the low temperature geothermal fields that are found in the Western arm of the East African Rift system. The Panyimur hot springs are divided into three hot springs which include Amoropii, Okumu and Avuka. All three lie on the Rift Valley escarpment. They extend in a northwesterly direction and are likely to be controlled by a major boundary fault [50]. The hot springs are located on escarpment front just near the shores of Lake Albert, in Panyimur sub-county, Nebbi District.

#### 3.4.1 Fluid temperature

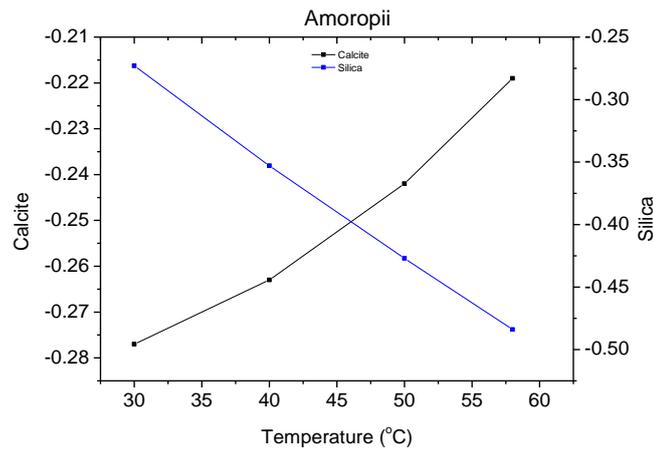
Geothermometry using reliable silica and Na/K geothermometers has given subsurface temperature estimates of 80 - 120°C. The presence of hydrogen sulphide however suggests that the source might be hotter than predicted by geothermometry [10].

#### 3.4.2 Geochemistry

The fluids are slightly above neutral with a pH of 7-9 and low salinity of 300-900 mg/kg total dissolved solids. The presence of hydrogen sulphide in Avuka (6.1 ppm), Okumu (10.7 ppm) and Amoropii (12.0 ppm) hot spring waters indicates that the source of heat could be magmatic [47] and, therefore, the possibility of a high subsurface temperature in the area. However, there exists a possibility of contamination of the thermal waters with cold ground water owing to the high magnesium concentration.

**Table 3.6: Additional values for calcite and silica scaling potential for other locations in the Panyimur prospect**

Location	Temperature	Calcite	Silica
Okumu	45	0.052	-0.406
	30	0.001	-0.288
Avuku-1	35	-0.586	-0.418
	30	-0.638	-0.379



**Figure 3.6 : Graph showing the calcite and silica scaling potential for Amoropii in the Panyimur geothermal prospect**

The samples for the Panyimur prospect were assessed for scaling potential using WATCH software. The results gave negative values for SI for silicate and values of SI for calcite below 0.2 (see Table 3.6 above and Figure 3.6 above). This therefore implies that there is no potential for either silica or calcite scaling. The potential for corrosion is also considered to be low owing to the high pH values and very low chloride values.

### 3.4.3 Market status

The main economic activities in Nebbi district are crop agriculture, animal husbandry and fishing. Some of the crops grown include; coffee, maize, tea, cotton, cassava, millet, sorghum, simsim, pineapples, tomatoes, cashew nuts, okra, to mention but a few. Fishing is done on lake Albert and in the Albert Nile and is practiced widely for subsistence and commercial purposes. The common fish caught are the Nile perch (*Lates Niloticus*) and Tilapia (*Oreochromis Niloticus*). The region also prides in production of honey, and hosts a modern honey processing factory.

Some of the possible uses of geothermal heat in this region include; coffee, maize and/or fish drying as well as honey processing.

### 3.5 Rubaare

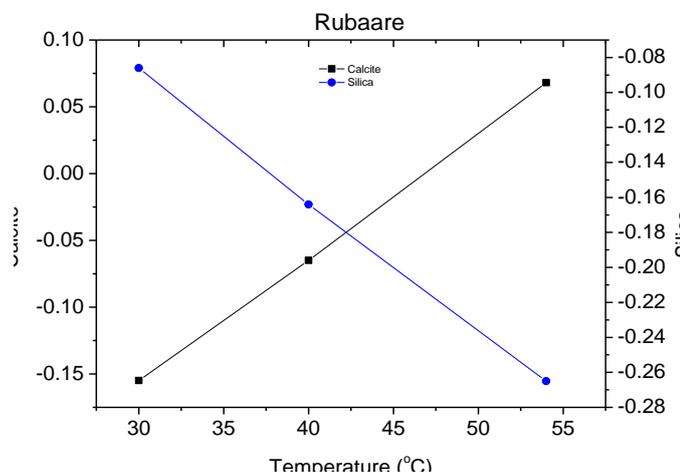
The geothermal area is located in Rugarama sub-county, Rushenyi county in Ntungamo District.

### 3.5.1 Fluid temperature

The subsurface temperatures at Rubaare are estimated to be 134 - 140°C based on reliable Na/K and silica geothermometers [10]. Rubaare seems to be recharged at moderate altitudes although not locally and permeability is considered to be good [10]

### 3.5.2 Geochemistry

The waters of Rubaare have a neutral pH of 7.52 and low total dissolved solutes of 800 mg/kg. The magnesium concentration is high in most of the samples suggesting a substantial influence of cold groundwater.



**Figure 3.7: Graph showing the calcite and silica scaling potential for the Rubaare geothermal prospect**

Following the analysis of the available geochemical data in WATCH, no possibility of either silica or calcite scaling were observed. There were no values above 0.3 in both cases as can be seen in Figure 3.7 above. It is also expected that there will be no major challenges with corrosion owing to the low concentrations of chloride and high pH of the representative sample.

### 3.5.3 Market status

The major crops grown include banana, coffee, pulses (beans and peas), cereals (millet, maize and sorghum), potatoes and vegetables. Banana production is a major economic activity in this area and takes up a considerable area of cultivated land.

Tourism in Ntungamo District is not well developed but there are several potential tourism sites, including: the Karegyeya Rock, Lake Nyabihoko, the Uganda-Rwanda Border and bird-watching in the wetlands.

Possible direct use geothermal applications include: matooke and/or millet drying and a geothermal spa as well as electricity generation from a binary power plant.

### **3.6 Kitagata**

Kitagata geothermal area is located in Kitagata subcounty, Igara county, Bushenyi district. It is situated on Ishaka - Kabale road at a distance of approximately 16 km from Ishaka town and 0.8 km from Kitagata trading center.

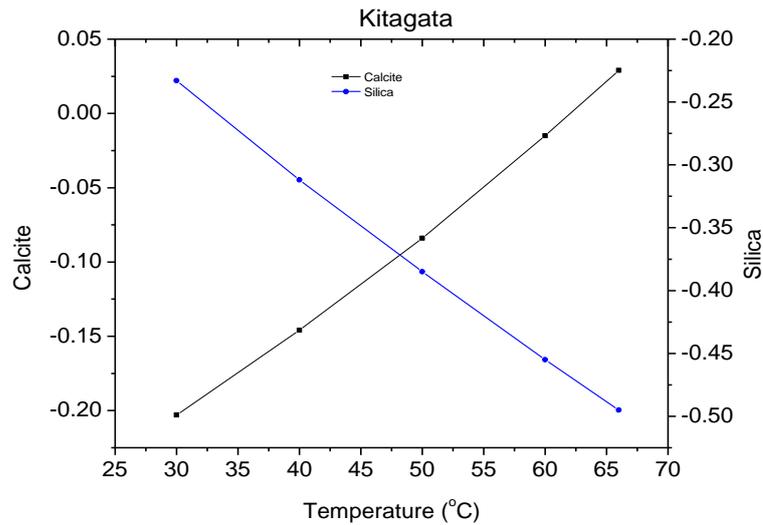
#### **3.6.1 Fluid temperature**

The subsurface temperatures are estimated at 120 - 140°C based on reliable Na/K and silica geothermometers [10]. Like Rubaare, the Kitagata geothermal prospect seems to be recharged at moderate altitudes although not locally [10] and have a permeability which is considered to be good.

#### **3.6.2 Geochemistry**

The pH of the waters is 7.92, which lies within in the neutral range and the total dissolved solids reach 552 mg/kg.

WATCH analysis based on the chemical composition of the sample for this prospect showed that there is neither silica nor calcite scaling anticipated with the use of this geothermal fluid from this prospect (Figure 3.8 below). Corrosion is also not expected to be a challenge in this prospect due to the high pH and low chloride concentrations as observed in the chemical data available.



**Figure 3.8: Graph showing the calcite and silica scaling potential for the Kitagata geothermal prospect**

### 3.6.3 Market status

Bushenyi district has a land area of 3, 949 square kilometers and lying between 910 and 2,500 meters above sea level. The main physical features include natural tropical forests of Karinzu and Imaramagambo covering an area of 784 km which serve as tourist attractions. The district’s main economic activity is agriculture. Bushenyi is well known for the growing of bananas and dairy farming, however, coffee and tea are also grown on a considerably large scale. The people are also involved in semi-intensive agriculture, trade and commerce, transport, stone quarrying, sand mining, mineral mining, construction, tourism, and lumbering.

Electricity generation using a binary power plant is possible in this region, in addition to direct uses including: drying of millet and of bananas, commonly called matooke, milk pasteurization, geothermal spa and timber drying.

### 3.7 Ihimbo

Ihimbo geothermal area is located in Bwambara sub county, Rujumbura county, Rukungiri district. The geothermal area is situated in Ihimbo forest at a distance of about 1.5 km from the Rukungiri - Kihigi road via Bugangari, Bwambara and Nyamirama and about 2 km from River Ntungwa, River Birara being its main tributary.

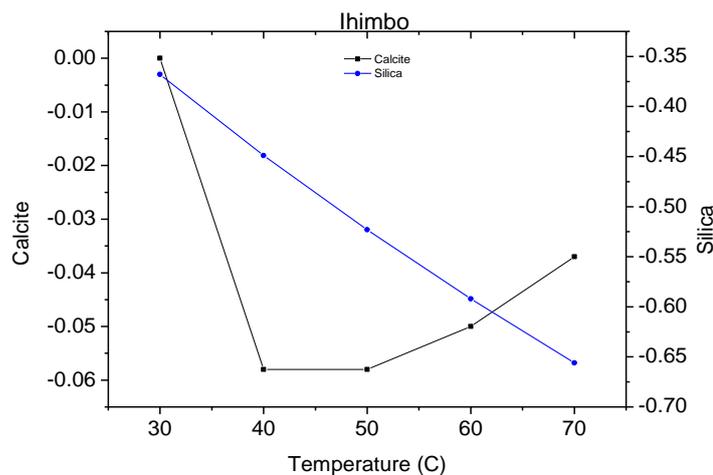
### 3.7.1 Fluid temperature

Using reliable Na/K and silica geothermometers, the temperatures are estimated to be 80 – 100°C [10]. The presence of hydrogen sulphide however suggests that the source might be hotter than predicted by geothermometry. Ihimbo seems to be recharged at moderate altitudes although not locally [10]

### 3.7.2 Geochemistry

The Ihimbo waters have a high pH of about 9.2 and a low salinity of 444 mg/kg of total dissolved solids.

The WATCH results for Ihimbo showed no possibilities for either silica or calcite scaling given that the SI values were well below 0.3. The chemistry shows really low chloride concentrations and a high pH, this implies that corrosion will not be a challenge during the use of this geothermal fluid.



**Figure 3.9: Graph showing the calcite and silica scaling potential for the Ihimbo geothermal prospect**

### 3.7.3 Market status

The main economic activity in Rukungiri district is agriculture, however, production is mainly subsistence although the potential for intensive commercial farming exists. The two chief cash crops are coffee and matooke. Due to its altitude, Rukungiri District is ideal for cultivation of all crops including temperate fruits. Thus in many sub counties there are successful farmers engaged in the production of grapes, apples, pears and peaches. The district also has some of the best dairy farms in the country especially in the sub counties of

Kebisoni and Buyanja. About 3.52 million liters of milk are produced in the district annually.

A number of people also derive their livelihood from fishing, particularly from Lake Edward. Fish farming is also practiced by some families and fish processing takes the forms of; smoking (598,272 kg), salting (435,107 kg) and frying (54,388.4kg). The district also has very scenic views and a number of tourist attractions including; Bwindi impenetrable forest national park, Queen Elizabeth national park, Kisizi falls, Ilimbo and Minera hot springs.

Some of the potential direct uses for this region include; drying of coffee and matooke, milk pasteurization and geothermal spa.

### **3.8 Kanangorok**

Kanangorok geothermal area is located in the Kidepo Valley National Park, Kaabong district near the border of Uganda, Sudan and Kenya. This area is located 9 km south of Mt. Lotuke that marks the border of Uganda and Sudan.

#### **3.8.1 Fluid temperature**

Kanangorok is considered to be a promising area owing to permeability and subsurface temperatures of 140 - 160°C with reliable Na/K and silica geothermometers [10].

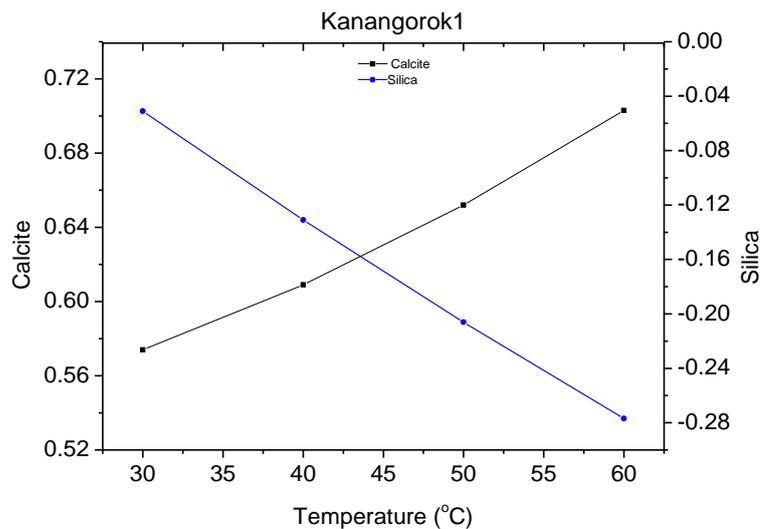
#### **3.8.2 Geochemistry**

The pH of Kanagorok waters is slightly high at 8.44, with a relatively low salinity of about 830 mg/kg. The magnesium concentration is high in all of the samples suggesting a substantial influence of cold groundwater.

**Table 3.7: Additional values for calcite and silica scaling potential for other locations in the Kanangorok prospect**

<b>Location</b>	<b>Temperature</b>	<b>Calcite</b>	<b>Silica</b>
Kanangorok-2	42	0.568	-0.109
	30	0.532	-0.014
Kanangorok-BH	38	0.595	-0.08
	30	0.574	-0.016

Following assessment for scaling potential using WATCH, the chemical analysis of the water samples gave values of SI above 0.3 for cooling temperatures as high as 60 °C (Table 3.7 above and Figure 3.10 below). The waters of Kanangorok therefore pose a high challenge of calcite scaling during use. The samples showed low concentrations of chloride, about 97 mg/kg, and the high pH values. This shows that the potential for corrosion is very low. However, due to the high potential for calcite scaling, careful system design and material selection have to be done for sustainability of the system.



**Figure 3.10: Graph showing the calcite and silica scaling potential for Kanangorok1 in the Kanangorok geothermal prospect**

### 3.8.3 Market status

Agriculture is the major economic activity in Kaabong district. The majority of farmers are small holders who grow both perennial and annual crops. The perennial crops include Banana, Coffee, and Tea, while the annuals include maize, sweet potatoes, beans, cassava and groundnuts [51]. Animal husbandry is the main economic activity in the district. A great majority of the district population are nomadic pastoralists who roam the landscape looking for grass and water for their animals. Due to severe climatic conditions, agriculture is not widely practiced.

Some of the possible uses of geothermal heating in this region include; electricity generation using a binary power plant and direct applications such as; maize drying and milk pasteurization may be possible. However, development of such projects may be

difficult because of the nomadic nature of the inhabitants, thereby rendering most of the projects closet to the unfeasible scale than the feasible one.

### **3.9 Other prospects**

There exist a number of other prospects that would be suitable for study in the future. These include; Birara (140 - 160°C), Minera (120 – 130°C) and Rubabo (120 –140°C) whose subsurface temperature predictions using the silica and Na/K geothermometers are in agreement [10].

## **4 POTENTIAL GEOTHERMAL DIRECT USE APPLICATIONS**

### **Outline**

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## **4.0 Introduction**

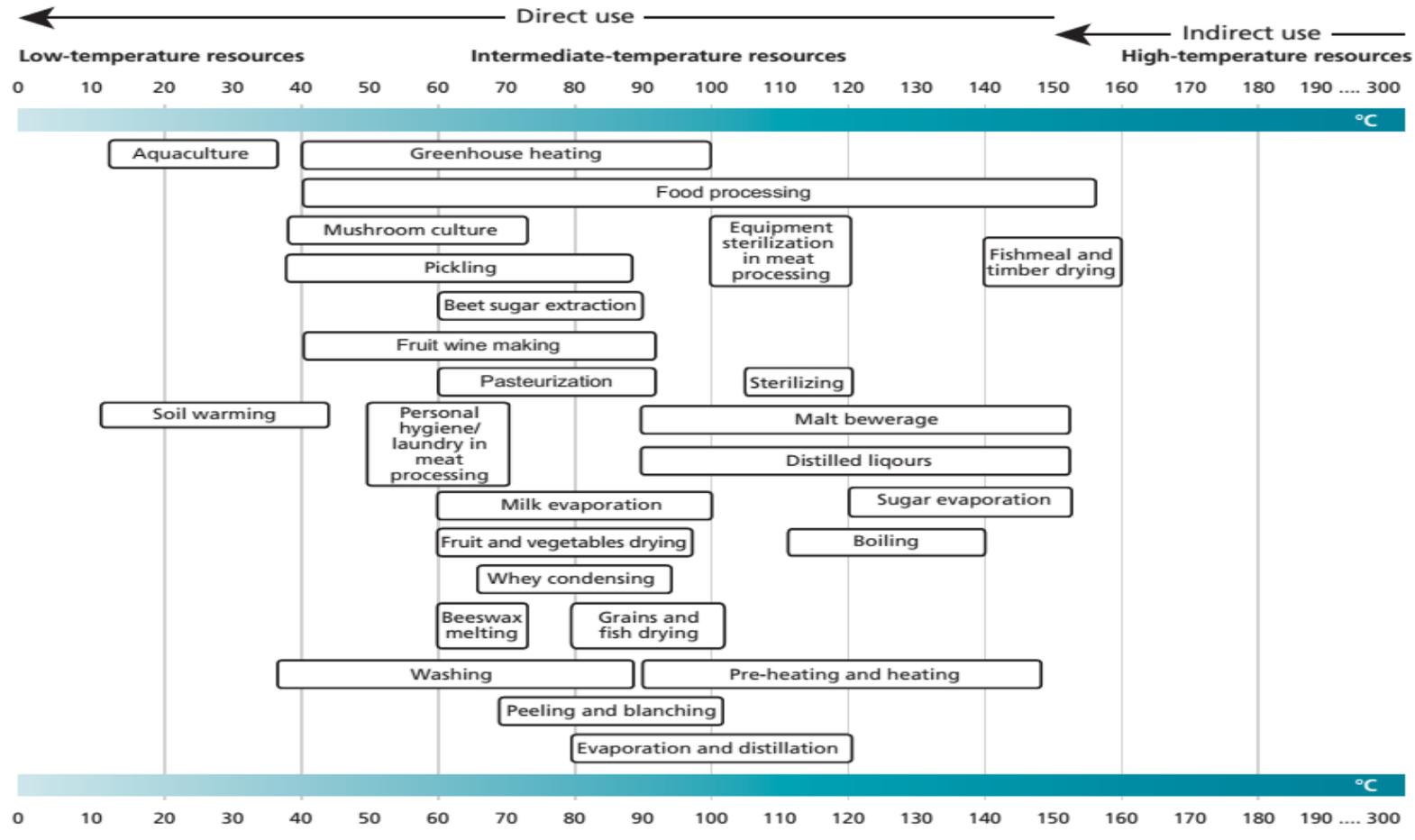
The direct use of geothermal resources is the application of the heat energy or the fluid from geothermal resources without an interfering medium, as would be the case if it first converted to other forms of energy such as electrical energy (Chatenay, 2014). Most direct use applications can be applied for geothermal fluids in the temperature range of 30 - 150°C. Utilization of low temperature geothermal resources has for centuries been applied in many parts of the world. The oldest known application being bathing in the geothermal fluid, which was later followed by application in space heating and farming. Most of the fields used for direct applications can hardly be utilized for power generation in steam turbines and in some cases binary plants, mainly due to economic reasons.

The fundamental principle used in geothermal direct use applications is that, heat naturally flows from a region of high temperature to that of low temperature. This principle is dependent on the existence of a temperature difference; the greater the difference in temperature between the two points, the greater the heat flow. According to [52], two primary temperature differences govern feasibility, flow requirements and design of direct use projects, and these are: the difference between the;

1. Temperature of the geothermal fluid entering the system and the desired process temperature. This difference determines whether or not an application will be feasible. The fluid temperature entering the system needs to be sufficiently high to allow the system to be constructed with reasonably sized heat transfer equipment. The greater the temperature difference between the geothermal resource and the process, the lower the cost of heat exchange equipment.

2. Temperature of geothermal fluid entering the system with that leaving the system. This difference is critical in determining the flow rate necessary to meet the heat input requirement of the application. The greater the temperature difference between the entering and leaving temperatures, the lower the geothermal flow required. The process temperature plays a role since the leaving geothermal temperature cannot be lower than the process temperature to which it is providing heat.

The Lindal diagram in Figure 4.1 below shows some of the direct use applications for geothermal heat based on fluid temperature.



Source: P.G. Pálsson, 2013.

Figure 4.1: Lindal diagram showing possible direct uses and corresponding temperature range

Source: CGS (n.d)

## **4.1 Agricultural Drying**

Agricultural drying is a process which involves deliberate removal of moisture from a product. Various agricultural products such as vegetables, fruits, fish, coffee, cocoa and tobacco are being dried using open-air drying technique. In Uganda, owing to the tropical climate, this process is often done by open-air sun drying, a process that is slow, wasteful and affected by seasonal changes, however, this is usually on a small scale. At an industrial scale, electricity is used as a heat source, but this is a very costly method, therefore, most industries opt for the more affordable option of using fuel wood as the heat source.

Drying of agricultural produce is advantageous in that; it increases the shelf life of products, minimizes costs of transportation, handling and storage, maintains the main calorie-providing constituents, provides a consistent product and makes packaging and disposal economical. There is a broad range of products that can be dried; vegetables, fruits, grains and others each of which has specific temperature requirements. The basic energy requirements involve heating the product to suitable temperatures in order to initiate the process of evaporation of the moisture and energy necessary to evaporate certain percentage of the moisture.

Drying of agricultural products using geothermal energy has reported applications in fifteen countries as of 2015 compared to 13 in 2010 and 15 in 2005. A broad range of agricultural products can be dried using geothermal heat including: seaweed (Iceland), onions (USA), wheat and other cereals (Serbia), fruit (El Salvador, Guatemala and Mexico), Lucerne or alfalfa (New Zealand), coconut meat (Philippines), and timber (Mexico, New Zealand and Romania). A total of 161 MW<sub>t</sub> and 2,030 TJ/year are being utilized, an increase of 28.8 % and 24.2% respectively compared to WGC<sup>2</sup> 2010 [3].

The basic requirements for designing a dryer system include air as the drying fluid, heat exchangers, a geothermal source, pre-drying and post-drying processes and dryer design.

### **4.1.1 Factors affecting quality dried product**

**Humidity ratio:** the ratio the mass of water in a sample to the mass of dry air.

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<sup>2</sup> WGC – World Geothermal Congress

**Moisture content:** the moisture content of most agricultural products is often given on a wet basis, however, this is liable to changes owing to fluctuations in moisture content through absorption or evaporation. In cases where a constant benchmark is required, dry basis weight is used.

$$m = \frac{m_w}{m_w + m_d} = \frac{m_w}{m_t} \quad (4.1)$$

$$M = \frac{m_w}{m_d} \quad (4.2)$$

Where:

- m = decimal moisture content wet basis (wb)
- M = decimal moisture content dry basis (db)
- M<sub>d</sub> = mass of dry matter in the product
- m<sub>w</sub> = mass of water in the product
- m<sub>t</sub> = total mass of the product, water plus dry matter

**Water activity:** The amount of water in food and agricultural products affects the quality and perishability of these products. However, perishability is not directly related to moisture content. In fact, perishability varies greatly among products with the same moisture content. A much better indicator of perishability is the availability of water in the product to support degradation activities such as microbial action [53]. Water activity indicates the amount of water available in a product.

$$a_w = \frac{P_w}{P_{ws}} \text{ or } a_w = \Phi \text{ where } \Phi = \frac{P_w}{P_{ws}} \quad (4.3)$$

Where:

- Φ = relative humidity, decimal
- P<sub>w</sub> = partial pressure of water vapor at the specified conditions
- P<sub>ws</sub> = partial pressure of water vapor at saturation and the temperature specified

**Drying rate:** moisture is removed from the drying product in two separate phenomena; firstly, through movement from the interior of the material to its surface by either capillary action (in the initial stages) or diffusion (in the later stages) and secondly, evaporation of water vapor from the surface of the material into the air [53]. The rate of drying is dependent on a number of factors such as; nature of the material, shape, size and arrangement of the

pieces in dryer, air temperature, air velocity, relative humidity, and partial pressure of water vapor. Drying rate can generally be expressed as:

$$\text{Drying rate, } N = - \frac{m_d}{A} \frac{dM}{dt} \quad (4.4)$$

Where A is the evaporation area in m<sup>2</sup> and t is time in hours.

#### 4.1.2 Geothermal heat requirement

The heat energy from geothermal is equivalent to the heat supplied by the air. Therefore, the amount of geothermal supplied, W<sub>G</sub> can be obtained by:

$$W_G = q_a \cdot c_w \cdot (T_{in} - T_{out}) \quad (4.5)$$

Where:

W<sub>G</sub> = total amount of geothermal utilized in kg

T<sub>in</sub> = Inlet temperature of geothermal fluid into the heat exchanger

T<sub>out</sub> = Exit temperature of geothermal fluid from the heat exchanger

The mass flow rate of geothermal fluid, m<sub>G</sub> in kg/s is given by:

$$m_G = \frac{W_G}{3600 \times t} \quad (4.6)$$

[54].

#### 4.1.3 Mechanism of drying

When hot air is blown over wet food, heat is transferred to the surface and latent heat of vaporization causes water to evaporate. Water diffuses through a boundary film of air and is carried away by the moving air. This creates a region of lower water vapor pressure at the surface of the food, and a water vapor pressure gradient is established from the moist interior of the food to the dry air. This gradient provides the driving force for water removal from the food.

There are two main drying rate regimes for agricultural products, namely the constant drying rate period and the falling drying rate period. The constant rate drying period is where moisture removal with respect to time is constant, usually very brief if it exists. Capillary movement of water from the interior equals to evaporation rate from the surface, and the surface temperature is maintained at wet-bulb temperature. the end of the constant rate and

beginning of falling rate is called the critical moisture content. During the falling rate drying period, the drying rate slowly decreases until it approaches zero, at the equilibrium moisture content of the drying air. The rate of water movement to the surface is less than the evaporation from the surface, the surface becomes drier than the interior forming a crust and the temperature of the product increases.

#### **4.1.4 Dryer design types**

The type of dryer used for drying is dependent on the item to be dried, the desired characteristics and physical form of the dried product, as well as the operation costs. There exist many dryer designs with classifications ranging from whether they are active or passive, size of particles, source of heat, direction of flow.

## **4.2 Aquaculture**

Aquaculture or aqua farming is the raising of aquatic animals such as fish, crustaceans, mollusks and aquatic plants [20]. The farming activities are practiced under controlled conditions so as to enhance the growth rate of the animals or plants. The most common species raised are catfish, bass, tilapia, sturgeon, shrimp, and tropical fish. The use of geothermal resources in aquaculture depends on the type of aquatic animals raised, the quality of water and its composition. The geothermal fluid is in general used directly in the pond or pool to provide the heat required. Heat exchanger might be required if the geothermal fluid is unfit for the aquatic animals raised.

According to [3], worldwide use of geothermal energy in aquaculture experienced an increase amounting to 6.7% in installed capacity to 695 MW<sub>t</sub> and 2.7% in annual energy use to 11,958 TJ/yr. in 2015 from 2010. The leading countries in terms of annual energy use continue to be USA, China, Iceland, Italy and Israel. Tilapia, salmon and trout seem to be the most common species, but tropical fish, lobsters, shrimp and prawns, as well as alligators are also being farmed.

### **4.2.1 Typical temperature requirements**

The most important factors in determining the source geothermal temperatures for an aquaculture farm are the optimum growth temperatures for fish species to be grown and the climate of the region. The climate of a region will affect the rate of evaporation and

convection from the pond, these two are the main areas of heat loss. Covering of the ponds with a plastic bubble can go a long way in minimizing evaporative heat losses while construction of the ponds in such a way that the long axis of the pond is perpendicular to the prevailing winds will minimize on convective heat losses thereby reducing the overall geothermal heat requirement. Ponds require geothermal water of 38 to 66 °C and a peak flow of 10 to 25 l/s for 0.2 ha of uncovered surface, depending on the climate [15]. The ponds are normally constructed of excavated Earth, this can result in seepage losses depending on the soil type, however, lining of the walls with clay or plastic where necessary can prevent seepage losses. Table 4.1 below gives some of the commonly farmed fish species and their temperatures for optimum growth.

**Table 4.1: Temperature requirements and growth periods for selected aquaculture species**

Species	Tolerable extremes (°C)	Optimum growth (°C)	Growth period to market size (months)
Oysters	0 - 36	24 - 26	24
Lobsters	0 - 31	22 - 24	24
Penaeid shrimp			
Kuruma	4 - ?	25 - 31	6 - 8 typically
Pink	11 - 40	22 - 29	6 - 8
Salmon (Pacific)	4 - 25	15	6 - 12
Freshwater prawns	24 - 32	27 - 30	6 - 12
Catfish	17 - 35	27 - 29	6
Eels	0 - 36	23 - 30	12 - 24
Tilapia	8 - 41	22 - 30	-
Carp	4 - 38	20 - 32	-
Trout	0 - 32	15	6 - 8
Yellow perch	0 - 30	22 - 28	10
Striped bass	? - 30	16 - 19	6 - 8

*Source: Rafferty (1995)*

Although the use of geothermal heat in aquaculture has experienced growth over the years, its viability for application in the tropical regions is limited to those with average temperatures of below 25 °C. Most of the aquaculture species farmed have optimum growth temperatures that are normally experienced within the tropics, and being natively tropical, they will grow and develop in these regions with minimal need (if any) for the supply of geothermal heat.

#### **4.2.2 Design considerations**

In most geothermal applications, the maximum heat available from the resource restricts the maximum pond area that can be developed [55]. Aquaculture ponds are uncovered bodies of water, and they exchange heat with the atmosphere by four mechanisms; evaporation, radiation, convection and conduction, each mechanism affecting different parameters.

*Evaporation losses* are the largest component of heat loss from the pond and can have some evident effects on the loss of volume. The rate at which evaporation occurs is a function of air velocity and the pressure difference between the pond water and the water vapor in the air (vapor pressure difference). As the temperature of the pond water is increased or the relative humidity of the air is decreased, the evaporation rate increases.

*Convective losses* are a function of wind velocity and temperature difference between the pond surface and the air over the pond. The shape of the pond also has influence on convective losses and these are usually 25 percent lower for very large ponds [55].

*Radiative losses* are primarily dependent on the temperature difference between the surrounding air temperature and the pond surface temperature. Although radiant heat exchange is often considered to be between solids without taking into account the air in between them, there comes a time when the air above the pond contains a large quantity of water such that the pond surface radiates to the water vapor in the air which is assumed to be at the temperature of the air itself.

*Conductive losses* are associated with the walls of the pond. They are the smallest of the four losses and may be neglected in many calculations without detrimental effects. According to ASHRAE 1985, the following method is valid for a pond depth of 0.9 to 1.5 m.

## Flow requirements

This is a function of the temperature difference between the pond water and the resource temperature. The flow rate,  $\vartheta$  can be calculated from the equation:

$$\vartheta = \frac{Q_{\text{tot}}}{15,040 \times (T_r - T_w)} \quad (4.7)$$

Where:

$\vartheta$  = resource flow requirement (l/s)

$Q_{\text{tot}}$  = total calculated pond heat loss (kJ/h). It is the sum of evaporative, convective, radiative and conductive heat losses.

$T_w$  = pond temperature ( $^{\circ}\text{C}$ )

$T_r$  = resource temperature ( $^{\circ}\text{C}$ )

In cases where the resource temperature is at levels too high to be added directly into the pond, and there is an available supply of cold water; the resource water can be mixed with cold water before it is added to the pond, or have some pond water recirculated. This quantity can be determined by the equation:

$$\vartheta_c = \vartheta_h \frac{(T_h - T_m)}{(T_m - T_c)} \quad (4.8)$$

Where:

$\vartheta_c$  = Required cold flow rate (l/s)

$\vartheta_h$  = Hot water flow rate (l/s)

$T_h$  = Temperature of hot water ( $^{\circ}\text{C}$ )

$T_c$  = Temperature of cold water ( $^{\circ}\text{C}$ )

$T_m$  = Temperature of desired mixed water ( $^{\circ}\text{C}$ )

## 4.3 Greenhouses

Geothermal energy has seen extensive use in the area of greenhouses across the world. Values on the amount of geothermal energy used in green houses and covered ground heating globally have seen an increase in 2015 from figures in 2010 with a 19% increase in installed capacity to 1, 830 MW<sub>t</sub> and 16% increase in annual energy use to reach 26, 662

TJ/yr. The leading countries in annual energy use are: Turkey, Russia, Hungary, China and Netherlands [3].

Greenhouse heating is one of the most common applications of geothermal energy in agriculture. It is being applied on a large scale in many countries and enables the cultivation of flowers and vegetables in unnatural conditions or out of season. A greenhouse is aimed at creating a protected space for plant cultivation in a controlled environment.

#### **4.3.1 Parameters for plant development**

The key parameters for the development of plant life are: light, temperature, carbon dioxide concentration and water. A green house should be able to provide these within the optimum ranges so as to enable proper plant growth and good yield. In order to make light available greenhouses are made from transparent material such as; glass, plastic films, and plates, fiberglass, and others [15]. The choice of the construction material is a critical factor in determination of the total heating requirements of the greenhouse. Some of the common materials used and their characteristics are detailed as follows;

1. **Glass:** this is the most expensive material to use for greenhouse construction owing to the cost of glazing material and the need for a strong support framework. Glass has superior light transmission properties that make it suitable for plants that require high light intensities. However, it has a poor energy efficiency owing to its poor insulation quality of single glazing and high infiltration of cold air through many “cracks” in construction hence making the heating requirements rather high. Double glazing panels have been introduced to counter this problem, however, they are expensive and had a lower light transmission ability hence most glass greenhouses remain single layer.
2. **Fiberglass:** this is similar to glass in terms of mode of construction although they require less structural support due to its low weight. Fiberglass has a lower conductivity than glass hence require less heating although the difference is quite small compared to that in glass.
3. **Plastic film:** the use of plastic film is a more recent variation in greenhouse construction. Plastic films are lighter than glass and fiberglass and are almost always used in arched roof design constructions. They however require high maintenance

and frequent replacement depending on the quality of the material. The continuous nature of the plastic film minimizes infiltration of cold air into the greenhouse through the elimination of “cracks”. Often times, plastic film greenhouses employ a double layer of film separated by air space; this increases energy efficiency because it reduces transmission losses through the walls and roof by 30 to 40%.

It is not advisable to invest in expensive installations so as to meet the peak heat demand as this only occurs for a very short period within the year [15].

#### 4.3.2 Design considerations

A geothermal greenhouse is almost always located close to the geothermal source for economic reasons. The cost is a great advantage of the geothermal greenhouse. The initial construction costs are almost independent of the heating energy but the operating cost is usually incomparably cheaper in geothermal greenhouses.

##### *Transmission pipelines*

The choice of pipeline diameters is based mainly on two factors, the pressure drop in the pipes and the water velocity. First of all, a diameter is suggested and the factors are evaluated. The water velocity is designated as:

$$\mathbf{u} = \frac{m_v}{A} \quad (4.9)$$

Where:

- $u$  = water velocity [m/s];
- $m_v$  = Volumetric flow rate [ml/s];
- $A$  = Cross-sectional area of the pipe [m<sup>2</sup>]

The pressure drop is calculated as:

$$\Delta P = L \frac{f}{D} \rho \frac{u^2}{2} \quad (4.10)$$

Where:

- $\Delta P$  = pressure drop (Pa)
- $L$  = pipeline length (m)
- $f$  = friction factor

- D = pipe diameter (m)  
 $\rho$  = density of water (kg/m<sup>3</sup>)

The friction factor for turbulent flow in rough pipes is approximated by:

$$f = 0.0055 \left[ 1 + \left( 20000 \frac{k}{D} + \frac{10^6}{Re} \right)^{1/3} \right] \quad (4.11)$$

Where:

- k = pipe roughness  
 Re = Reynolds number

### ***Heating requirements***

The first step to selecting a heating system for a greenhouse is to determine the heating requirements. This is done by considering the heat losses from the structure which are categorized into: (a) transmission losses through the walls and roof, and (b) infiltration and ventilation losses caused by the heating of cold outside air. The total heat loss (in W) from a greenhouse is therefore given by:

$$Q = Q_T + Q_I \quad (4.12)$$

Where:

- $Q_T$  = Transmission losses through the roof and the walls (W);  
 $Q_I$  = Infiltration and ventilation losses due to the heating of cold outside air (W).

The transmission losses are evaluated by first calculating the surface area of the structure. This surface area is probably subdivided into various materials used and thereafter combining this value with the design temperature difference and a heat loss factor for each, which is the reverse of the overall thermal resistance as follows:

$$Q_T = Q_{Troof} + Q_{Trest} \quad (4.13)$$

Where:

- $Q_{Troof}$  = Transmission heat losses through the glazing-covering material [W];  
 $Q_{Trest}$  = Transmission heat losses through the side walls and end walls [W];

The design temperature difference is a function of: (a) design inside temperature which is the temperature to be maintained inside the space (it is dependent on the temperature requirement for the crop to be grown), and (b) design outside temperature which is considered to be the temperature that is valid for all except 22 hours per year during the heating season.

For greenhouse design, infiltration is generally analyzed via the air change method which is based upon the number of times per hour that the air in the greenhouse is replaced by cold air leaking in from outside. The number of air changes which occur is a function of wind speed, greenhouse construction and inside and outside temperatures. Air change values can be obtained from tables as shown in the appendix. If artificial ventilation is required in excess of infiltration, this should be added to the peak load. The infiltration losses  $Q_I$ , are determined based on the equation:

$$Q_I = 0.018 \times ACN \times V \times (T_i - T_o) \quad (4.14)$$

Where:

ACN = expected air changes per hour

V = inside volume of the greenhouse

#### 4.4 Apiculture and Honey Processing

The deliberate rearing of honey bees for the production of honey and other bee products. Bee keeping can serve not only as a source of income but the intake of honey has numerous benefits. Honey serves as a source of natural antioxidants that are effective in preventing deteriorative oxidation reactions in foods. It is also responsible for increasing serum capacity, total plasma anti-oxidation capacity and total plasma reducing capacity in humans [56].

##### 4.4.1 Products from beekeeping

Bee keeping gives a wide range of products including: comb honey (chunks of honey-filled combs taken directly from the hive), extracted honey (the extracted liquid portion), chunk honey (a combination of comb honey and extracted honey bottled together), beeswax (used in the manufacture of cosmetics, candles, foundation sheets (for hives), medicines, polishes, etc.), royal jelly (a substance secreted by worker bees to feed the queen), bee pollen (which contains up to 35% protein and can be eaten dry or added to other foods), and

propolis (a resin that bees collect from plants and use it to cover the inside of the hive. It has some therapeutic and antibiotic characteristics).

#### **4.4.2 Honey processing**

Thermal processing of honey eliminates the microorganisms responsible for spoilage. Unprocessed honey contains extraneous matter such as pollen, bits of wax variable amounts of sugar-tolerant yeasts, and potentially, crystals of dextrose hydrate. It is of necessity to remove these substances from extracted honey to make it marketable on a large scale. Honey with a very high moisture content is prone to fermentation, recommended moisture content is below 17%. Granulated honey is more prone to fermentation than liquid honey, however, most honey has a tendency to crystallize with time unless measures are taken to prevent this. Commercial honey processing includes controlled heating to destroy yeast and dissolve dextrose crystals, combined with fine straining and pressure filtration [56].

A number of methods exist for heating of honey to high enough temperatures to kill yeasts or to delay granulation, these include; conventional heating, microwave heating, infrared heating, ultrasound processing and membrane processing [57]. Nearly all changes to honey are a function of temperature and time, and low temperatures over a longer time period could have a similar result as higher temperatures with shorter time periods [58]. Some of the possible temperature and time combinations applied include; 65.6 °C for 30 s, 82.2 °C for 10 to 12 s, and 85 °C for 4 to 5 minutes [56]. The rate at which honey is cooled, whether rapidly or slow natural cooling after heating is also a major factor in quality of the honey ( [58]; [56]). Rapid cooling after heating to high temperatures is usually desirable. The effect of heat is cumulative, therefore, the effects of both processing and storage of honey ought to be considered together [56].

#### **Extraction**

The honeycombs are inserted into an extractor, a large drum that employs centrifugal force to draw out the honey. Because the full combs can weigh as much as 5 lb (2.27 kg), the extractor is started at a slow speed to prevent the combs from breaking. As the extractor spins, the honey is pulled out and up against the walls. It drips down to the cone-shaped bottom and out of the extractor through a spigot. Positioned under the spigot is a honey

bucket topped by two sieves, one coarse and one fine, to hold back wax particles and other debris. The honey is poured into drums and taken to the processing facility [59].

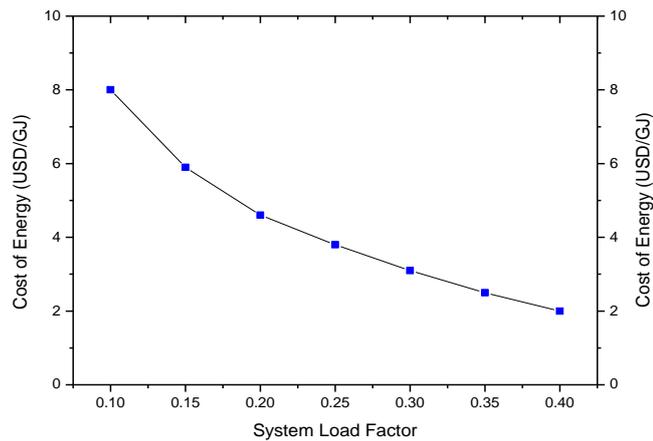
### **Production Process**

The processing of honey involves three major stages; filtration, heating and cooling. During the filtration stage, the extracted honey is first heated to 45 °C (which is below the melting point of beeswax) so as to decrease its viscosity. The foreign particles, pollen and wax are then filtered out. The honey is then heated to 60 °C - 65 °C for 10 to 15 min in order to kill the yeasts present and then passed into a falling film evaporator. Vacuum is simultaneously applied to boil the water in honey at a lower temperature so that moisture is separated which can be collected separately. This procedure also helps in destroying yeasts thereby preventing fermentation. Proper temperature and control and heating time is a most important factor in honey processing activity. Finally, the honey is cooled to atmospheric temperature and stored in closed vessels for 24-48 hours to rid it of air bubbles before it is packed and sealed.

## **4.5 Industrial Uses**

There is a broad range for application of geothermal energy in industrial process, however, only 15 countries worldwide are recorded to make use of this resource in industry. The installed capacity is 610 MW<sub>t</sub> and the annual energy use is 10,453 TJ/yr, an 18% increase and a 12% decrease compared to 2010. Examples include: concrete curing (Guatemala and Slovenia), bottling of water and carbonated drinks (Bulgaria, Serbia and the United States), milk pasteurization (Romania and New Zealand), leather industry (Serbia and Slovenia), chemical extraction (Bulgaria, Poland and Russia), CO<sub>2</sub> extraction (Iceland and Turkey), pulp and paper processing (New Zealand), iodine and salt extraction (Vietnam), and borate and boric acid production (Italy) [3].

Heat use for the industrial processes has one of the highest capacity factors of all direct uses because of almost year-around operation. Although this capacity factor has seen a fall of 0.54 in 2015, down from 0.70 in 2010, it is not clear the reason for this fall, and it may be due to more efficient operations and use of energy, or to fewer operating hours per year [3]; [60]. The high load factors in industrial applications reduce the cost per unit of energy used as is shown in Figure 4.2 below.



**Figure 4.2: Load factor versus cost of energy**

*Source: Lund (2010)*

The most important energy considerations for an industrial complex are the cost, quality, and reliability. Geothermal energy may be attractive to an industry provided: (a) the cost of energy/kg of product is lower than that presently used, (b) the quality of geothermal energy is as good or better than the present supply, and (c) the geothermal energy will reliably be available for the life of the plant. Reliability and availability can only be proven by long-term use or testing [15].

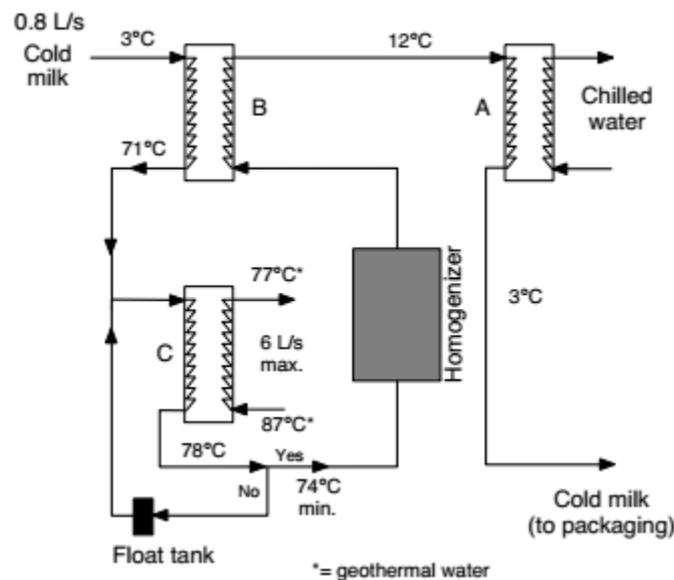
In some situations, where available geothermal fluid temperatures are lower than those required by the industrial application, the temperature can be raised by means of integrating thermal systems such as; boilers, upgrading systems, heat pumps, and others. In designing geothermal energy recovery and utilization systems, two main approaches are used. The more usual approach for utilization of geothermal fluid by proposed industries is to fit the industry to the available fluids. The alternate approach however, is to fit the available fluids to proposed industries; although, this approach requires developing ways to economically upgrade the quality of existing geothermal fluids or the fluids derived from them.

The basic processes in industrial application that require thermal energy in the temperature range of up to 150 °C include: preheating, cooking, blanching, peeling, sterilizing, drying, washing, evaporating, distilling and separating as well as refrigeration. In this section however, focus will be placed on the processes in the milk industry, although various other opportunities for industrial application do exist, such as; leather industry and textile dyeing.

### 4.5.1 Milk pasteurization

Pasteurization of milk is the process of heating milk to a required temperature so as to preserve it by slowing the growth of bacteria. *Mycobacterium tuberculosis* and *Coxiella burnetti* are the two major bacteria targeted by the pasteurization process.

Pasteurization can either be carried out as a batch operation or as a continuous process. The batch or LTLT (low temperature, long time) pasteurization process involves holding the product in an enclosed tank and heating it. The continuous operation (also known as HTST – high temperature, short time) has the product heated in a heat exchanger and then held in a tube for the required time. In order to satisfy the minimum pasteurization conditions, every particle of the milk has got to be heated; this is achieved by ensuring turbulent milk flow in the heat exchangers as well as heating milk to about 72 °C for 15 second in HTST pasteurization or 63 °C for 30 minutes in LTLT pasteurization [61].



**Figure 4.3: Medo-Bel milk pasteurization flow diagram**

*Source: Lund, 2010*

The process involves preheating of cold milk from the homogenizer in one section of the heat exchanger from temperatures of 3 °C to about 70 °C. In the second section, geothermal fluid is used to heat the milk to a minimum temperature of 78 °C for 15 seconds in a short time pasteurizer. The system is usually automated to ensure that the milk is recirculated if the temperature drops below 74 °C in order to ensure that the required exposure is obtained. Properly pasteurized milk is then passed through a homogenizer and

pumped back via the first heat exchanger so as to cool the milk to about 12 °C by the incoming cold milk. The milk is finally chilled to about 3 °C before being fed into cartons for packaging [62].

## **4.6 Geo-Bio Synergy**

Development in the global concerns relating to climate change have necessitated that new forms of energy be explored, one of which is the use of bioenergy in more efficient ways. Bioenergy is considered to be a carbon neutral energy, however, the process of harnessing it has the capacity to leave a noticeable carbon footprint. Many modern bioenergy forms such as biodiesel, bioethanol and biogas require a measure of heat during their production, this makes geothermal a suitable candidate for the supply of this heat.

### **4.6.1 Biogas production**

Anaerobic digestion is a process by which environmentally hazardous organic wastes from municipal, agricultural and industrial sources may be stabilised. The treatment has many side benefits, most notably the production of methane-rich biogas which can be used to generate electricity and heat. The process is performed by a consortium of micro-organisms which break down organic matter in the absence of oxygen thereby producing methane and carbon dioxide. Methods such as; aerobic digestion, direct application to land and combustion are alternative ways of dealing with organic wastes. These methods either utilize the available biomass as a fertiliser or a fuel, but not both as is the case with anaerobic digestion [63]. The use of anaerobic digestion is however not as widespread as the other options.

Three types of anaerobic digestion process can be identified [64]; [65]:

- **Psychrophilic Digestion:** the digester is usually beneath the ground in tropical areas. The digester temperature is maintained at temperatures of 15 - 25°C. Retention times are often longer than in other digester process types.
- **Mesophilic Digestion:** The digester is heated to 30-40°C and the feedstock remains in the digester for 15-30 days. Mesophilic digestion process tends to be more robust than the thermophilic process but produces less biogas.

- **Thermophilic Digestion:** The digester is heated to 55 - 60°C and the residence time is typically 12-14 days. Thermophilic digestion offers higher methane production and leads to greater pathogen removal than mesophilic digestion.

Anaerobic digestion occurs in two stages each consisting two processes. The first stage involves the conversion of the organic substances to hydrogen, carbon dioxide and volatile fatty acids (VFAs) by acidogenic bacteria, and the next, the conversion of VFAs into mainly carbon dioxide and methane by acetogenic and methanogenic bacteria [66]. Detailed expositions on the four biological processes that occur during anaerobic digestion, hydrolysis, acidogenesis, acetogenesis and methanogenesis can be found in ([67]; [68]), and a comparison of anaerobic digestion for the vegetable fraction of municipal waste under mesophilic and thermophilic conditions can be found in [69].

Anaerobic digestion requires stringent control of a number of parameters that determine the optimum performance of the process. These parameters are:

- **pH:** this should be kept majorly neutral, within a range of 6.5 to 7.5. changes in pH can affect metabolic rates of the bacteria thereby decreasing methane production.
- **Temperature:** temperature within the digester is critical to the amount of methane gas produced as the methane producing bacterial are very sensitive to temperature changes. For each 20°C decrease in temperature, the gas production falls by approximately 50 % [70].
- **Hydraulic retention time (HRT);** which is the measure of the average length of time that soluble compounds remain in a bioreactor.
- **Salts:** Bacteria require minimum amounts of salts for optimum growth. However, if salts are allowed to accumulated beyond requirements digestion is inhibited.
- A variety of other factors can also affect the rate of biogas production and these are explained in ([67]; [71]; [70]).

[72] in an experiment, studied the influence of temperatures at different hydraulic times on the methane production rate and found that at higher temperatures, about 60°C, the rate was lower than at lower temperatures of about 50°C.

### **Waste water treatment**

The potential uses of geothermal energy in the processing of domestic and industrial waste water by a treatment plant include: sludge digester heating, sludge disinfection, sludge drying and grease melting. Table 4.2 below shows possible applications of geothermal heat to waste water treatment processes.

**Table 4.2: Waste water treatment plant processes and corresponding temperature requirements**

<b>Process</b>	<b>Temperature range (°C)</b>
Sludge digester heating	29 to 38 (mesophilic)
	49 – 57 (thermophilic)
Sludge disinfection	
• Pasteurization	70
• Composting	55
Sludge drying	52 to 54
Grease melting	96

*Source: Fanelli and Dickson (1995)*

#### **1. Sludge digester heating**

The sludge and other solids collected throughout the treatment process are pumped from their various collection points to the thickeners where they are concentrated through settling and then pumped to digesters for anaerobic treatment. In the anaerobic digesters the contents are heated and mixed to enhance the digestion process. The sludge temperature is maintained between 32 and 38 °C, within the mesophilic range and 49 and 57°C for the thermophilic range. Heat exchangers are used to transfer heat to the sludge while it circulates within the digester through mixing [64]. Geothermal fluid can be used to supply the required heat. The anaerobic processes aided by heating and mixing break down the organic materials into a digested sludge and methane gas. The methane gas is collected and stored for further use, while the well-digested sludge is dried either atmospherically on drying beds and/or mechanically with artificial drying methods.

#### **2. Sludge drying**

Sufficiently dried sludge can have commercial value as a fuel or fuel supplement. It can also be used as manure to increase the fertility of fields. Sludge drying can be done using

drying beds exposed to the sun or mechanical de-watering with belt presses. The use of heat for drying may increase the sludge-handling capacity of a plant. According to [64], the minimum practical drying air temperature for sludge drying is approximately 77 °C, which would require geothermal fluid temperatures on the order of 88 °C or above. Using the 77 °C air, approximately 25,800 J will be required to evaporate 0.45 kg of water from belt press paste (80 percent moisture) to a dried product (10 per cent moisture).

#### **4.6.2 Biodiesel production**

Biodiesel production is based on trans-esterification of vegetable oils and fats through the addition of methanol (or other alcohols) and a catalyst, giving glycerol as a co-product [73]. Geothermal can be used in supplying the necessary heat to aid the processes of biodiesel extraction from biomass and microalgae. According to [74], the company Infinifuel Biodiesel has constructed a biodiesel processing facility at a small Nevada geothermal power plant in Wabuska where camelina oil seed algae is transformed into diesel fuel. The plant works by growing algae, crushing or pressing these materials into vegetable oil and biomass, adding the biomass to alcohol, and, finally, mixing the biomass/alcohol combination with vegetable oil and heated it using geothermal power for the biodiesel plant. This geothermal facility, which uses 220 °F (104 °C) water, produces enough power to run the Wabuska facility and sell additional power. The facility is almost entirely self-contained, largely due to heat supplied by a geothermal plant.

#### **4.7 Balneology**

For centuries, thermal waters have been used all around the world. Many of these are well known for their therapeutic properties. Geothermal heat can be used in swimming pools and spas; temperature of the resource and its mineral content are important parameters.

The most traditional type of health spa is the geothermal spa, featuring baths and pools of natural hot mineral waters. Swimming pools and spas given a range of benefits to the user, these include; improving health and appearance, and getting away from stresses to refreshing and revitalizing one's body and mind. Numerous health benefits can be derived from bathing in geothermal water, such as, improved blood circulation, cleaning and rejuvenating of the skin, eased muscle tension, enhanced detoxification processes, treatment of high blood pressure, skin diseases, diseases of the nervous system and relieving the

symptoms of rheumatism. The mineral composition of geothermal waters, especially silica, has also been proven to have considerable healing effects for psoriasis skin disease. swimming pools and spas also present opportunities for networking and enrichment of social lives [54].

The installed capacity is 9,140 MW<sub>t</sub> and the annual energy use is 119,381 TJ/year, up 36.4% and 9.1% respectively in 2015 compared to 2010. The largest reported annual energy uses are from China, Japan, Turkey, Brazil and Mexico [3].

#### **4.7.1 Design parameters – spa**

The sizing of a spa for temperature and flow rates depends on the following considerations Figure 4.4 below:

1. Conduction through the pool walls
2. Convection from the pool surface; these are dependent on temperature difference between the pool and the surrounding air.
3. Radiation from the pool surface, these are usually higher in the night but can be generally considered to cancel out with solar gains over the day; and
4. Evaporation from the pool surface: these constitute the greatest losses from the pools, about 50% - 60% (ASHRAE, 1999a). evaporation rate is dependent on air velocity and pressure difference between the water in the pool and water vapor in the atmosphere.

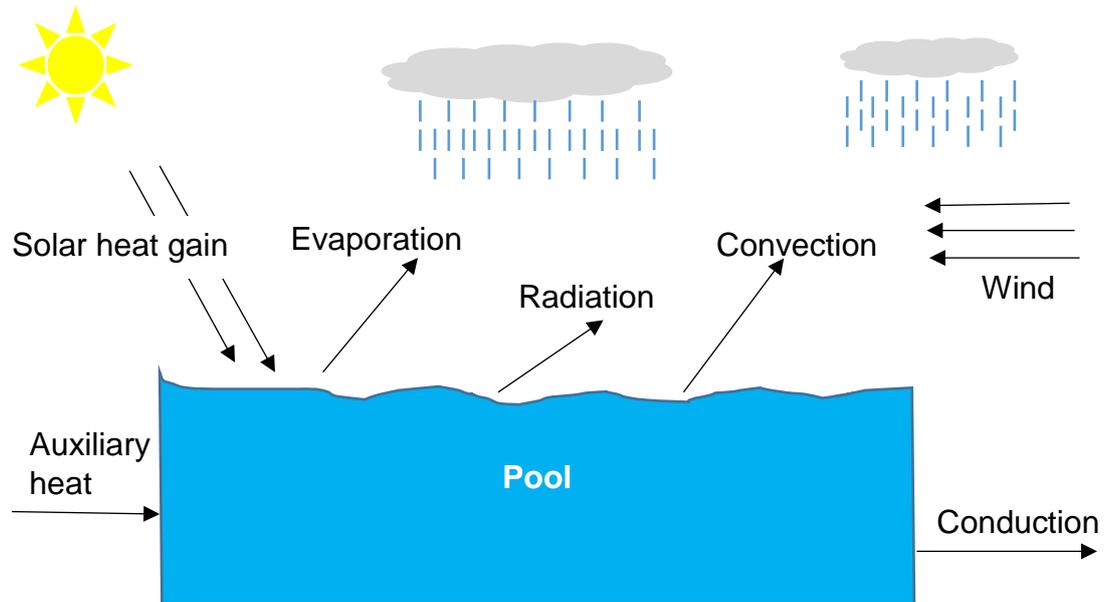


Figure 4.4: Losses associated with swimming pools and spas

Source: Woodruff (2013)

Required geothermal heating output  $q_t$  can be determined by

$$q_1 = gc_p V \frac{(T_f - T_i)}{t} \quad (4.15)$$

Where:

- $q_1$  = pool heat-up rate, kJ/h
- $g$  = density of water = 1,000 kg/m<sup>3</sup>
- $c_p$  = specific heat of water = 4.184 kJ/kg °C
- $V$  = pool volume, m<sup>3</sup>
- $T_f$  = desired temperature (usually 27 °C)
- $T_i$  = initial pool temperature of pool, °C
- $t$  = pool heat-up time (usually 24 hours)

$$q_2 = UA(T_p - T_a) \quad (4.16)$$

Where:

- $q_2$  = heat lost from pool surface, kJ/h
- $U$  = surface heat transfer coefficient = 214.4 kJ/h m<sup>2</sup> °C
- $A$  = pool surface area, m<sup>2</sup>
- $T_p$  = pool temperature, °C
- $T_a$  = ambient temperature, °C

$$q_t = q_1 + q_2 \quad (4.17)$$

Any spa design must consider the following variables; humidity control, ventilation requirements for air quality (outdoor and exhaust air), air distribution, duct design, pool water chemistry and evaporation rates [76].

### **Activity factors**

The following activity factors should be applied to the area of specific features, and not to the entire wetted area [76] are presented in Appendix B, Table B.1.

## **4.8 Salt Extraction and Processing**

The salt (NaCl) extraction from the brine appears to be suitable for the disposal fluid. The standard salt produced from brine has several uses like cooking, food preparation and industrial uses. The salt from the geothermal brine can be used for industrial purposes like textile, soap, leather treatment, etc. The basic extraction process is the evaporation of the brine in large ponds where the capacity of the ponds will depend on the season and the required production level. The most popular way of extracting salt is the evaporation of seawater or brine in large ponds. The main constraint on this use is the silica content.

On an industrial scale, brine is obtained either by mining or through collection from a salty lake or sea. The solution is then fed into enclosed vessels and boiled under partial vacuum with steam. Once it crystalizes, the salt dries on rotary filters. Air being passed through the salt cake is heated; the source of fuel/heat may be fossil fuels, biomass, concentrated solar or geothermal heat. The process of drying salt requires temperatures as high as 100 °C to enable the evaporation of water. Salt leaves the drying operation at a temperature of over 93 °C and is cooled to temperatures of between 66 – 76 °C [76].

Other industrial methods of extracting salt from brine do exist one of them being electrolysis. Several preliminary experiments have been undertaken to assess the salt extraction from the brine:

- Chlorine (Cl) in gas phase by electrolysis,
- Caustic soda (NaOH) by electrolysis,
- Potassium chlorate (KClO<sub>3</sub>) by electrolysis.

Laboratory experiments were carried out to evaluate the content of the salt formed by electrolysis. Results indicated quite low content range despite the fact that there are industrial processes with high extraction range. The process could be improved to gain more profit in the salt recovery, however the cost will increase [77]

## **5 GEOTHERMAL FIELD SELECTION**

### **Outline**

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## **5.0 Introduction**

The selection of a geothermal field for further assessment involves a number of factors, and is not always a clear cut task. The application of a geothermal resource to a given direct use is highly dependent on various factors such as [20]:

- The characteristics of the resource: temperature, flow, chemistry and other parameters related to its sustainable utilization,
- Economic considerations related to the potential market for the product resulting from the resource exploitation and how easily available the resource is as well as the capacity of the entity entitled to exploit the resource in terms of experience in exploiting geothermal resources and experience in the field of the application selected.

This section shows the process used in selecting a candidate field for a pre-feasibility study.

### **5.1 Screening**

The primary factor regarded during the screening process is the number of possible geothermal direct use applications in a given region. This factor is a function of reservoir temperature, prevailing climatic conditions and economic activities within the regions in which a geothermal prospect is located. For each location, the economic activities were matched with possible direct use applications. All the direct use applications considered are as shown in Table 5.1 below.

The symbol ‘x’ or ‘–’ was awarded depending on whether the selected field has temperatures suitable for application of a given direct use geothermal application and its possibility in that region given the climate and economic activities. The higher the number of potential direct use applications, the better the chances of selecting the prospect for the scoring process. The benchmark number was chosen to be five applications in order to maintain the possibility of maximum heat utilization from cascade or multiple use systems.

**Table 5.1: Screening process based on economic activity, climate and population density**

	<b>Drying</b>	<b>Aquaculture</b>	<b>Greenhouse</b>	<b>Biodigester</b>	<b>Milk Processing</b>	<b>Honey processing</b>	<b>Spa</b>	<b>Salt extraction</b>	<b>Binary Plant</b>	<b>Total</b>	<b>Continue?</b>
<b>Buranga</b>	x	x	x	x	x	-	x	-	x	7	Yes
<b>Kibiro</b>	x	-	x	x	x	-	x	x	x	7	Yes
<b>Katwe</b>	x	-	x	x	x	x	x	x	x	8	Yes
<b>Panyimur</b>	x	-	x	-	-	x	x	-	-	4	No
<b>Rubaare</b>	x	x	x	-	x	-	x	-	-	5	Yes
<b>Kitagata</b>	x	x	x	-	x	-	x	-	-	5	Yes
<b>Ihimbo</b>	x	-	x	-	-	-	x	-	-	3	No
<b>Kyangorok</b>	x	-	-	-	-	-	-	-	x	2	No
<b>Total</b>	8	3	7	3	5	2	7	2	4	41	

**Table 5.2: Scoring process to determine candidate field for pre-feasibility study**

		<b>Geothermal Prospect</b>									
		<b>Buranga</b>		<b>Kibiro</b>		<b>Katwe</b>		<b>Rubaare</b>		<b>Kitagata</b>	
<b>Selection Criteria</b>	<b>Weight</b>	<b>Rank</b>	<b>Weighted score</b>	<b>Rank</b>	<b>Weighted score</b>	<b>Rank</b>	<b>Weighted score</b>	<b>Rank</b>	<b>Weighted score</b>	<b>Rank</b>	<b>Weighted score</b>
Average Temperature	45%	3	1.35	5	2.25	4	1.8	3	1.35	2	0.9
Scaling potential	10%	3	0.3	3	0.3	2	0.2	4	0.4	4	0.4
Corrosion potential	5%	3	0.15	3	0.15	2	0.1	5	0.25	5	0.25
Market status	40%	5	2	2	0.8	3	1.2	2	0.8	2	0.8
	<b>Total</b>	3.8		3.5		3.3		2.8		2.35	
	<b>Rank</b>	<b>1</b>		<b>2</b>		<b>3</b>		<b>4</b>		<b>5</b>	
Continue?		Yes		No		No		No		No	

## 5.2 Scoring

In this section, weights were given based on the measure of the relevance of a given parameter to the successful development of a prospect once selected. The weights are percentages with a sum total of 100 percent. Successful projects from the screening process were further assessed in this section. For each prospect, a rating from 1 to 5 was given against each selection criterion to show how far or close a given criterion is to meeting the desired requirement (Table 5.2 above). The rated values are defined as follows; 1 – much worse than desired, 2 – worse than desired, 3 – desired, 4 – better than desired and 5 – much better than desired.

- **Average temperature:** the reference average temperature is selected to be 140°C in order to enhance feasibility of the source for use over a number of direct use applications.
- **Market:** the market looks at the availability of data related to production and marketing of a product to be considered under possible direct use applications. It also considers the measure of appeal given data on marketing has in a prospect compared with other prospects.
- **Scaling potential:** this was assessed using WATCH software, any samples in a given prospect found to have values of SI above 0.3 were considered to pose a scaling risk within a given prospect.
- **Corrosion potential:** this was assessed basing majorly on the chloride concentration in the samples from a given geothermal prospect. Although other factors such as pH, presence of oxygen and carbonate concentration also play a role, their values were considered harmless. Values of chloride concentration above 1,000 mg/kg were considered as a potential threat for corrosion.

## 5.3 Decision Making

Table 5.2 above shows that each of the geothermal prospects are competitive and have good potential for follow up. A decision was however made to proceed with a pre-feasibility study on the Buranga geothermal site, given that a range of geothermal direct use applications are possible, and market prospects are considerably favorable. Figure 5.1 below shows a variety of options for cascade and multiple use of the Buranga geothermal prospect, with minimum inlet temperature for a given process being the limiting factor.

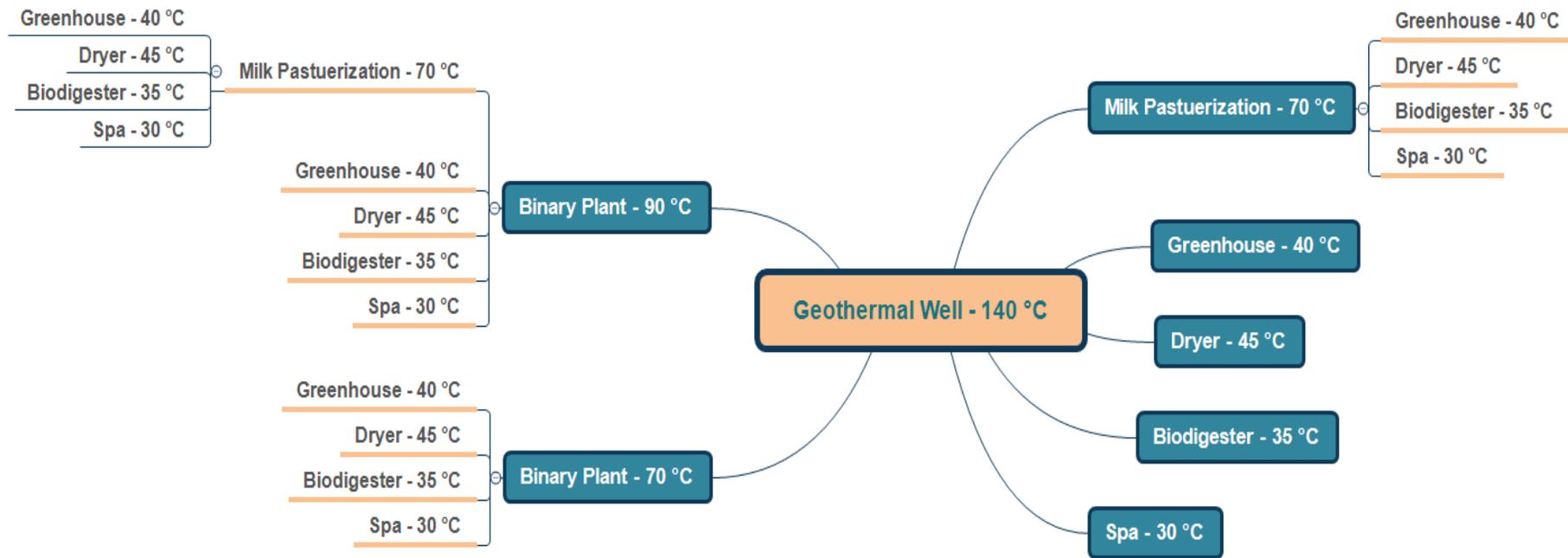


Figure 5.1: Different decision options on the application of direct use at the Buranga geothermal prospects

## **6 PREFEASIBILITY STUDY FOR BURANGA GEOTHERMAL PROSPECT**

### **Outline**

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## **6.0 Overview**

This study was done to assess the potential use of the Buranga geothermal prospect. The study serves as a good incentive towards the deployment of geothermal direct use systems in Uganda, benefiting the government, that has the goal of increasing the percentage of renewable energy use from 2% to 67% by 2017, while improving the livelihood of its citizens.

### **6.1 Location and Market Status**

Information on the location, climate, economic activities as well as market status can be found in section 3, sub sections 3.1 and 3.3.

### **6.2 Selected Scenarios**

The mass flow of a geothermal field is highly dependent on the permeability of the reservoir. Wells drilled in the medium to low temperature geothermal field are generally expected to have the capacity of delivering geothermal liquid of 20 – 60 kg/s [78]. Uganda has yet to carry out exploratory drilling and therefore field characteristics such as well discharge and borehole pressure can only be speculated at this point. A mass flow rate of 50 kg/s from each well has therefore been assumed in order to assess each scenario.

#### **6.2.1 Scenario A: Brine from binary power plant**

This scenario considers a cascade geothermal system. The start point is the supply of geothermal water at 100 kg/s to an optimized binary power plant for electricity generation. Brine from the power plant, that would otherwise be reinjected, is utilized downstream in suitable direct uses whose process temperature requirement is below the brine rejection temperature. The direct uses considered in this case are an agricultural dryer and a geothermal spa, all feeding from the waste brine from the binary plant to create a multiple use system. This system presents the advantage of no cost, or a low cost for the input heating water to industries downstream. The number of direct use applications that can be added or cascaded in this system is limited by the lower temperatures of the input heating geothermal water. Figure 6.1 below shows the schematic for the cascade-multiple system for scenario A.

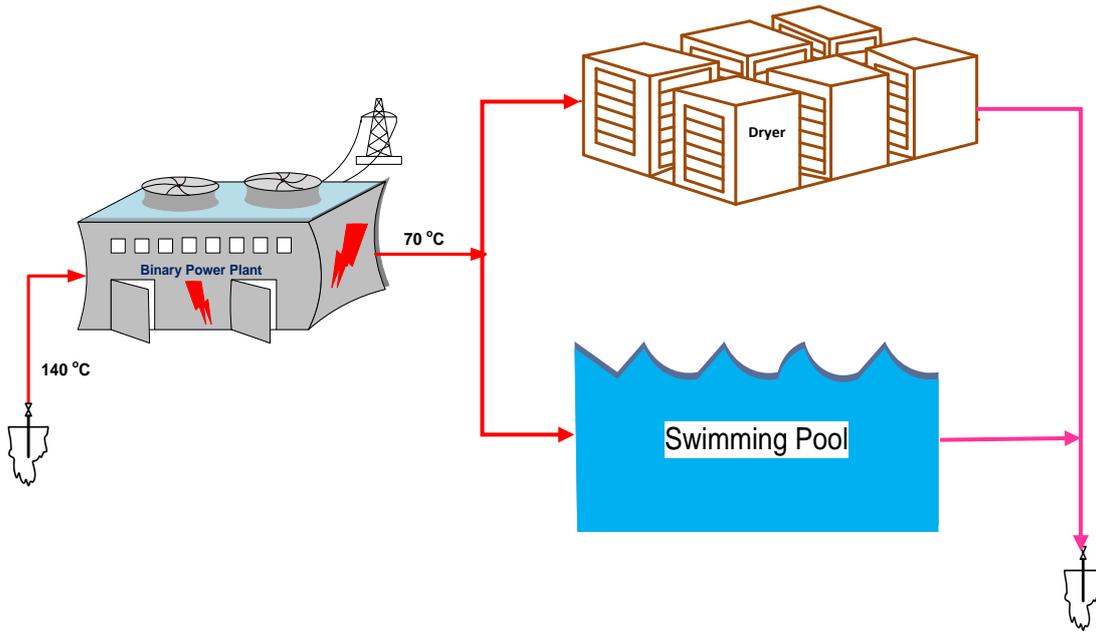


Figure 6.1: Schematic of scenario A

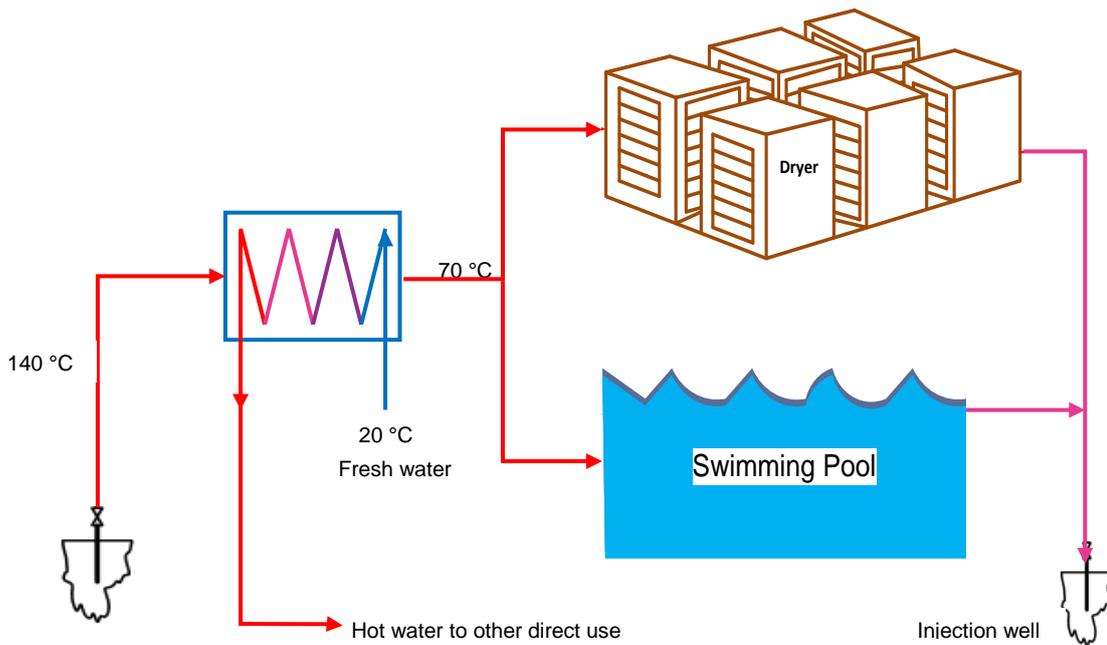
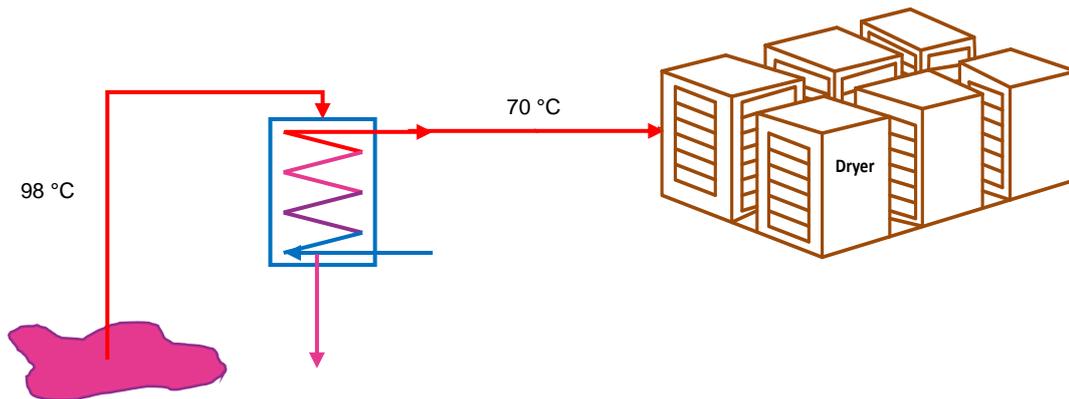


Figure 6.2: Schematic of scenario B

### 6.2.2 Scenario B: Brine from drilled well

Scenario B considers the use of brine directly from a drilled well for use in cascade and multiple applications from industry and other uses before finally disposing it off. This scenario is most applicable in areas that are connected to the national grid and that experience a stable and reliable supply of electricity. Additional costs will however have to

be incurred in the development of this scenario compared with scenario A. These costs include, but are not limited to; the costs related to drilling of geothermal wells, as well as costs for some additional heat exchangers to ensure that temperatures available to the next use are as required. The direct uses considered under this scenario are agricultural drying and a geothermal spa.



**Figure 6.3: Schematic of scenario C**

### 6.2.3 Scenario C: Hot water from a geothermal hot spring

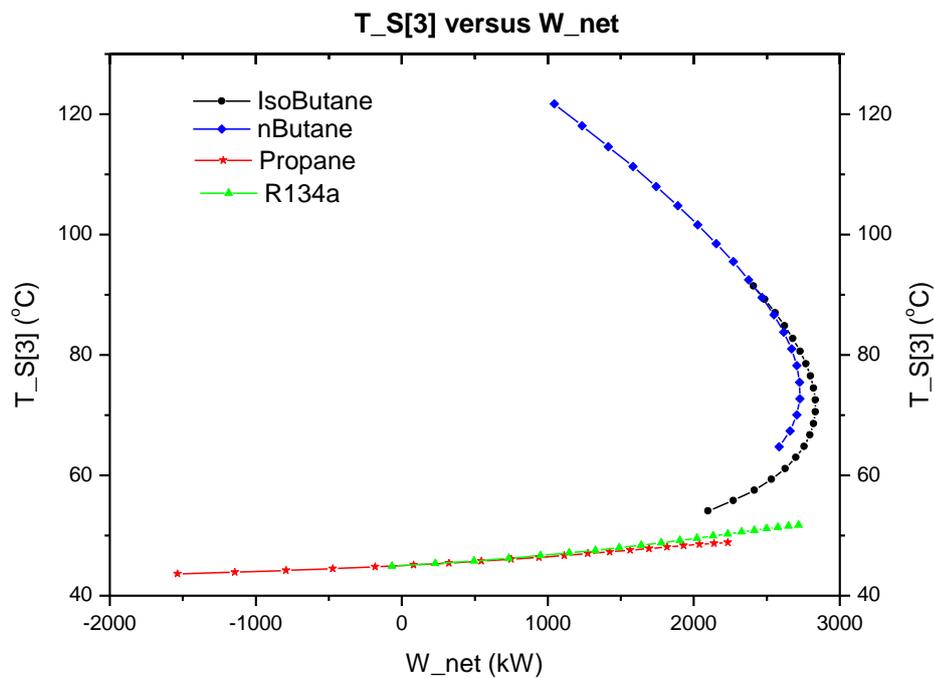
This scenario considers the use of brine from a geothermal hot spring. A shallow bore hole may be drilled to ensure less oxygen contaminated waters are obtained, else, a costlier corrosion resistant material may have to be used. The geothermal hot spring for this scenario is the Nyansimbe hot spring with average water temperatures of about 86 °C and a flow rate of 15 liters per second. Direct applications ranging from industry to waste water treatment can be considered; however, only agricultural drying is assessed in this scenario. The supply hot spring feed flow rate would sustainably allow for tapping of a portion for use in the drying process, but would not suffice in supplying the geothermal spa considered in scenarios A and B. This scenario has the advantage of providing opportunities for industrial development thereby improving both the economic and social status of an area at relative costs. However, additional costs are very likely to be incurred in terms of choice of material as well as maintenance due to the high risks of corrosion from the use of water exposed to oxygen.

### 6.3 Technical Analysis

This section assesses the different applications that are regarded in each of the scenarios. Design, analysis and optimization of each application is done to determine possible capacity.

#### 6.3.1 Binary power plant

The binary plant optimization was done using a source temperature of geothermal fluid of 140 °C and a total mass flow rate of 100 kg/s. The optimization was based on an assessment of different working fluids over varying vaporizer pressure. The working fluids each had a vaporizer pressure that gave the best work net ( $W_{net}$ ) output value and a corresponding temperature for the outlet geothermal fluid. The Figure 6.4 below shows a comparison of the different working fluids over variable vaporizer pressures.



**Figure 6.4: Comparison of different working fluids in terms of  $W_{net}$  and  $T_{s[3]}$  over varying  $P_{vaporizer}$**

Of the fluids with a negative slope for the saturation curve, isobutane gives the best  $W_{net}$  value compared to nbutane. R134a gives better  $W_{net}$  values overall, and could be a suitable choice of working fluid for the power plant. However, isobutane was chosen over R134a because it has a much higher latent heat of vaporization and only a small change in pressure can result in desirable temperature conditions. Isobutane gives good outlet temperatures that

can be extracted downstream and the plant will not have to operate over very high pressures as would be the case with R134a. Table 6.1 below give the maximum  $W_{net}$  values for each working fluid and corresponding vaporizer pressure ( $P_{vaporizer}$ ) and outlet temperature ( $T_{s[3]}$ ) for the geothermal fluid.

**Table 6.1: Comparison of values of  $W_{net}$ ,  $T_{s[3]}$  and  $P_{vaporizer}$  for different working fluids**

Working fluid	$W_{net}$ (kW)	$T_{s[3]}$ (°C)	$P_{vaporizer}$ (bar)
Isobutane	2833	70.55	17.11
n-butane	2726	72.73	12.37
Propane	2234	48.85	25.00
R134a	2718	51.72	25.00

Using a turbine efficiency of 85% and generator efficiency of 95 %, the binary power plant was rated to have a gross capacity of 2.9 MW<sub>e</sub> where the working fluid used is isobutane.

### 6.3.2 Cocoa dryer

#### *Cocoa bean data*

The average weight per bean and area of each bean in the dryer were obtained basing on the following parameters:

Parameter	Quantity
Pod weight	400 g
Average number of beans per pod	50 beans
Average bean length	30 mm
Average bean width	10 mm
Water mass fraction before fermentation	0.8
Water mass fraction after fermentation	0.6
Water mass fraction after drying	0.07

#### *Tray and rack capacities*

The dryer trays are meant to hold the beans during drying. Each tray was considered to be made out of a steel net held by a wooden frame of dimensions 1 m by 1 m. A steel net is used to ensure strength to hold a give quantity of beans, and the size was made small enough to ease handling.

The racks are holding frames for the trays. Because ease of handling during loading and off-loading is an essential, the rack height becomes an important design parameter. The following dimensions were used in determining tray and rack capacities<sup>3</sup>.

Parameter	Quantity
Tray length	1 m
Tray width	1 m
Tray thickness	20 mm
Tray spacing	50 mm
Tray height above floor	200 mm
Maximum rack height	2.1 m

The tray area was obtained by:

$$A_{\text{tray}} = \text{Tray length} \times \text{Tray width} \quad (6.1)$$

Number of beans that can be held by each tray:

$$\text{Tray capacity} = \frac{A_{\text{tray}}}{A_{\text{bean}}} \quad (6.2)$$

The rack capacity was determined by first obtaining the number of trays that each rack can hold by the equation;

$$\text{Trays per rack} = \frac{\text{Maximum rack height} - \text{Tray height above floor}}{\text{Tray base thickness} + \text{Tray spacing}} \quad (6.3)$$

Therefore,

$$\text{Rack capacity} = \text{Trays per rack} \times \text{Tray capacity} \quad (6.4)$$

For the batch dryer considered of dimensions 5m by 3m by 3m, 5 racks can fit along the length, and 3 racks along the width. This gives a total number of racks for the dryer as 15 racks. Dryer capacity was therefore obtained from the equation;

$$\text{Dryer capacity} = \text{Trays per rack} \times \text{Number of racks} \times \text{Rack capacity} \quad (6.5)$$

### Mass balances

The dryer capacity obtained corresponds to a given mass of beans from the fermentation process and a given mass of moisture that has to be evaporated from the beans for the desired

---

<sup>3</sup> Capacities implies the number of beans without considering their weight

rying to be achieved. The thin layer drying principle was applied, where the beans are laid in a single layer, with full exposure to drying air under constant drying conditions.

The maximum mass of beans that the dryer is capable of holding was obtained from the equation;

$$\mathbf{Mass\ of\ beans}_{initial} = \mathbf{Dryer\ capacity} \times \mathbf{Mass\ per\ bean}_{dryer} \quad (6.6)$$

The dryer was found to be able to accommodate a mass of 5.5 tons of wet cocoa beans per batch with each tray holding only a single layer of cocoa beans.

Water mass into dryer

$$\mathbf{Water\ mass}_{initial} = \mathbf{Dryer\ capacity} \times \mathbf{w}_{after\ fermentation} \quad (6.7)$$

And the final mass after drying with a 7% moisture content

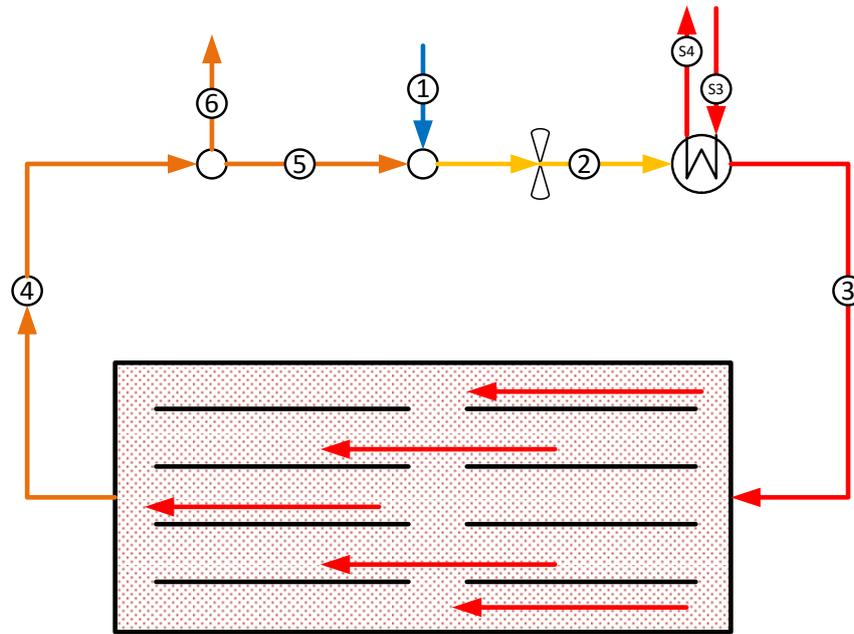
$$\mathbf{Mass\ of\ beans}_{final} = \mathbf{Dryer\ capacity} \times \mathbf{w}_{after\ drying} \quad (6.8)$$

The average drying rate in kg of water evaporated per hour is a function of the mass of water before and after drying for a given dryer capacity, and the drying time. The drying period considered was 48 hours per batch.

$$\mathbf{Drying\ rate} = \frac{\mathbf{Water\ mass}_{initial} - \mathbf{Water\ mass}_{final}}{\mathbf{Drying\ time}} \quad (6.9)$$

### **Energy balances**

The dryer, as shown in figure 11, was assessed based on the following input parameters; average annual ambient temperatures of 22 °C, humidity ratio of 67% and average annual ambient pressure of 0.90 bar from [79]. A predetermined drying temperature of 60 °C and drying relative humidity of 40% from Mollier chart and exhaust air temperature of 48 °C. The inlet relative humidity was set to 40% to ensure that the air being used for drying of the cocoa is not so dry, very dry air can result in case hardening and cracking which would lower the quality of the beans. The exhaust temperature on the other hand was set to 48 °C in order to ensure no condensation of vapor in the dryer which from the Mollier chart is expected to be below a temperature of 43 °C.



**Figure 6.5: Schematic of dryer for the analysis of its thermodynamic properties**

The thermodynamic properties of the dryer model were assessed using the EES program. A recirculation percentage of 70 % was done in order to minimize on the energy consumption, without condensation of moisture within the dryer as well as to ensure an acceptable moisture content in the air that prevents case hardening and shrinking of the beans. The data obtained is as shown in Table 6.2 below whereas a representation of this data on a psychrometric chart can be seen in Figure 6.5 above.

**Table 6.2: EES values of the thermodynamic parameters for the assessment of the dryer model**

Point	h[i] (kJ/kg)	RH[i] (%)	T[i] (°C)	w[i] (g/kg)	rho[i] (kg/m3)	DP (°C)
[1]	53.9	67	22	12.49	1.041	15.6
[2]	168.9	87	40.7	49.72	0.9252	38.1
[3]	218.3	40	60	60.51	0.8577	41.5
[4]	218.3	76.9	48	65.67	0.8831	42.9
[5]	218.3	76.9	48	65.67	0.8831	42.9
[6]	218.3	76.9	48	65.67	0.8831	42.9

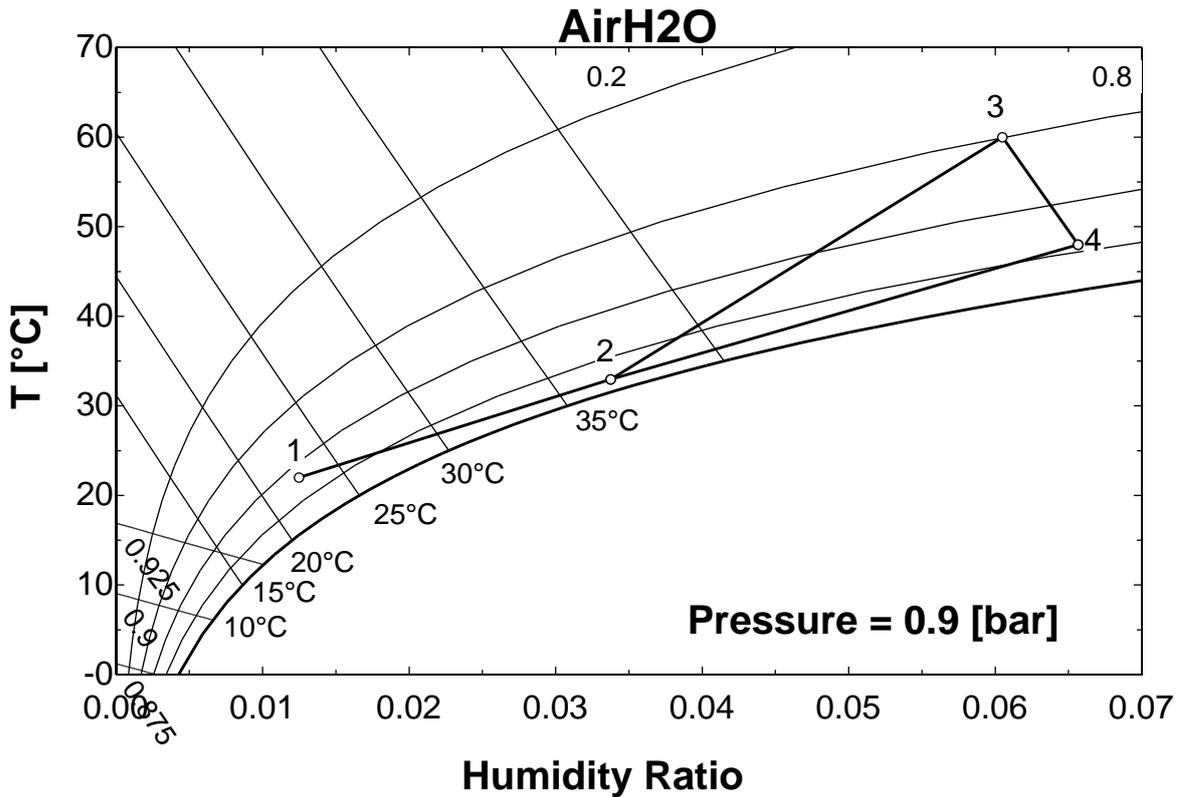


Figure 6.6: Mollier chart with overlay plot of cycle in dryer

**Air flow requirements**

The velocity with which air flows over the beans is an important parameter in determining their quality. A very high velocity can result in shrinking and low flavored beans, whereas, as very low velocity could result in molding of the beans within the dryer.

Using data obtained on the specific humidity at different locations within the dryer, the mass flow velocity of air,  $G$  was calculated from the equation;

$$G = \frac{\text{Drying Rate}}{w_4 - w_3} \tag{6.10}$$

And the volumetric flow rate,  $\dot{V}$  is obtained from the mass velocity and air density at dryer temperature.

$$\dot{V} = \frac{G}{\rho_{\text{air}}} \tag{6.11}$$

To determine the velocity of flow of the air,  $u_{\text{air}}$ , the free flow area within the dryer was used.

$$\mathbf{u}_{\text{air}} = \frac{\dot{V}}{A_{\text{freeflow}}} \quad (6.12)$$

Where  $A_{\text{freeflow}}$  excludes the area covered by the beans, trays and rack columns, and can be estimated to be half the dryer area along the cross section over which air blows.

$$A_{\text{freeflow}} = \frac{\text{Dryer width} \times \text{Dryer Height}}{2} \quad (6.13)$$

### **Heat requirement**

The amount of heat that is needed to be supplied for the drying process is calculated by;

$$\dot{Q} = \mathbf{G} \times (\mathbf{h}_3 - \mathbf{h}_2) \quad (6.14)$$

Therefore, required flow rate of geothermal brine as the heat source was determined from;

$$\dot{Q} = \dot{m}_{\text{geo}} c_p \Delta T \quad (6.15)$$

Where;

- $c_p$  = specific heat capacity (kJ/kg-°C),
- $T$  = temperature (°C), and
- $\dot{m}_{\text{geo}}$  = mass flow rate of geothermal brine (kg/s).

### **Fan Power**

Fans and blowers are used to induce high air flow rates to suit a given application. They can be used in one of two ways; to force draft by blowing air into a combustion or drying chamber, or to induce draft through drawing air out of the combustion or drying chamber. In cases where bit ways are used, the system is referred to as a balanced draft system. Fans and blowers used to induce draft are often of larger size, and higher cost than those used to force draft. Forced draft fans and blowers are used to provide the necessary air velocity for the process at hand.

An axial fan was selected because of the higher efficiencies it gives and greater airflows than centrifugal fans given the same power requirement.

The fan power was determined for an estimated pressure drop of 4.5 mbar and an overall fan and motor efficiency of 70 % based on the equation:

$$P_{\text{motor}} = \frac{\dot{V}\Delta p}{\eta_{\text{overall}}} \quad (6.16)$$

Where:

$P_{\text{motor}}$  = Power rating of fan motor

$\Delta p$  = Pressure drop

$\eta_{\text{overall}}$  = Overall efficiency of fan

The cocoa beans are dried for 48 hours from an initial moisture content of 60% to 7% with an air flow velocity of about 1.2 m/s within the dryer. Additional dryer results are shown in Table 6.3 below.

**Table 6.3: Results for dryer design**

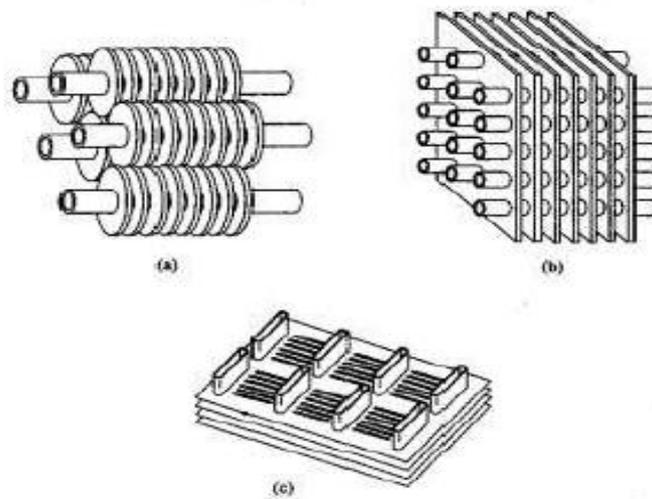
	Parameter	Symbol	Amount	Unit
<b>Air</b>	Dryer capacity wet beans		5429	kg
	Dry beans		2335	kg
	Drying rate		64.45	kg/hr
	Mass velocity	$G$	12483	kg/hr
	Volume flow rate	$\dot{V}$	14553	m <sup>3</sup> /hr
	Velocity	$velocity_{\text{air}}$	1.28	m/s
	Fan Power		2.6	kW
<b>Geothermal water</b>	Outlet temperature	$T_{\text{geo,out}}$	45	°C
	Heat required	$\dot{Q}$	161.4	kW
	Mass flow rate	$\dot{m}_{\text{geo}}$	5868	kg/hr

The annual water consumption of the dryer is 51, 404 tons and this translated into an annual heat need of 1, 414 MWh<sub>t</sub>. The annual capacity of cocoa beans processed considering an average of 90 cycles per annum amounts to 488, 610 kg of wet beans. This capacity was obtained on the basis of the output from the two peak seasons, and can be even higher when considering harvests during other periods of the year.

### **Heat exchanger**

Heat exchangers are available in different designs and sizes depending on the job at hand. However, when considering heat transfer between a gas and a liquid, compact heat exchangers of finned type are most suitable. Compact heat exchangers boast of high values

for the ratio of heat transfer surface area to volume, in the tune of  $700 \text{ m}^2/\text{m}^3$  and higher. The heat transfer coefficient of liquids is usually of higher magnitude than that of gases, and therefore, in order to create a thermal balance with minimum heat exchanger size, fins become a good addition to the gas side to increase the surface area for heat exchange [80]. The fins come in different geometries, the most commonly used are as shown in Figure 6.7 below; (a) circular finned-tube geometry, (b) plat fin-tube geometry and (c) plate-fin flat-tube geometry.



**Figure 6.7: Geometric configurations for fin type heat exchangers**

*Source: Lee, T. H., et al (2002)*

However, some special fin configuration, such as a wavy fin and spine fin, will produce a higher heat transfer coefficient. Spine finned heat exchangers have superior air-side performance over other heat exchangers in dry conditions because their considerably short length does not allow for the growth of a thermal boundary [81].

### ***Design of heat exchanger of dryer***

The heat exchanger used is of the circular-fin circular-tube type in order to ensure increased surface area for heat transfer. Geothermal brine flows on the inside of the circular tubes, while the air flows across the circular fins in a direction normal to the tubes which are in staggered arrangement. The geothermal brine flows in the tubes in multi-pass mode, and the air stream is mixed, whereas the water stream is unmixed.

The overall heat transfer coefficient based on the airside was assumed to be 70 W/m<sup>2</sup>C, and used to determine the length of each circular tube as well as the area to occupied by the heat exchanger for the dryer heat requirement obtained from dryer thermodynamic analysis.

The area was obtained based on the equation;

$$\dot{Q} = UA\Delta T_{LMTD} \quad (6.17)$$

Where:

U – Overall heat transfer coefficient in W/m<sup>2</sup>°C based on the airside

A – Airside total heat transfer area in m<sup>2</sup>

$\Delta T_{LMTD}$  – Logarithmic mean temperature difference in °C and is given by

$$\Delta T_{LMTD} = \frac{(T_{geo,in} - T_{air,out}) - (T_{geo,out} - T_{air,in})}{\ln\left(\frac{T_{geo,in} - T_{air,out}}{T_{geo,out} - T_{air,in}}\right)}$$

The subscripts geo and air represent inlet and outlet temperatures of geothermal brine and air respectively.

The length of each tube was then obtained from;

$$A = \pi L N_t \left\{ d_r (1 - t_f N_f) + N_f \left[ \left( \frac{d_f^2 - d_r^2}{2} \right) + d_f t_f \right] \right\} \quad (6.18)$$

Where:

L – tube length (m)

$N_t$  – Total number of tubes

$N_f$  – Number of fins per meter

$d_r$  – Effective diameter of root of fin (m)

$d_f$  – Diameter at outer edge of fin (m)

$t_f$  – Fin thickness (m)

**Table 6.4 : Design parameters for the circular fin – circular tube compact heat exchanger**

	Parameter	Symbol	Amount	Unit
Pipe	Inner diameter	$d_i$	25	mm
	Outer diameter	$d_o$	30	mm
Fin	Frequency	$N_f$	400	fins per meter
	Thickness	$t_f$	0.3	mm
	Fin diameter	$d_f$	58	mm
Pitch	Transverse	$P_t$	60	mm
	Longitudinal	$P_l$	60	mm
	Number of tubes	$N_t$	<b>625</b>	Tubes
Area	Total Area	$A$	<b>108.6</b>	m <sup>2</sup>
	Fin Area	$A_f$	<b>24.18</b>	m <sup>2</sup>
	Primary Area	$A_p$	<b>84.39</b>	m <sup>2</sup>
Length	Tube length	$L_1$	<b>1.63</b>	m
	Transverse length	$L_2$	1.5	m
	Longitudinal length	$L_3$	1.5	m
	Header thickness	$t_h$	0.035	m
	Total length	$L_t$	<b>1.7</b>	m

An increase the fin frequency (number of fins per meter) results in an increase in conductance and hence, heat transfer coefficient owing to a smaller hydraulic diameter.

### 6.3.3 Geothermal spa

The geothermal spa will be a home for leisure, relaxation and rejuvenation, and can in the future be expanded to offer balneological services.

Sizing of the pools was done on the basis of estimated number of people the pool can accommodate at full capacity, and the retention time or turnover period. The area required per person in a pool as recommended by [82].

The water surface area was obtained using the equations;

$$A_{water} = N_G \times S_G \quad (6.19)$$

Where:  $A_{water}$  = Surface area of water in the pool (m<sup>2</sup>)

$N_G$  = Number of guests in pool at full load

$S_G$  = Recommended area per guest

And the volume obtained from:

$$V_{water} = A_{water} \times H_{pool} \quad (6.20)$$

Where:  $V_{water}$  = Volume of water ( $m^3$ )

$H_{pool}$  = Average pool depth (m)

Actual pool boundary dimensions were estimated from the water surface area and volume obtained from preliminary sizing calculations. The pools are constructed with concrete walls and floors. A wall thickness of 250 mm was considered for each pool for concrete walls.

The flow rate into each pool was estimated on the basis of the retention time and water volume per pool. Retention time is the period over which a complete change of the water in a pool is experienced.

$$\dot{m}_{water} = \frac{V_{water}}{N_{turnovers} \times time} \quad (6.21)$$

Where:

$\dot{m}_{water}$  = Water flow rate into pool (liters/hr.)

$N_{turnovers}$  = Number of turnovers per cycle

$time$  = Operating period over which turnovers occur (hours)

The required flow rate of refill water that allows for a complete change of water in the pool, as well as factors heat and pressure losses was thereafter determined. Geothermal water will be supplied in a flow through mode; this implies that; no heat exchanger will be used to heat up water as would be the case for systems that involves the heating of fresh water that will be recirculated in the pool to the desired temperature. In this mode, chlorination of the water is not required as it will be a wasteful venture, however, the retention time has been set to be considerably small, and therefore, a considerably high flow rate is used in order to maintain suitable hygiene conditions of the water for the users.

### ***Heat losses***

Knowledge relating to the heat losses from the pools is an important design consideration. The amount of heat lost does not only show how much flowrate of the feed-in water ought to be used, but is important on determining how much money is lost in paying for lost heat, as well as inspires the development of mechanisms to curb further losses.

The heat losses that were used as a design factor for the geothermal spa are; convection, evaporation, radiation, conduction and rain, each being obtained from one of the formulae given below;

**Evaporation heat losses**

The design mass flow rate had to factor in the rate of loss of vapor due to evaporation from the surface of each pool. This mass flow rate is termed the evaporation rate, and was determined using the equation below.

$$W_p = (11.0 + 4.30 v) \times (P_w - P_a) \times A \quad (6.22)$$

Where:

- $W_p$  = rate of evaporation (kg/h)
- $A$  = pool surface area (m<sup>2</sup>)
- $V$  = air velocity (m/s)
- $P_w$  = saturation vapor pressure of the pond water (bar-absolute)
- $P_a$  = saturation pressure at the air dew point (bar-absolute)
- $F_a$  = Activity factor. A value of 1.0 was used as recommended for spas and hot tubs (Table B.2 – Appendix B).

The heat loss due to evaporation was therefore obtained by;

$$Q_E = 2440 \times W_p \quad (6.23)$$

**Convection heat losses**

$$Q_{CV} = (9.05 v) \times A \times (T_w - T_a) \quad (6.24)$$

Where:

- $Q_{CV}$  = convection heat loss (kJ/h)
- $V$  = air velocity (m/s)
- $A$  = pond area (m<sup>2</sup>)
- $T_w$  = water temperature (°C)
- $T_a$  = air temperature (°C)

**Radiative heat losses**

$$Q_{RD} = 1.836 \times 10^{-8} \times [(492 + 1.8 T_w)^4 - (492 + 1.8 T_a)^4] \times A \quad (6.25)$$

Where:

- $Q_{RD}$  = radiant heat loss (kJ/h)  
 $A$  = pond surface area (m<sup>2</sup>)

**Conductive heat losses**

$$Q_{CD} = \{[(L + W) \times 12.45] + (L \times W \times 0.4084)\} \times [T_w - (T_a + 8.33)] \quad (6.26)$$

Where:

- $Q_{CD}$  = conductive heat loss (kJ/h)  
 $L$  = length of pond (m)  
 $W$  = width of pond (m)

The above equation considers a lined pond with no significant water leakage from the walls or floor of the pond.

The total heat loss is given by the summation of all the heat losses including those incurred from the necessity to heat up rain water to the temperature of the pool. These values are determined based on the area occupied by a given pool.

**Table 6.5: Design parameters and results for the geothermal spa**

Entity	Shape	Temp	Radius(m)	Depth	Pool load (people)	Space required (m <sup>2</sup> /person)
Main pool	Kidney	32	4.72	0.8 – 1.8	25	2.8
Kid’s pool	Kidney	32	3.57	0.8	20	2
Hot tub 1	Circular	38	1.38	1	6	1
Hot tub 2	Circular	40	1.38	1	6	1
Hot tub 3	Circular	42	1.38	1	6	1
Hot 4	Circular	44	1.38	1	6	1
Relaxation pool	Circular	32	1.78	0.2	10	1
Cooling pool	Circular	70	4	3	-	-
Reinjection pool	Circular	-	4	3	-	-

Heat losses; evaporative, convective, radiative and conductive for each pool or hot tub were determined to ascertain the heat requirement for each hour. Figure 6.8 below shows how they compare with each other. Generally, evaporative losses are the highest for all the pools, especially those being operated t higher temperatures.

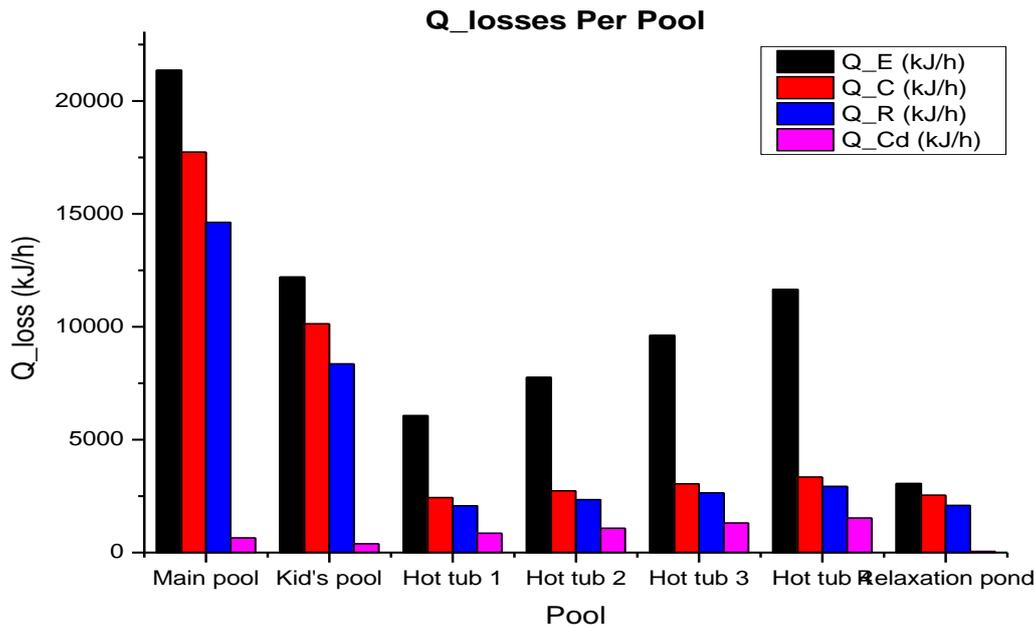


Figure 6.8: Comparison of the measure of heat losses as well as heat losses experienced per pool

## 6.4 Economics and Operation

The investment cost and cost of operation and maintenance were estimated from current cost estimated for the different items considered. An economic analysis was then done for each scenario over a life span of 25 years to determine payback period and profitability.

### 6.4.1 Costs of drilling geothermal wells

For scenario B and to some extent scenario C where drilling of geothermal wells is incurred as a direct development cost, the cost of drilling will be estimated as a percentage of the total investment cost. According to [83], the cost of drilling production and injection wells for geothermal power projects is about 40 – 50% of the total investment cost. This percent range will be considered in scenario B where depths of about 2, 000 – 2, 500 meters will be considered. For Scenario C, an assume percentage of about 20 – 30% of the total investment costs will be used, given that the drilling depths considered are shallower.

In [83], while using a reference depth of 2, 175 m estimated the average costs for drilling a large diameter geothermal well to fall within the range of \$3, 517, 000 to \$5, 262, 000. The risks associated with drilling geothermal wells are mostly associated with the nature of

geological formation, as well as problems related to collapsing of walls in case a rig gets stuck.

#### **6.4.2 Costing for binary plant**

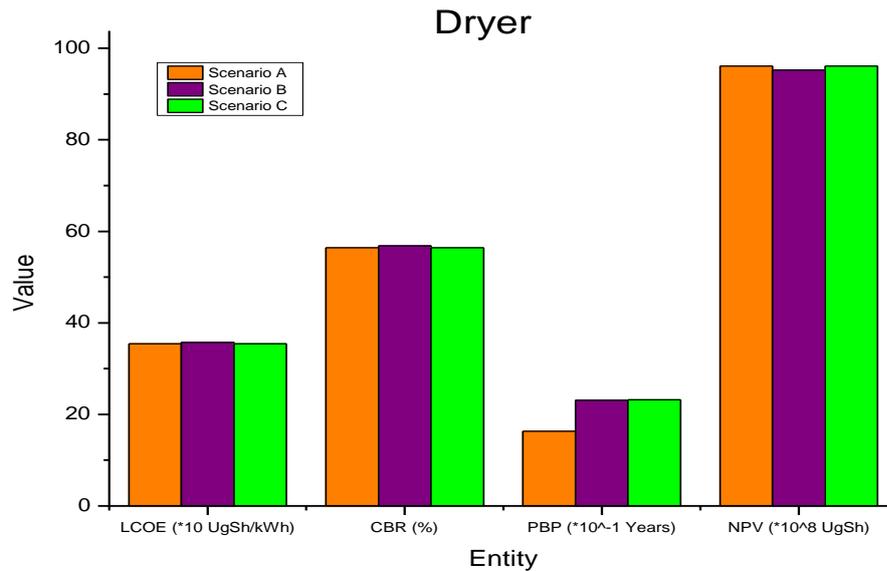
The capital cost of a binary geothermal power plant falls within the range of USD 2,000 – 6,500 per kilowatt [84]. The costs for the binary plant are however not included in the financial analysis given that the optimization of the binary plant was simply used as a means to better estimate outlet temperatures for reinjection.

#### **6.4.3 Costing of dryer**

The materials considered for the construction of the dryer have been selected with a basis on their availability locally and ease for local production. Polished plywood is used for the body of the drying chamber, and wooden beams for the rack frames. Wood was chosen owing to its relatively low cost, and its properties as a poor conductor of heat.

The dryer has an operation time of 90 cycles per year for cocoa drying within the peak seasons. However, it may be used for drying of other agricultural produce in the off peak seasons. The number of days per batch was considered to be 2 days.

Scenarios A, B and C show very close values for LCOE, cost-benefit ratio and net present value. However, scenario B registers higher values of LCOE and cost-benefit ratio compared with scenarios A and C, and lower values for net present value. The period over which the investment cost is paid back is lowest for scenario, and very close for scenarios B and C. This is because the cost of investment for scenario A is lower given that the used water from the binary plant is not paid for, whereas in scenario B, the costs associated with drilling result in a substantial rise in the investment cost. In scenario C, the investment costs are higher due to expenses related to installation of an additional heat exchanger to carry a loop of geothermal water that heats up fresh water for the dryer.



**Figure 6.9: Comparison of LCOE, cost -benefit ratio, payback period and net present value for the dryer in the three scenarios**

#### 6.4.4 Costing of geothermal spa

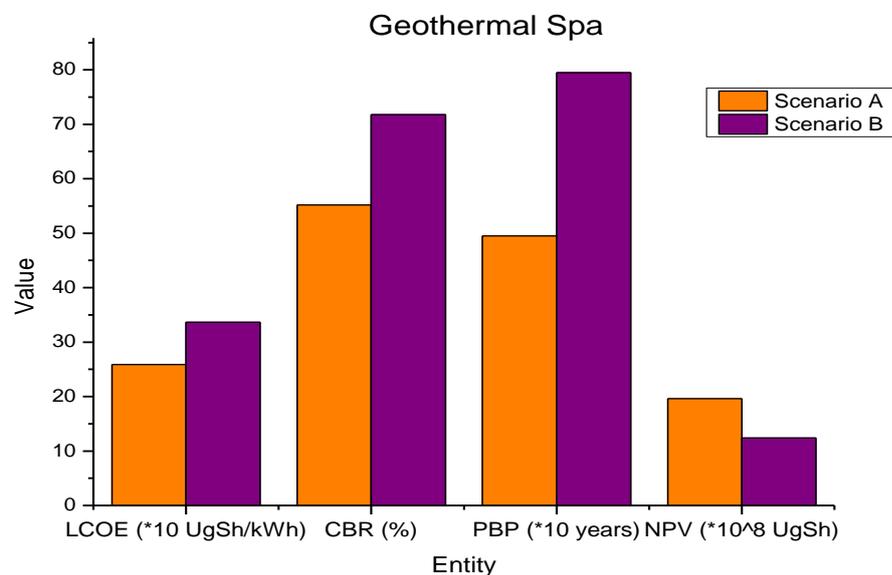
The investment cost for the geothermal spa was done basing on the estimated cost per square meter of pool area. This cost is however, not limited to the construction cost for a given pool, but also includes the costs related to piping and pumping for the given pool. [85] estimates the cost to be USD.50 per square foot, and the price of concrete pools to fall between USD.45, 000 – 65, 000, whereas, [86] estimates the price to range between USD.20, 000 – 55, 000 for concrete/gunite and custom pools. These prices are however all dependent on the size of pool being considered.

The geothermal spa was considered to be in operation for 330 days annually, and having a daily average number of customers of 40 people each paying Ugx.10, 000 to access the facilities.

The profitability of the different scenarios was assessed while including the additional costs associated with each scenario. The assessment was done under the consideration of 75% equity investment, with the other 25% being served by a loan which is serviced over a period of 10 years. The interest rate used was 23.24%, inflation rate of 5.4% and a depreciation rate of 0.5% of the production value [86]. The costs of operation and maintenance were set at 10% of the investment cost to cater for costs related to buying of

wet beans, transportation and labor, whereas insurance was considered to be 0.2% of the capital cost [87].

Scenario A registers lower values of LCOE, cost-benefit ratio and payback period compared to scenario B, (see Figure 6.10 below). This implies that the costs related to investment are higher for scenario B than scenario A; and this is evidenced by the difference in values of net present value for the two scenarios. Scenario A has a higher net present value than scenario B. although scenario A is of higher profitability than scenario B (55% compared with 71% respectively), both scenarios are can be profitably implemented depending on the prevailing conditions.



**Figure 6.10: Comparison of LCOE, cost -benefit ratio, payback period and net present value for the geothermal spa in the three scenarios**

## 6.5 Legal and Policy aspects

As part of its drive to fast-track geothermal energy development, the government of Uganda is now establishing a Geothermal Resources Department within the Ministry of Energy and Mineral Development, with the goal to assist the development of geothermal energy resources of Uganda for power generation. The plan is still awaiting approval from the Finance Ministry [87].

There exist number of policies related to the production of electricity from renewable energy sources. The sector on the harnessing or production, delivery, costing and direct use of heat is still a virgin area within the country. There exist no energy policies in this sector and this could pose a challenge to the implementation of geothermal direct use projects within the country.

## **6.6 Environmental Aspects**

Geothermal energy is generally an environmentally friendly resource with low carbon dioxide emissions, and can easily be blended with the environment, making it a suitable source of energy. The initial stages of developing a geothermal resource come with some negative environmental impacts such as;

- The release of some greenhouse gases trapped deep within the earth including carbon dioxide, hydrogen sulphide, methane, to mention but a few. This however is not as pronounced in direct use systems because most low temperature sources low release values of geothermal gases. Carbon dioxide emissions are therefore generally reduced in the long run if the system is compared to one that uses conventional fuels.
- Noise during drilling, contamination and destruction of flora and fauna will only be an issue caused in the two scenarios that require drilling to access the geothermal heat. For scenario A, it can be considered that the environmental impact in this wise is negligible, given that the direct uses are a secondary use for the geothermal heat,
- The surface disposal of the geothermal brine after use will result in diverse effects on living organisms and possibility of ground water contamination. This however can be mitigated by reinjection of the geothermal brine.

## **6.7 Social Aspects**

Many of the inhabitants of Bundibugyo district are cocoa growers and will benefit higher returns from improved quality of the beans. An improved dryer allows for better control of the drying conditions, thereby allowing for uniformity in quality of the cocoa beans.

Bundibugyo district has a high record of absenteeism of pupils during the cocoa harvesting seasons, this is because families need labor for not only harvesting, but also

preparing cocoa for fermenting and drying all the way to marketing [44]. The presence of a cocoa dryer will minimize on this labor requirement especially for the drying process, allowing more time for students to study.

Food security will be improved within the region given that the dryer has the capacity to be used for drying of other crop produce in off peak seasons when the cocoa bean yield is not so high.

The livelihood of the people will see an improvement from the direct application of geothermal energy. This will be in terms of job opportunities at the dryer and geothermal spa units, as well as through infrastructural development.

## **7 CONCLUSIONS AND RECCOMENDATIONS**

### **Outline**

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## **7.1 Conclusions**

Uganda has the capacity to utilize geothermal in both the production of electricity and the supply of heat for direct uses. There exists a broad range of direct use applications that can be established in the various regions of the country where geothermal potential is evidenced. Agricultural drying, milk pasteurization, geothermal spas, greenhouses, salt processing, apiculture, to mention but a few are all viable options for direct use of geothermal energy in the country. The drying of agricultural products, however, stands out as a key area in which geothermal could play a major role owing to the dependence of the economy of Uganda on agriculture.

Most of the fields considered in this study met some of the main decision criteria in terms of fluid temperature, geochemistry and number of possible direct use applications. However, in relation of the market status, although a market does exist, information as to the measure of the market was not readily available for the study. The Buranga geothermal prospect in Bundibugyo district stood out in this study owing to the presence of data, especially in terms of market base compared with the other prospects, and was therefore considered for a prefeasibility study.

The prefeasibility study showed that it is possible to utilize a geothermal resource in multiple applications from the same source. For both cases, dryer and geothermal spa, the scenario A which taps waste heat from a binary power plant is the most profitable to venture into because it excludes the costs for drilling and purchase of feed-in water. The LCOE in all scenarios is favorable and within the appropriate range for geothermal systems.

The direct use of geothermal energy can be feasibly carried out in Uganda, and will not only be a boost to the industrial sector, but will also improve quality of life both economically and environmentally as well as on a social scale.

## **7.2 Recommendations**

Further chemical analysis of the geothermal water should be done during the exploration drilling to confirm the chemical properties, scaling and corrosion potential before material selection and systems design.

Depending on the outlet temperature of the geothermal brine from the dryer, for a scenario where the dryer is situated at a vicinity close to the fermentery for the cocoa beans, geothermal aided biogas extraction from the pulp and fermentation effluent can be added. This process can serve to ensure that as much heat is extracted out of the geothermal brine before its reinjection.

Prefeasibility studies for application of other direct uses in the different geothermal field locations should be carried out to encourage further development of geothermal energy use.

A more detailed feasibility study should be carried out after the resource has been reliably quantified and the resource temperatures and reservoir depths reliably known.

## 8 REFERENCES

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## **APPENDIX**

### **Outline**

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## Appendix A: Geochemical Data

Table A.1: Buranga analytical results - concentrations in (mg/kg) and (%) for stable isotopes

Location	Sample No.	Temp (oC)	pH	CO2	H2S	SiO2	Na	K	Ca	Mg	SO4	Cl	B	Li	d18O	dD	TDS
Mumbuga2	UG-93-09	93.4	7.87	2445	0	7.9	5320	195	2.45	2.13	3720	3580	4.3	1.34	-3.6	-17.1	14600
Mumbuga5	UG-93-10	93.6	7.73	2411	0	76.4	5160	190	2.56	2.27	3570	3490	4.2	1.3	-3.49	-12.8	14030
Nyansimbe9	UG-93-16	95.8	8.15	2638	0	87.7	5940	222	0.95	1.74	4180	4010	4.71	1.48	-3.21	-12.2	16250
Nyansimbe13	UG-93-11	80.3	7.61	2889	0	88.6	6160	230	2.1	2.63	4330	4160	4.96	1.51	-3.54	-12.4	17050
Nyansimbe17	UG-93-32	98.2	8.57	2635	0	85.1	6270	235	0.39	0.28	4400	4210	4.96	1.51	-3.45	-13.4	17080
Nyansimbe19	UG-93-13	85.8	7.81	2878	0	85.7	6300	234	2.04	1.98	4220	4240	4.8	1.54	-3.46	-12.9	17050
Kagoro20	UG-93-12	89	7.5	2798	0.3	81	5950	219	2.69	2.19	4160	4030	4.7	1.47	-3.69	-12.7	16400
R.Mungera	UG-93-15	21.8	7.52	57	0	37.2	11.1	3.7	11.2	3.61	1.7	1.8	0	0.008	-2.24	-3.7	74
Kyakatimba1	UG-93-17	23.8	7.54	197	0	36.3	21.2	8.1	54.7	14.3	27.6	2.1	0	0.034	-2.57	-4.6	208

Source: Bahati, Kato & Nyakecho (2010)

Table A.2: Kibiro analytical results - concentrations in (mg/kg) and (%) for stable isotopes

Location	Sample No.	Temp (oC)	pH	CO2	H2S	SiO2	Na	K	Ca	Mg	SO4	Cl	B	Li	d18O	dD	TDS
Mukabiga2	UG-93-19	86.5	7.06	146	10.4	129	1530	169	62	8.14	46.7	2500	2.26	1.5	-2.01	-11.3	4576
Mukabiga5	UG-93-20	81.1	7.14	155	13	125	1490	164	62.9	7.96	26.4	2450	2.23	1.48	-2.08	-11.8	4436
Mwibanda14	UG-93-21	71.8	7.14	155	17.3	122	1480	165	65.7	9.21	15.4	2440	2.21	1.46	-1.98	-10.6	4384
Muntere15	UG-93-22	39.5	8.05	115	0	135	1570	182	75.9	8.71	49.9	2580	2.47	1.53	-1.01	3.9	4548
L.Albert	UG-93-23	30	8.93	236	0	0.5	72.3	49.4	9.75	27.3	19.3	24.2	0	0.012	5.47	39.8	338
Wantembo	UG-93-24	29.8	6.89	367	0	90.5	87.5	7.7	75.8	39.5	139	31.2	0	0.06	-3.58	-15.2	662
Kiganja1	UG-93-25	23.6	6.26	130	0	70.8	12.4	2.6	14.8	8.03	5.3	5.2	0	0.003	-1.57	-4.1	124
Ndalagi1	UG-93-26	24.9	6.72	232	0	76.1	50.6	7.5	138	39.5	227	123	0	0.015	-2.08	-5.2	680

**Table A.3: Katwe analytical results - concentrations in (mg/kg) and (%) for stable isotopes**

Location	Sample No.	Temp (°C)	pH	CO2	H2S	SiO2	Na	K	Ca	Mg	SO4	Cl	B	Li	d18O	dD	TDS
L.Katwe13	UG-93-01	28.6	7.61	156	0	29.3	44.7	35.1	10.1	5.92	7	3.9	0	0.03	0	-9	132
L.Katwe6	UG-93-02	28.5	9.64	11316	5.3	88.6	25600	3500	0.1	0.95	9940	19000	1.9	0.067	1.9	-6	72000
L.Nyamunu1	UG-93-03	27.5	9.42	5523	0	32.2	8950	722	0.13	0.49	6450	3340	0.27	0.025	1.12	9.1	24690
L.Edward1	UG-93-04	23.3	8.55	223	0	18.2	83.7	41.5	16.8	27.3	18	20.2	0	0.01	2.52	22.1	254
Katunguru1	UG-93-05	26.6	6.95	1000	0	53.7	952	89.7	296	232	1800	723	0	0.023	-1.88	-8	4870
L.Kitagata5	UG-93-06	66.6	8.41	3105	0	91	9310	644	0.6	0.85	13400	2430	0.82	0.063	-0.73	0.5	27770
L.Kitagata2	UG-93-07	56.6	8.03	2544	0	105	6510	523	1.45	6.27	8970	1770	0.59	0.031	-0.6	3.2	19410
KazingaCh1	UG-93-08	26.2	8.28	108	0	21.5	38.5	7.8	22.9	11.2	11	10.3	0.06	0.005	0.98	12.6	180
L.Kitagata1	UG-93-09	61.1	9.33	10350	19.4	210	33600	1840	4.1	2	44000	8370	2.77	0.16	2.2	0	99515
L.KitagataW	UG-93-10	36	9.57	19470	0.3	389	87300	4780	4.3	1.47	110300	22200	6.9	0.08	10	24	256000
L.KatweW	UG-93-11	28	9.55	9008	4.8	237.6	124500	22500	5.3	32.5	71300	86600	17.5	0.11	9.6	24.5	372000

*Source: Bahati, Kato & Nyakecho (2010)*

**Table A.4: Kitagata, Rubaare and Ihimbo analytical results - concentrations in (mg/kg) and (%) for stable isotopes**

Location	Sample No.	Temp (°C)	pH	CO2	H2S	SiO2	Na	K	Ca	Mg	SO4	Cl	B	Li	d18O	dD	TDS
Kitagata	UG-05-19	66	7.92	56	0	76	203	10.7	36	0.28	346	55	0.61	0.5	-3.3	-3.1	552
Rubaare	UG-05-18	54	7.52	85	0	106	285	14.9	70	1.4	417	177	0.78	0.29	-4.2	-12.1	800
Ihimbo	UG-05-20	70	9.2	45	0.92	66	186	5.6	3.8	0.02	219	71	0.27	<0.05	-3.45	-4.1	444

*Source: Armannsson, Kato & Bahati (no date)*

**Table A.5: Kanangorok analytical results - concentrations in (mg/kg) and (%) for stable isotopes**

Location	Sample No.	Temp (oC)	pH	CO2	H2S	SiO2	Na	K	Ca	Mg	SO4	Cl	B	Li	d18O	dD	TDS
Kanangorok-1	UG-05-58	60	8.35	216	0	118	322	17.7	24	2.7	341	95	0.18	0.19	-4.92	-18.8	815
Kanangorok-2	UG-05-59	42	8.39	207	0	129	323	19.2	21	1.5	343	97	<0.1	0.2	-4.83	-17.2	812
Kanangorok-BH	UG-05-60	38	8.44	207	0	129	342	22	21	1.5	352	96	0.76	0.22	-4.88	-16.6	825

*Source: Armannsson, Kato & Bahati (no date)*

**Table A.6: Panyimur analytical results - concentrations in (mg/kg) and (%) for stable isotopes**

Location	Sample No.	Temp (oC)	pH	CO2	H2S	SiO2	Na	K	Ca	Mg	SO4	Cl	B	Li	d18O	dD	TDS
Amoropii	UG-05-62	58	8.66	71	5.61	73	352	10.9	4.5	0.36	26	470	0.65	0.12	-3.52	-7.7	890
Okumu	UG-05-63	45	8.45	109	2.48	69	321	9.5	8.5	0.68	36	379	0.58	0.08	-3.29	-5.5	794
Avuka-2	UG-05-64	35	7.56	142	0	54	138	7.3	8.4	3.1	19	83	0.22	<0.05	-2.5	1.9	337

*Source: Armannsson, Kato & Bahati (no date)*

## Appendix B: Design Data

**Table B.1: Air change data for various glazing materials**

Material	Air Changes/h
Single glass	2.5 to 3.5
Double glass	1.0 to 1.5
Fiberglass	2.0 to 3.0
Single poly	0.5 to 1.0
Double poly	0.0 to 0.5
Single poly w/low fiberglass sides	1.0 to 1.5
Double poly w/low fiberglass sides	0.5 to 1.0
Single poly w/high fiberglass sides	1.5 to 2.0
Double poly w/high fiberglass sides	1.0 to 1.5

*Source: Fanelli and Dickson (1995)*

**Table B.2: Typical activity factor values for common pool types**

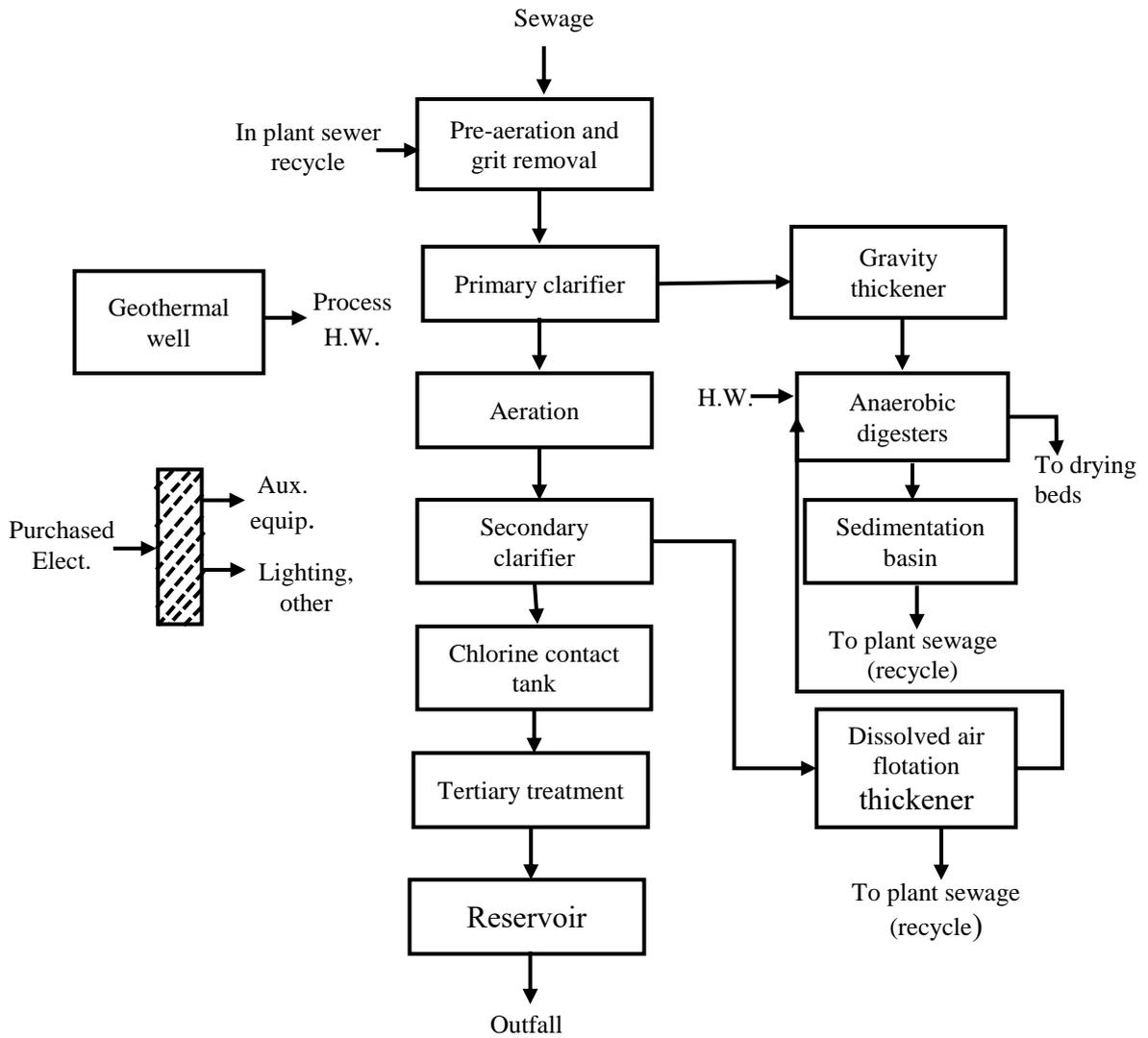
Type of pool	Typical activity factor (F <sub>a</sub> )
Residential pool	0.5
Condominium	0.65
Therapy	0.65
Hotel	0.65
Public, schools	1.0
Whirlpools, spas	1.0
Wavepools, water slides	1.5 (minimum)

*Source: Lund (no date)*

**Table B.3: Typical temperature, humidity and pressure values for Bundibugyo**

Lat 0.43 Lon 30.04	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
<b>Temperature</b>													
<b>22-year Average</b>	22.8	23.7	22.8	21.8	21.6	23.4	23.4	23.4	22.2	21.4	21	21.3	22.3
<b>Humidity (%)</b>													
<b>22-year Average</b>	58.9	57.1	70.5	78.1	71.7	59.7	51.4	58.2	70.6	79.5	79.2	70.3	67.1
<b>Atmospheric pressure (kPa)</b>													
<b>22-year average</b>	88	88	88	88	88.1	88.2	88.3	88.3	88.2	88.1	88.1	88.1	88.1

*Source: Stackhouse (2016)*



**Figure B.1: Waste water treatment process**

*Source: Fanelli and Dickson (1995)*

## Appendix C: Economic Analysis Data

**Table C.1: Investment cost considered for the agricultural dryer**

Item	Quantity	Unit cost (USD)	Unit	Total cost (USD)	Total (UGX)
Tray bed	405	1.5	/piece	607.50	2,044,238
Tray support beams	648	0.8	/piece	518.40	1,744,416
Rack frame beams	120	20	/piece	2,400.00	8,076,000
Rack rigidity beams	60	1	/piece	60.00	201,900
Rack roller wheels	72	1.2	/piece	86.40	290,736
Dryer frame	8	15	/piece	120.00	403,800
Fan	1	3000	/piece	3,000.00	10,095,000
Heat exchanger	110	100	/m <sup>2</sup>	11,000.00	105,997,500
Pipe	12	700	/ton	8,400.00	28,266,000
Control system				1,000.00	3,365,000
Labour				1,000.00	3,365,000
<b>Total</b>				<b>28,192.30</b>	<b>94,867,090</b>

**Table C.2: Investment cost considered for the geothermal spa**

Entity	Shape	Temperature	Investment cost (USD)	Cost in UGX
Main pool	Kidney	32	15,787.20	53,123,807
Kid's pool	Kidney	32	10,952.10	36,853,836
Hot tub 1	Circular	38	8,345.51	28,082,650
Hot tub 2	Circular	40	8,345.51	28,082,650
Hot tub 3	Circular	42	8,345.51	28,082,650
Hot tub 4	Circular	44	8,345.51	28,082,650
Relaxation pond	Circular	32	4,461.16	15,011,808
Cooling pool	Circular	70	24,217.60	81,674,037
Exit pool	Circular	-	24,217.60	81,674,037
Additional costs			45,250.30	152,267,251
<b>Total</b>			<b>158,376.00</b>	<b>532,935,378</b>

