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Opportunities for Direct Use of Medium Enthalpy Geothermal Resources in Mwananyamala Geothermal Prospect, Kenya

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ABSTRACT

Mwananyamala geothermal prospect is located in the coastal region of Kenya within Kwale District. Evidence of existence of a geothermal resource in the prospect is commonly manifested as hot springs, referred by locals as 'Maji Moto' with temperatures ranging between 55°C and 70°C, alongside mildly altered grounds, with secondary minerals such as chalcopyrite, pyrite and calcite. Other manifestations occur in form of limited spread *Fimbristylis exilis,* informally known us 'geothermal grass', especially at hot spring areas. The hot springs occur in faulted areas and the rocks are mainly dominated with Permo-Triassic sandstones. These hot springs discharge slightly alkaline NaCl−$NaHCO_3$ waters from underground, suggesting the springs are most likely being controlled underneath by an intrusive hot body. This paper focuses on the direct use opportunities in Mwananyamala geothermal prospect, best practice of multi-stage utilization where successive lower and lower water temperature are used to maximize benefits focusing on regional economic activities, generation designs as well as equipment and fiscal considerations.

INTRODUCTION

Mwananyamala geothermal prospect is located in-between Jombo and Mrima Hills in the coastal region of Kenya within Kwale District, about 100km South on the Mombasa-Lunga Lunga Road covering approximately 200 km^2. Temperatures of up to 63°C were measured from the hot springs at Kitungure, 70°C at Mbunguni (with high H2S gas odour and CO^2 g emission) and 55°C at Maphombe. These hot springs discharge slightly alkaline NaCl−NaHCO3 waters from underground, suggesting the springs are most likely being controlled underneath by an intrusive hot body.

The prospect is lowland with an average altitude of 120 masl. Dzombo and Mrima hills are the highest peaks in the area and rises to a height of 477m and 265m above the sea level, respectively (Figure 1). The drainage in the area is strongly controlled by structural elements of the region. The dominant water body in vicinity of the prospect is the Indian Ocean which is approximately 8.5km away. River Ramisi is the major river with Rivers Chorochoro, Ndzovu and Sadani as the major tributaries. Aquifer depths in water-point boreholes and wells in the entire prospect area indicate huge volume of shallow hydrogeological regime. Fresh waters exist at a maximum depth of 50m beyond which saline water is tapped. Brackish water at deeper depth could be as a result of mixing of ocean waters with underground water.

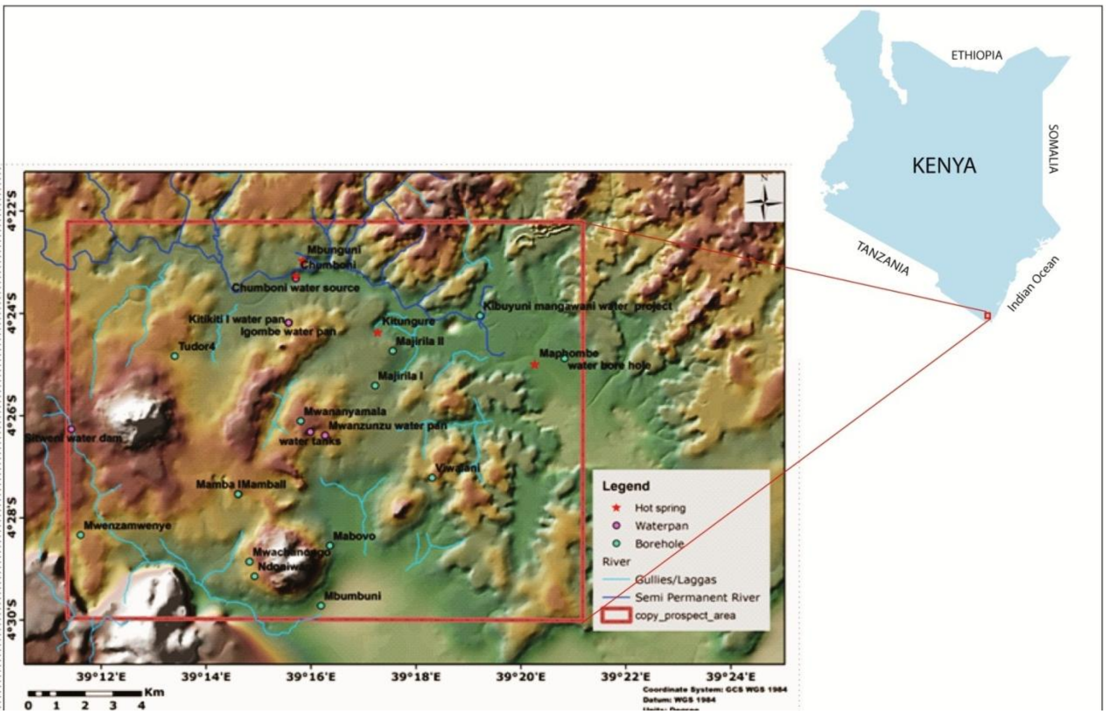


Figure 1: Mwananyamala geothermal prospect.

A multi-disciplinary scientific study was conducted in the prospect to assess geothermal potential and evaluate whether it would make economic sense to invest in this field. The potential as revealed by scientific results has been used to discuss whether geothermal will tend to add value to the local economy if developed.

ECONOMIC ACTIVITIES

Agribusiness Industry

The fishery sector contributes reasonably high national Gross Domestic Demand (GDP) and an important foreign exchange earner with the marine fisheries accounting for about 10 % of the total fish landed in Kenya. Marine fisheries in Kenya are mainly, artisanal and undertaken mostly from small, non-motorized boats such as outriggers, dhows, cataracts and planked pirogues (Ruwa et al., 2003). The use of the most rudimentary equipment by local fishers has exacerbated the problem of over fishing in coastal waters, coupled with heightened conflicts due to the destruction of traditional fishermen fishing nets, competition for common resources, distrust between the semi industrial prawn industry and the local fishermen, and the rampant resources wastage because of the high amount of fish by-catch associated with prawn trawling (Government of Kenya, 2007).

Agricultural activities in the coast of Kenya produce food and non-food products at subsistence and commercial levels. The main food crops in Kwale District are maize, cassava and rice while tree crops like coconut, cashewnuts, bixa, citrus and mangoes are the main cash crops (Government of Kenya, 1997a). Agribusiness applications, i.e. aquaculture and agriculture, are particularly attractive as they require heating at the lower end of the temperature range where there is a plenty of geothermal resources.

Minerals and Energy Resources

Coastal geological formations are predominantly sedimentary in origin, with marine, shallow water and lacustrine characteristics forming a strip of about 50 km wide along the southern part of Kenyan coast. Mineral deposits that occur in economically meaningful quantities include salt, coral rocks, limestone, rutile, ilmenite, building sand, pyrochlore, gypsum, barites, gypsum, silica sands, iron ore and clay. Other lesser minerals are apatite, galena, and manganese oxide. Salt can be considered as the most widespread mineral in Eastern Africa and its recovery from the sea is a comparatively simple process given certain environmental conditions (UNEP 1998). Limestone deposits are extensive along the coastal zone from the Tanzania border to the Malindi area. Good source rocks and reservoir rocks for hydrocarbon deposits have been observed along the Kenyan coast, with conditions becoming more favourable offshore (see UNEP, 1998; Government of Kenya, 1997a; Government of Kenya, 1997b; Government of Kenya, 1997c, Government of Kenya, 1997d).

Tourism Industry

The first hotels directed at tourism were built in Malindi during the early part of the 20^{th} century. Tourism has been steadily growing in Kenya since independence and over time has turned out to be one of the leading foreign exchange earners (Government, 2007). The main attractions for this new industry include the warm coastal climate slightly mellowed by a cool sea breeze, the beautiful coastal scenery and foremost, the beautiful and clean sandy beaches. All the facilities that support the new expansion in the tourism industry are therefore located next or adjacent to beach environments. In some areas, such as the coastal strip around Mombasa, the rapid development of tourism has put pressure on the sustainable use of coastal resources such as the coral reef. However, demand for seafood, shells and coral souvenirs has risen sharply as local supplies have become depleted.

MWANANYAMALA GEOTHERMAL SYSTEMS

Thermal Potential

Thermal activities in Mwananyamala geothermal systems occurs in four zones, three of which occur in close proximity while the fourth to the east of project area. Mwananyamala springs are not associated with high temperature geothermal activity such as fumaroles and altered ground but are found in a sedimentary formation with intruding igneous dykes. The estimated total flow from natural springs is in excess of 90 litres/second and the spring discharge temperatures range from 55 to 70ºC.

The Maji Moto hot springs at Kitungure stretches across an area of approximately 100 square meters comprising of numerous bubbling hot springs and a few cold springs. Emissions of gases from these pools are abundant. Calcite depositions are observed in small areas while pyrites are observed in the pools. At Maji Moto hot springs, Chumboni I, the manifestation are noticeable along an area of approximately 500 square meters and encompasses multiples of thermal springs with a few cold springs on swampy domes. It is characterized by calcite deposits in veins with growth of green and brown algae based on temperature levels. Pyrite and chalcopyrite are also observed in the hot springs. Adjacent to Chumboni I and located also in Maji Moto thermal spring, is Chumboni II. These hot springs cover approximately 800 square metres to the north of Kitungure thermal springs. The springs discharge along a stream in close vicinity to an igneous dyke with a north-south running trend. There are multiple springs with green and brown algae observed along the flow. Maphombe thermal springs is found to the east of Maji Moto in the periphery of the prospect area. The manifestations are evident in approximately 400 square meters. Metered hot water flows were metered using the v-notch weir and a total convective heat transferred from these hot springs gave estimated total lost thermal output of 5.54 MW_t.

Fluid Chemistry

Hydrochemical facies of the thermal fluid is mainly mature Na–Cl water-type unlike Na-Mg-HCO_3-Cl & Na–Mg-Cl water-types for boreholes. Analysis suggests that the overall thermal-springs water chemistry is largely influenced by Indian Ocean water infringement. All the hot springs waters plot in the partially equilibrated waters according to Na-K-Mg relative concentrations and therefore suitable for use in the estimation of reservoir temperatures. Chemical geothermometers calculated temperatures were observed to scatter about a mean of 145ºC.

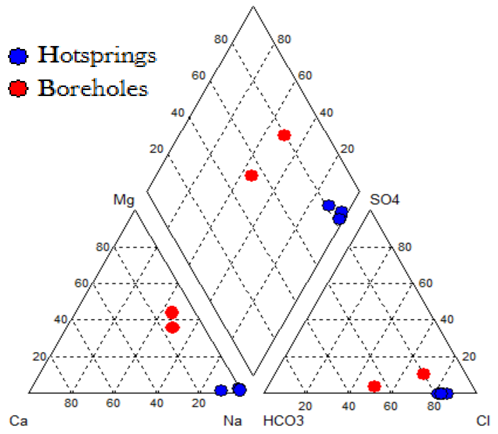


Figure 2: Hydrochemical facies of thermal springs waters.

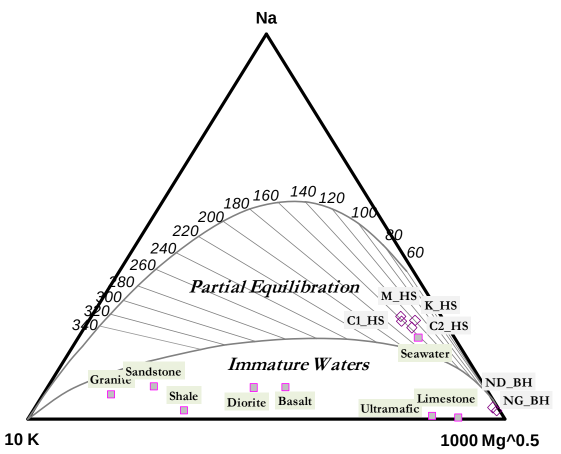


Figure 3: Relative Na-K-Mg contents from the discharges of Mwananyamala thermal springs (K_HS, C2_HS, M_HS and Cl_HS) and boreholes (NG_BH and ND_BH) waters.

GEOTHERMAL ENERGY IN KENYA

Geothermal Utilization

Geothermal utilization is divided into two categories, electricity production (i.e. indirect application) and direct application. Whereas conventional electric power production is restricted to fluid temperatures above 150°C, considerably lower temperatures can be used with application of binary fluid technology (Fridleifsson, 1996). The primary forms of direct use include swimming, bathing, space heating, agriculture (greenhouses), fish farming and industrial processes. In Kenya, because of relatively higher enthalpy resources concentrated along the Kenyan rift, geothermal energy is mainly utilized indirectly alongside few notable direct applications in agriculture. Geothermal energy contributes only 11% in electricity generation in the country compared to hydropower and fossil fuel providing 57% and 32% of electricity supply, respectively (Mwangi 2005), proved to be economical and running at 98% availability (Mariita 2010). The low to intermediate enthalpy resources are localized mainly away from the Kenyan rift. With the creation of Geothermal Development Company, GDC, as a government's tool to accelerate utilization of geothermal energy, utilization of this resource is expected to increase.

Direct Use of Geothermal Energy in Kenya

Although the emphasis is on developing geothermal energy for the generation of electricity, the government through GDC is looking to increase non-power uses of geothermal energy. The direct-use applications of geothermal energy in Kenya are limited to greenhouse and small scale drying of agricultural products utilizing mainly temperature of between 30°C and 100°C although restricted to high enthalpy geothermal fluids from the Olkaria and the Eburru Geothermal Fields. Total installed thermal capacity is 16.0 MWt and thermal annual energy used is 126.2 TJ/year (or 35.2 GWh/year), while the capacity factor stands at 0.25 (see Table 1).

Average capacity determined for African countries suggest variations from 0.25 to 1.00, and shown in Table 1 above Kenya has the lowest capacity factor of 0.25. With the recent formation of GDC to front and accelerate utilization of geothermal (both direct use and electricity generation), the numbers on Kenyan side might have to change significantly in few years to come.

The development of non-power applications of geothermal energy resources in Kenya is awaiting full realization. This was initially hampered by to a lack of financing, public awareness, among others. The direct utilization of geothermal energy is difficult to determine since there are many miscellaneous uses of the energy and these are

Table 1: Summary if direct-use data in Africa and total worldwide, 2010 (edited from Lund et al. 2010).

Country	Capacity (MWt)	Annual Use (TJ/yr)	Annual Use (GWh/yr)	Capacity Factor
Kenya	**16.0**	**126.6**	**35.2**	**0.25**
Algeria	**66.8**	**2,098.7**	**583.0**	**1.00**
Egypt	**1.0**	**15.0**	**4.2**	**0.48**
Ethiopia	**2.2**	**41.6**	**11.6**	**0.60**
South Africa	**6.0**	**114.8**	**31.9**	**0.61**
Tunisia	**43.8**	**364.0**	**101.1**	**0.26**
Total (Africa)	**135.9**	**2,760.7**	**767.0**	**0.64**
Total (worldwide)	**48,493**	**423,830**	**117,740**	**0.28**

sometimes small and located in remote areas in Kenya and thus the capacity and energy use can only be estimated. Direct use accounted under greenhouse, spa and drying of farm produce are at the high to intermediate enthalpy geothermal fields. There are, however, other geothermal fields with operational thermal springs and other diverse manifestations which are currently being considered.

There exists a huge potential for geothermal heat in crop drying but this is hampered by the preference of a lot of farmers for solar energy which traditionally is the source of energy for drying in the country. People have yet to realize the benefits of using geothermal heat, especially in terms of time saved in drying owing to its high temperature and non-seasonality compared to sunlight. With the extensive exploitation of the economically feasible, high-enthalpy geothermal resources and since some of the remaining geothermal prospects of the country are of the intermediate to low-enthalpy types, there is a need to refocus on the development of small-scale geothermal resources and exploiting waste heat from high enthalpy resources for direct utilization.

As discussed by Mburu (2010), locations of geothermal prospects in Kenya favour diverse modes of low heat energy utilisation. For instance, absorption cooling applications would be ideal in the Northern part of the Rift Valley with characteristic semi-arid climate whereas agricultural applications would be favourable in the central and southern Rift, where the geothermal energy is located in highly productive areas with majority of the population practicing arable and dairy farming. This as well applies to coastal region as it has more less same climatic condition. Tourism activity in these areas would also be enhanced by ensuring that hotels and tourist centres are supplied with clean, environmentally friendly energy for heating, swimming, and other balneological uses.

DIRECT-USE OPPORTUNITIES FOR MWANANYAMALA

The use of Lindal diagram (see Figure 4) in the geothermal community to depict temperature as a guideline of direct applications is catholic. The diagram shows several current and potential uses of geothermal energy, ranging from fish farming and soil heating at low temperatures, through space heating and drying at intermediate temperatures, to electric power generation and industrial processing at high temperatures. With estimated aquifer temperature in excess of 145°C, thermal energy harnessed from this prospect can be utilized in many direct uses as shown in Figure 4.

Agribusiness Applications

Agribusiness applications, i.e. horticulture and aquaculture, are known to be attractive for the reason that they require heating at the lower end of the temperature range where there is an abundance of geothermal resources. This may entail the use of waste heat or the cascading of geothermal energy. In Mwananyamala, a number of agribusiness applications include greenhouse farming, aquaculture and animal husbandry facilities heating, soil warming and irrigation, mushroom culture heating and cooling, and bio-gas generation (see Suyanto et al. 2010, Lund et al. 2010, Lund 2010, Omer 2008, Bloomquist 1987, etc.).

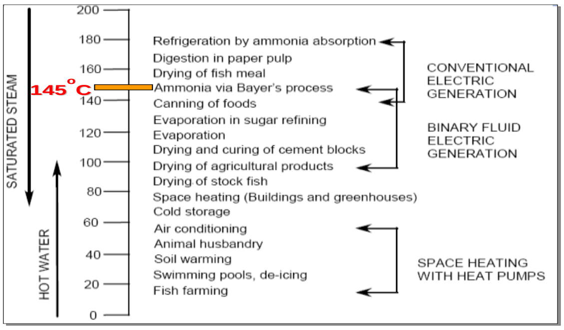


Figure 4: The Lindal diagram showing the potential of geothermal energy in relation to the temperature of the fluid.

Aquaculture

Aquatic species largely produced in the commercial aquaculture industry are cold blooded and hence maintaining them in a warm environment increases the metabolism, and allows the animal to feed and thus grow, at increased rates enhancing the production of market sized products in a shorter period of time. The main species reared in this way are carp, catfish, bass, tilapia, frogs, mullet, eels, salmon, sturgeon, shrimp, lobster, crayfish, crabs, oysters, clams, scallops, mussels, abalone and tropical fish (cichlids), alligators and crocodile. It has been demonstrated that more fish can be produced in a shorter period of time if geothermal energy is utilized as opposed to solely depending on sun (Lund 2005). When the water temperature falls below the optimal values, the fish lose their ability to feed because their basic metabolism is affected (Johnson 1981). Table 2 provides some data on culture temperatures for key aquaculture species whereas.

With temperatures of about 145°C indicates that the spring water from Mwananyamala geothermal prospect can be conditioned to favour the growth of most aquatic organism aforementioned. The economics of raising certain aquatic species will therefore be determined by the quality and flow rate of geothermal water, market availability and engineering limitations. The pond size is mainly reliant on the quantity among other factors including financial constraints. Being a touristic city, Mombasa has the potential to serve as an incessant good market for both freshwater and marine products.

Table 2: Temperature requirements and growth periods for selected aquaculture species (Behrends, 1978)

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 to 8	
Pink	11 – 40	22 – 29	6 to 8
Salmon (pacific)	4 – 25	15	6 to 12
Freshwater prawns	24 – 32	27 – 30	6 to 12
Catfish	17 – 35	27 – 30	6
Eels	0 – 36	23 – 30	12 to 24
Tilapia	8 – 41	22 – 30	...
Carp	4 – 38	20 – 32	...
Trout	0 – 38	15	6 to 8
Yellow Perch	0 – 30	22 – 28	10
Striped Bass	? – 30	16 – 19	6 to 8

Construction of aquaculture pond for geothermal heating is one of the simplest applications, as it usually uses the geothermal water directly in the pond to provide the required heat demand. For instance, where 50°C geothermal water is supplied to heat the pool water to 30°C, the ΔT is 20°C, and using a flow rate of 10 L/s, the energy supplied would be 837 kW (3.0 GJ/hr) (kW = L/s × ΔT × 4,184). If the supply temperature were instead 40 °C the flow rate would have to be doubled to provide the same amount of energy, and four times at 35°C, and eight times at 32.5°C (Rafferty, 2004). For the freshwater fish, where the geothermal water cannot be used directly, then a heat exchanger is necessary to heat freshwater from boreholes for the pond. As Lund (2010) describes the heated water to the pool should be 10°C above the pond temperature, and thus for this case 40°C secondary water would have to be provided to the pond (see Figure 5). Using a heat exchanger between the geothermal water and the secondary water an additional ΔT of 5°C is required to accommodate the heat transfer between the geothermal water and the secondary water. Thus 45°C geothermal water would be required, and on the return side of the heat exchanger the geothermal reject fluid should be 5°C above the return temperature of the secondary water.

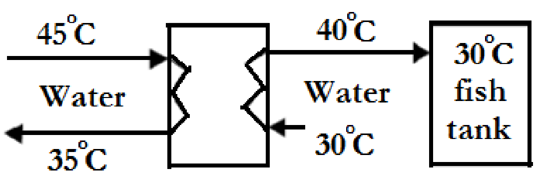


Figure 5: Pond heating with heat exchanger (edited from Lund (2010)). Minimum acceptable supply water temperature = process temp. + 10 °C; Maximum available supply water temperature = resource temp. – 5 °C; Minimum achievable geothermal leaving temperature = process temperature + 5°C.

To accomplish the maintenance of temperatures, it may be necessary to supply substantial quantities of heat to the water in the culture tanks. This may prove impractical for outdoor operations since a non-covered body of water, exposed to the elements, exchanges heat with the atmosphere (i.e. by convection, evaporation, radiation and conduction). The heat and water will be supplied by artesian geothermal wells flowing at approximately 90 l/s.

Horticulture and Agricultural Drying (and Dehydration)

Geothermal water and its constituent carbon dioxide gas are very useful in the agricultural sector. Agricultural applications make direct use of geothermal water by using it to heat and water plants, to warm greenhouses, or to dry crops. Carbon dioxide on the other hand is used as a stimulant to naturally accelerate plant growth thus giving yield to bigger produce within a shorter duration. As with most other uses of geothermal energy, geothermal agriculture is only practical in areas that have geothermal resources. The primary aim of greenhouses in tropical areas is for heating to control night-time (and wet season) humidity levels, thereby alleviating fungal disease. Mwananyamala is located within the coastal region of Kenya and enjoys good tropical weather all year round. Although, geothermal water is used mainly as a source of heat and moisture for green houses, its use as a warming media in green houses may not be applied in this particular resource area. However, the aspect of carbon dioxide supplementation on plant growth and production within the greenhouse environment is one that is well understood and it is for this reason among others the geothermal resource in Mwananyamala is deemed vital.

Carbon dioxide (CO_2) is an essential component of photosynthesis (also called carbon assimilation). Photosynthesis is a chemical process that uses light energy to convert CO_2 and water into sugars in green plants. These sugars are then used for growth within the plant, through respiration. The difference between the rate of photosynthesis and the rate of respiration is the basis for dry-matter accumulation (growth) in the plant. In greenhouse production the aim of all growers is to increase dry-matter content and economically optimize crop yield. CO_2 increases productivity through improved plant growth and vigour. Some ways in which productivity is increased by CO_2 include earlier flowering, higher fruit yields, reduced bud abortion in roses, improved stem strength and flower size. Growers should regard CO_2 as a nutrient.

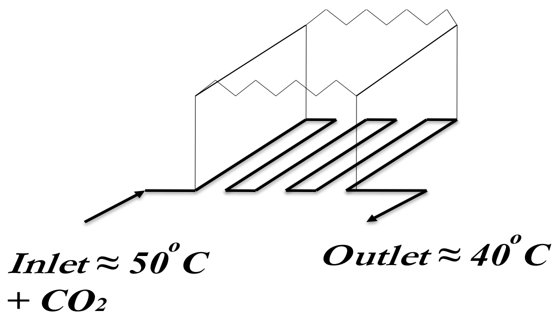


Figure 6: Schematic diagram for greenhouse farming.

According to Rafferty (2004), heating of greenhouses often involves the transfer of heat to the air in the structure using a water-to-air heat exchanger called a coil, usually consisting of finned copper tubes (see Figure 6). In order to heat the space, heated air should be delivered at least 15 °C above the space temperature, 20°C. Thus, the air should be delivered at 35 °C or above from the water to the coil. The reason for the large difference, 15 °C, is to limit the required quantity of air circulated to meet the heating requirements at reasonable levels. Also, as the difference becomes less, the fan and duct sizes become large and the fan power consumption can be excessive.

The above assumption is based on the fact that the geothermal water is suitable to flow directly through the water-to-air heat exchanger (coil); nevertheless, if hydrogen sulphide is present, then this gas will attack copper and solder in the coil and cause leakage and failure to the unit (Lund, 2010). The results for Mwananyamala indicated that hydrogen sulphide are generally <0.5 ppm although this might not be the case after drilling. Thus, in the event where the geothermal must be isolated from the heating system equipment, a plate heat exchanger is normally placed between the two circuits to protect the heating equipment [Rafferty, 2004]. A plate heat exchanger is then added to the water-to-water side of the equipment. All the previous temperatures are still valid; the difference is that the plate heat exchangers will require additional temperature input to maintain the space (home) temperature of 20 °C. As in the previous example a ΔT of 5 °C is required between the geothermal supply and the output from the secondary water. Thus, the new geothermal temperature required to meet the needs of the system is 50°C. The return geothermal water can only be cooled to 35 °C as a result of the intermediate water loop return temperature of 30 °C and the required 5 °C ΔT (see Figure 7).

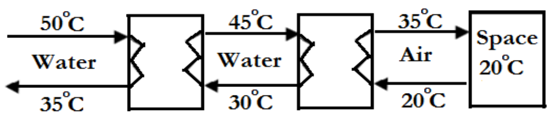


Figure 7: Space heating 15/10/5 rule with geothermal isolation plate heat exchanger (edited from Rafferty (2004)). Supply air to space air = 15 °C; Water/air heat exchanger = supply water to supply air of 10 °C; Water/water heat exchanger = supply water to supply water of 5 °C.

The mechanism of agricultural drying and dehydration is similar to greenhouse space heating but rather requires temperatures of between 40°C and 100°C as shown in Figure 8. Dying and dehydration tends to decrease post-harvest losses and extend shelf life; creates variety by widening the market, and; adds value, hence generating extra income for produce such as coconut meat, mangoes, among others.

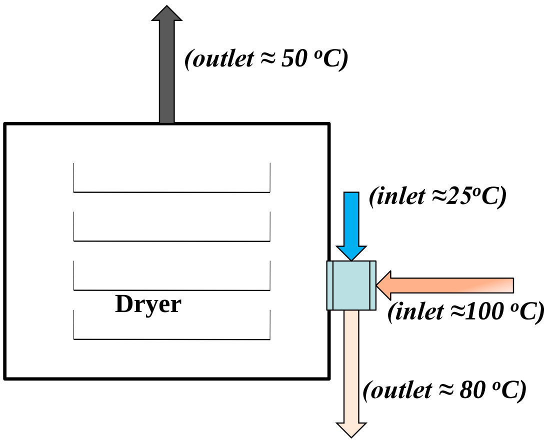


Figure 8: Agriculture drying and dehydration.

GENERAL DESIGN AND CONSIDERATION

Equipment Considerations

Although standardized equipment is used in most direct-use projects, two most important considerations are made for the nature of geothermal water quality and the temperature. The common engineering problems, corrosion and scaling, caused by the sometimes distinctive chemistry of geothermal fluids, may lead to operating problems when the equipment is exposed to flowing water. As shown in Figure 9, calcite scaling is most likely to occur whereas amorphous silica scaling is less likely. Dissolved oxygen, which is absent in most geothermal waters, except perhaps the lowest temperature waters is one of the main engineering concern. Design of storage tanks, among others, should be done in such a way that care is taken to prevent atmospheric oxygen from entering the waters in the system. The isolation of geothermal water by installing a heat exchanger may also solve this and similar water quality derived problems.

The most important apparatus of most low-temperature direct-use systems are downhole and circulation pumps, transmission and distribution pipelines, peaking or back-up plants, and various forms of heat extraction equipment. Fluid disposal is either surface or subsurface (injection).

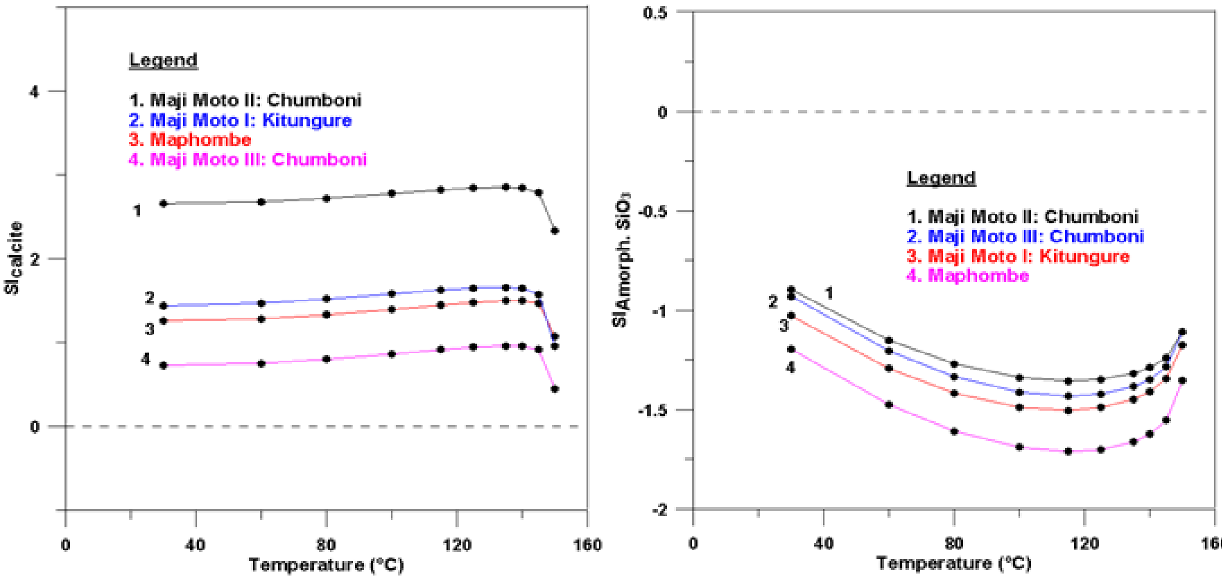


Figure 9: Calcite ($CaCO_3$) and Amorphous Silica (SiO_2) scaling potential.

A peaking system may be necessary to meet maximum load. This can be done by increasing the water temperature or by providing tank storage. Both options mean that fewer wells need to be drilled. The equipment used in direct-use projects represents several units of operations. The major units will now be described in the same order as seen by geothermal waters produced for district heating.

Economics Considerations

In common situations, geothermal projects require a fairly large initial capital investment, with small annual operating costs thereafter. Thus, the projects considered in the preceding sections, including with corresponding cost of production wells, pipelines, heat exchangers, and injection wells, may cost several million dollars. However the annual operation and maintenance costs for the geothermal is relatively low and more stable

Geothermal resources are known to fill many needs, but considered separately, some of the uses may not promise an attractive return on investment because of the high initial cost. Thus for Mwananyamala, multi-stage utilization of geothermal fluids would be appropriate, where lower and lower water temperatures are used in successive steps, in order to maximize benefits. A simple and complex schematic diagram showing proposed cascading or waste heat utilization plan for Mwananyamala Direct Utilization project is given in Figures 10 & 11.

Figure 10: Simplified schematic flow diagram of potential direct use for Mwananyamala geothermal prospect.

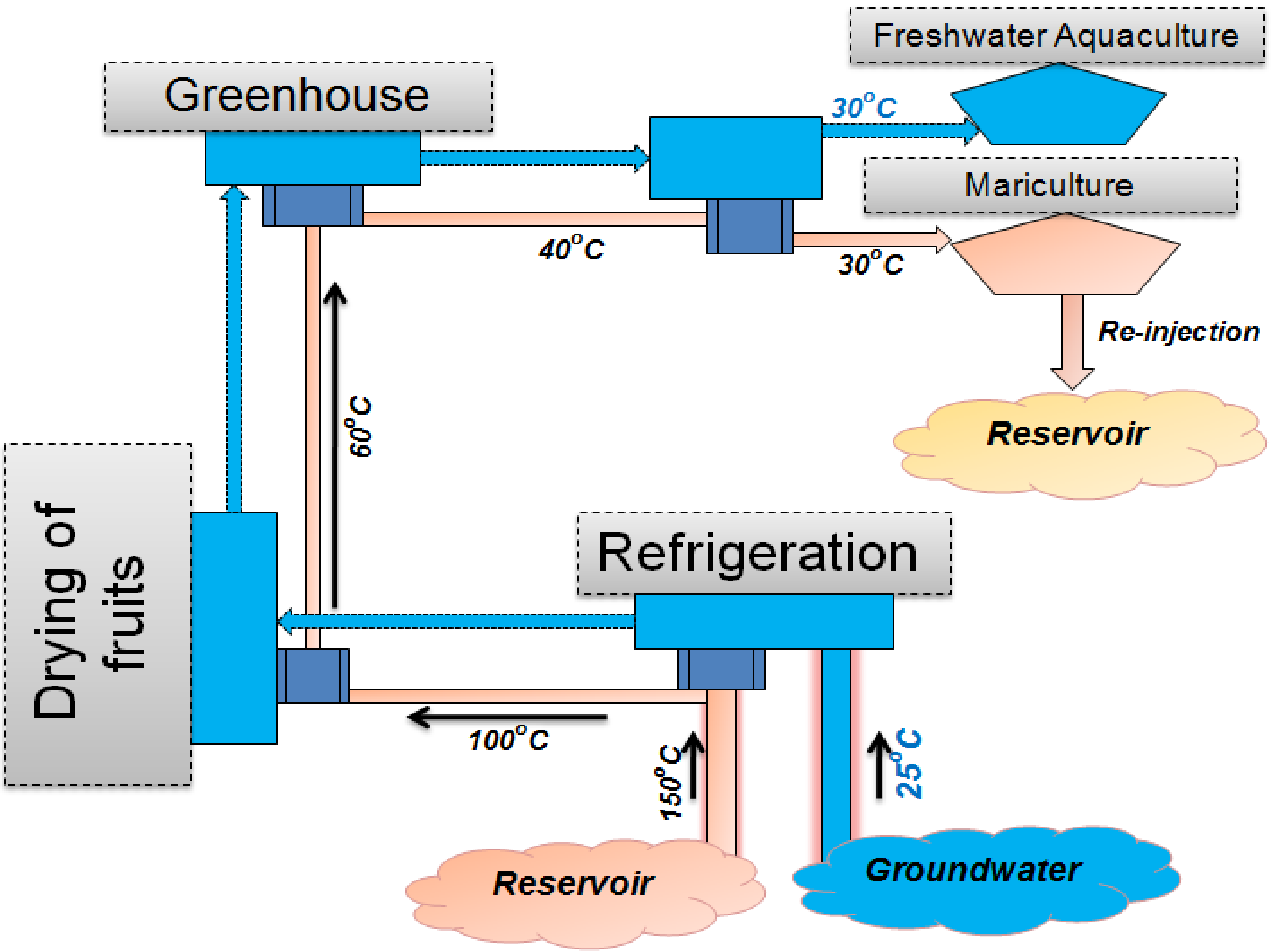
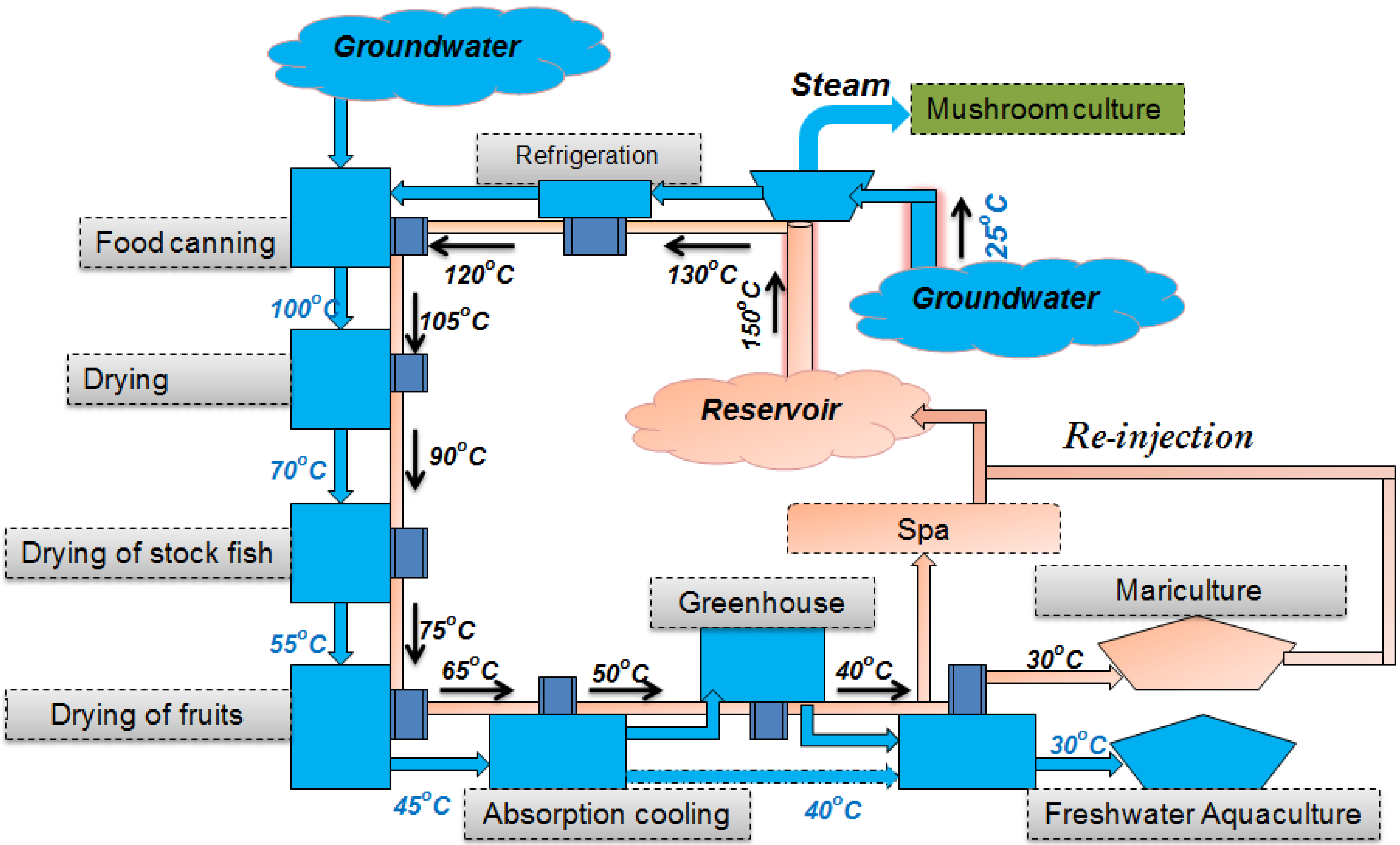


Figure 11: Complex schematic flow diagram of potential direct use for Mwananyamala geothermal prospect.



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