Chapter 19
Geothermal Energy for PICTs

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A geothermal approach to combine renewable energy and alternative design principles.

Abstract The following chapter explores the utilization of geothermal resources to provide energy, food, and water solutions in both urban and rural populations in the Pacific—several of which have vast geothermal reservoirs. A variety of geothermal-based technologies are presented providing alternative approaches to essential services such as electricity, food drying, refrigeration, and desalination. A set of design principles for geothermal solutions in the Pacific is also outlined and explored in further detail via a brief pre-feasibility case study for a geothermal village development on Tanna Island, Vanuatu. Finally, the opportunities of direct heat using underground geothermal implementations are discussed, indicating that these may well be an excellent means to provide low-cost solutions to rural areas, reduce investment risks associated with deeper geothermal well drills, and recycle waste heat to provide a wide range of services.

Keywords Geothermal · Heat · Refrigeration · Renewable · Energy · Sustainable · Development · Cascade · Nature · Vanuatu

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19.1 Introduction

Electricity requirements in rural Pacific communities are usually low, attributable to low levels of lighting, cooling loads, and phone charging (Sen and Ganguly 2017). Such requirements may be met with relatively small-scale systems. Photovoltaic installations have been extensively explored but have historically experienced vast challenges in terms of environmental durability (especially in the case of high levels of cyclone incidence), implementation programs, technical training, operation and maintenance, and replacement costs (Lefale and Lloyd 1993; Urmee and Harries 2009).

In terms of renewable sources at large, hydropower is a reliable and mature technology and constitutes a significant portion of total energy production in countries like Fiji, where it displays roughly 134 MW of capacity (or ~52% of total capacity) (IRENA 2015; Weir 2018). It is also an excellent option in its micro-hydro form to meet rural energy requirements (Kuang et al. 2016). However, it requires high rainfall, favourable land conformations, and a large initial investment (Weir 2018). Wind is an excellent solution given its maturity and resource abundance but is still in its early stages of monitoring and assessment in the Pacific (Mofor et al. 2013). Biomass is also traditionally used to meet cooking needs (Connell 2006) and can act as a diesel substitute or additive (Cloin 2007), but presents challenges associated with purpose-grown fuel (timber) displacing agriculture on limited cultivable land. More details on the challenges in the electrification of the Pacific may be found in Chap. 12 of this work and its references.

The Pacific rim is richly endowed in geothermal energy (Oppenheimer 2011). Most prominently, Papua New Guinea, Solomon Islands, Vanuatu, Fiji, Samoa, and Tonga could benefit from this natural underground power (Tawake, 2017). Utilization of this renewable resource can address many of the challenges related to energy access, renewable energy intermittency, rural poverty, fresh food, and clean water sources, thus addressing several of the Sustainable Development Goals (SDGs) set forth by the United Nations (SDGs 17 and 13 especially, but also supporting many others, including SDG 1, 2, 3, 6, and 11).

Geothermal energy, as a baseload power source where large energy storage capacity does not exist, is an ideal complement to other renewable energies such as solar, wind, tidal, and concentrated solar in particular. The longevity of geothermal power installations is also unparalleled in the energy landscape, allowing much of the early technology from the 1960s to still be used today (Fig. 19.1), while the reliable continuous heat supply pays off the initial high upfront investments many times over. Although geothermal energy is a highly competitive and important energy source in volcanic regions, raising enough capital is a major problem. Deep pockets are needed for upfront investment into exploration and drilling to ascertain viability. Consequently, there is an underappreciation of the vast geothermal resources present in several PICTs, with very few projects having been implemented (Lucas et al. 2017).

Fig. 19.1 The Black Current Generator currently in the Ohaaki Geothermal Power Station, New Zealand showcases the robustness of the technology where many early generators from the 1960s are still operable today (©Klaus Regenauer-Lieb)

At the appropriate scale, locally generated geothermal energy may be particularly attractive for small island communities in the Pacific due to their high dependency on imported diesel (which incurs high ongoing fuel costs) and the fixed costs of extending energy access to disperse and isolated settlements. The average cost of electricity paid by small domestic consumers across the Pacific varies dramatically depending on international diesel prices, electricity tariff subsidies, utility regulatory fees, and government taxes (Utilities Regulatory Authority of Vanuatu 2019). In general, the average electricity price in the Pacific is roughly 0.21 USD/kWh—or roughly on the same level as France, but with the Pacific having only 11% of its GDP per capita (Utilities Regulatory Authority of Vanuatu 2019; Statista 2021). This has placed a burden on island communities and is an immense barrier to rural electrification, as income in these areas is insufficient to bear energy costs (Dornan 2014).

Most geothermal power stations are large, costly, and can sometimes function as a nucleus for large subsidiary industries based around waste heat from the power plant. Pioneering installations in Iceland and New Zealand provide testimony of the economic and environmental success of subsidiary industries, displaying a plethora of waste heat uses including timber drying, food drying, aquaculture, greenhouses, and thermal spas (Dell et al. 2013; Kelly 2011).

However, there also exist plentiful small-scale geothermal solutions (Lund et al. 2005, 2011) which may be more aligned with the technological and financial capacity, and traditional modalities of living, of rural communities across the Pacific (Dornan 2014, Rousseau and Taylor 2012). Until large development banks provide investment capital and local land disputes are resolved, these small-scale systems provide a low capital entry into geothermal energy, mostly involving direct heat use rather than electricity generation. This greatly reduces the upfront capital needed and the risks associated with failed exploration drilling, environmental damages, and community project failures.

This chapter looks at alternative energy pathways to enable a transition from either a substantial diesel dependency or complete absence of modern energy services to geothermal developments. An extensive array of small-scale geothermal technologies are explored as meaningful solutions to secure water, energy, and food security in PICTs. Discussion of some larger scale systems is also included, although these are dependent on greater financial resources. A set of design principles centred around a bottom-up community approach and efficiency maximization is presented. A pre-feasibility case study for a remote community on Tanna Island in Vanuatu, conducted in partnership with University of New South Wales (UNSW), is also presented in support of the geothermal technologies and design principles hereby explored.

19.2 Geothermal Resource Assessment

South-western PICTs are located in an area with prominent seismic and volcanic activity. This activity is mainly driven by subduction zones formed between various oceanic plates (Fig. 19.2), or by deep mantle plumes interacting with surface plates (Petterson 2016). As a result, vast geothermal resources are present. Table 19.1 summarizes these as per McCoy-West et al. (2011). The countries with the highest number of thermal areas are Fiji, Papua New Guinea, and Vanuatu, with hot springs temperatures ranging from 30 °C to 200 °C. Other countries listed in Table 19.1 are either yet to be assessed in terms of geothermal potential or do not present any viable heat sources.

19.2.1 Geothermal Energy in Fiji

The Fijian Department of Energy, in collaboration with the International Renewable Energy Agency (IRENA), commissioned a Renewables Readiness Assessment (IRENA 2015). The report, which identifies a wide variety of opportunities for renewable developments in the country, features an overview of the geothermal potential in Fiji (Fig. 19.3). The currently known total geothermal capacity is reported as 42 MW for Vanua Levu (twice the island's current needs) and 28 MW for Viti Levu. Although hot spring activity is widespread and several development proposals have been put

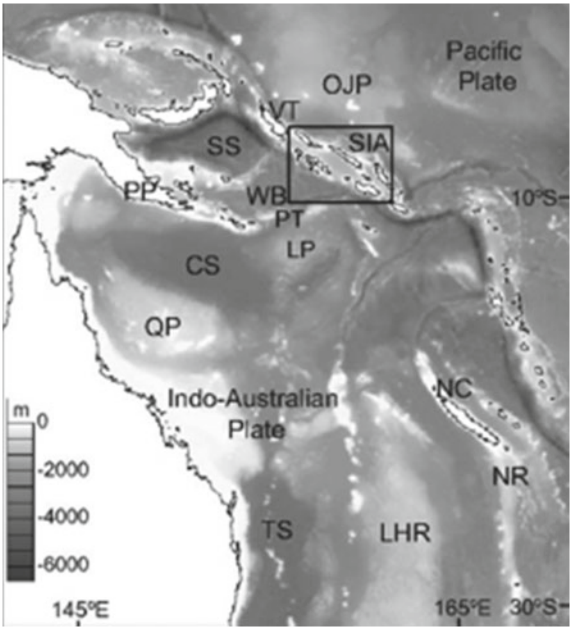

Fig. 19.2 Ocean bathymetry of South-West Pacific. The Solomon Island Arc (SIA) is highlighted as a zone with high convergence between the Indo-Australian and Pacific plates (©Tapster et al. 2014 Geological Society of America. Gold Open Access. This paper is published under the terms of the CC-BY license. Figure created with GeoMapApp (www.geomapapp.org) / CC BY)

forward, there has been no exploratory drilling at the time of the publication of this book.

A suitable area for geothermal applications is the Savusavu hot spring area, in Vanua Levu. The boiling springs are currently used for cooking purposes (Fig. 19.4) and were described by early European explorers as displaying an intermittent geyser behaviour with hot water ejections at 12–18 m of height (Guppy 1903; Cox 1980), although these have now ceased. Ásmundsson (2008) provides the most recent publicly available scientific report on the South Pacific's hot spring activity, reporting at least eight thermal springs near Savusavu.

Key information from a Japanese Government report to the Fiji Government in 2009 was released stating that there is "a potential for 23 MW of geothermal-based electricity generation in Vanua Levu, at least 20 MW of which is near to the urban centres of Savusavu and Labasa (10 MW is near to each grid)" (IRENA 2015).

In the medium to long term, the Fijian Government proposes to build a new USD 600 m (excluding exploration costs) geothermal installation with a 150 MW_e geothermal capacity (Fiji Ministry of Economy 2018). Although geothermal energy is a highly competitive and an important energy source in volcanic regions, raising sufficient capital to cover the high upfront costs of exploration to ascertain viability is a major barrier to its implementation (Richter 2017).

Table 19.1 Summary of geothermal resources in PICTs, including indication of temperatures recorded at various hot spring locations, the state of geothermal developments, and volcanic activity.

	Youngest volcanism	Heat source	Geothermal locations	Hot Spring temperature range (°C)	Development barriers	Development potential
Fiji	Last 50 ka	Excellent	53 thermal areas	31–102	–	High
Papua New Guinea	Last 500 a	Excellent	41 thermal areas	36–101	Rugged Terrain	High
Vanuatu	Last 500 a	Good	20 thermal areas	30–200	Active Volcanism	High to moderate
Tonga	Last 500 a	Good	Hot springs	–	Distance to population	Moderate
N. Marianas Islands	Last 500 a	Excellent	Submarine only	–	Active Volcanism	High to moderate
Samoa	Last 500 a	Good	Prospective rift valley	–	–	Moderate
Solomon Islands	Last 500 a	Good	8 thermal areas	57–99	–	High to moderate
New Caledonia	Unknown	Unknown	2 thermal areas	22–43	–	Moderate
French Polynesia	Last 50 ka	Possible	Submarine?	–	–	Low to moderate
American Samoa	~1 Ma	Possible	None	–	–	Low
Cook Islands	1.5 Ma	Possible	None	–	–	Low
Pitcairn	0.45 Ma	Possible	None	–	–	Low
Palau	~20 Ma	None	None	–	–	Extremely low
Guam	~32 Ma	None	None	–	–	Extremely low
Niue	>20 Ma	None	None	–	–	Extremely low
Kiribati	~80 Ma	None	None	–	–	Extremely low
Marshall Islands	~80 Ma	None	None	–	–	Extremely low
Micronesia	Unknown	None	None	–	–	Extremely low
Nauru	Unknown	None	None	–	–	Extremely low

(continued)

Table 19.1 (continued)

	Youngest volcanism	Heat source	Geothermal locations	Hot Spring temperature range (°C)	Development barriers	Development potential
Tuvalu	Unknown	None	None	–	–	Extremely low

(Adapted from McCoy-West et al. 2011)

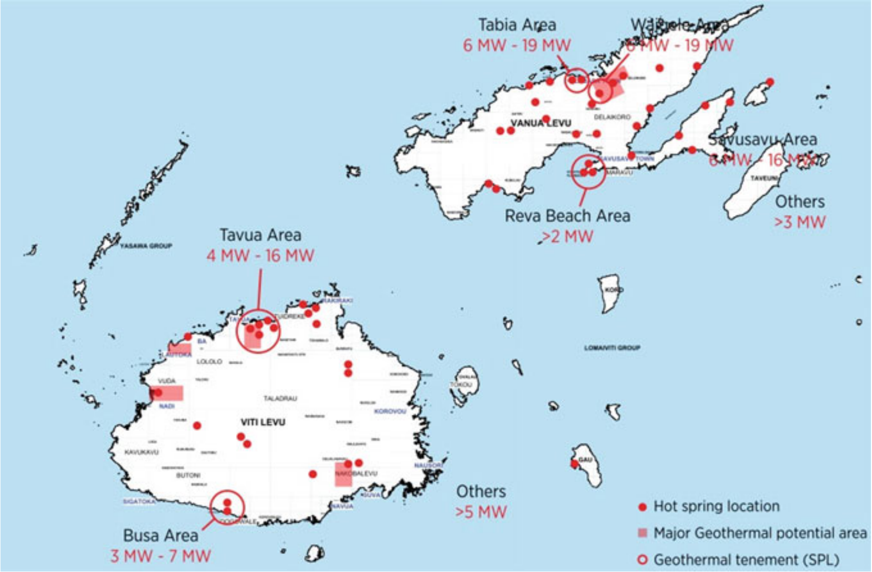

Fig. 19.3 Geothermal potential of Fiji compiled by the Government of Fiji, Rapid Assessment and Gap Analysis February 2014 (©IRENA 2015)

19.2.2 Geothermal Energy in Papua New Guinea

Geothermal resources in Papua New Guinea (PNG) may be of either volcanic or radiogenic nature due to the geological makeup of the area, which is also rich in copper and gold deposits (Berhane and Mosusu 1997; Williamson and Hancock 2005; Kawagle 2005). Several reconnaissance studies, some of which are associated with mining interests, have been conducted, especially in New Britain in the Islands Region of PNG (McCoy-West et al. 2011; Williamson and Hancock 2005). However, there is a lack of geochemical and geophysical data in the public domain for many areas. Figure 19.5 provides an overview of the country's geothermal areas.

The sole geothermal electricity development in PNG is a 68 MW plant located at Newcrest's Lihir epithermal gold mine in New Ireland in the Islands Region of PNG, accessing a 240–300 °C hydrothermal reservoir (Australian Geothermal

Fig. 19.4 Near-boiling temperature hot spring in Savusavu used for cooking. Chemical analysis of the hot spring water suggests 170 °C at depth in this area—although slim holes drilled to a depth of at least 800 m are recommended for confirmation (Ásmundsson 2008), © Klaus Regenauer-Lieb

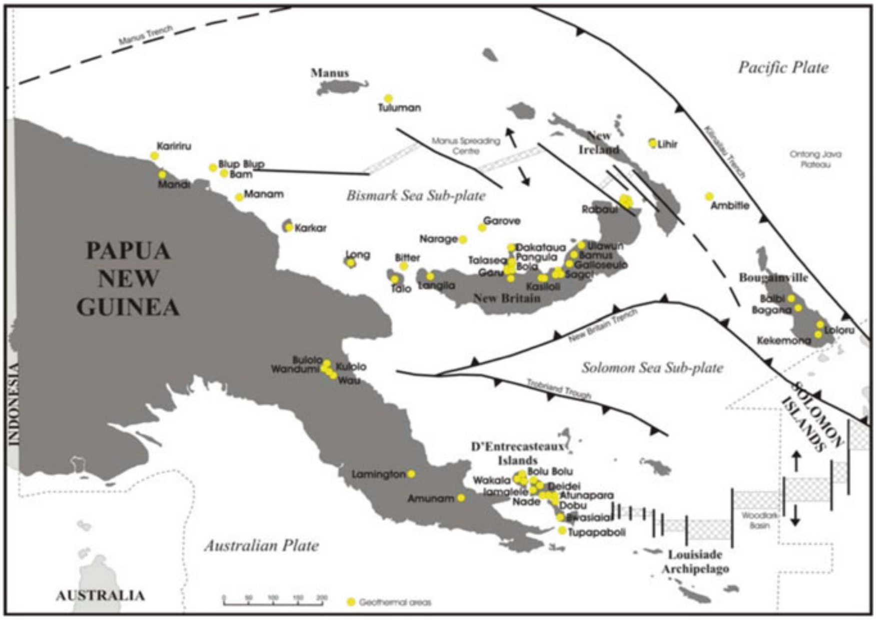

Fig. 19.5 Overview of geothermal areas in PNG (*Source* McCoy-West et al. 2011)

Association 2020). There are two main reservoirs on-site: a shallow reservoir (5–600 m, 240–250 °C) and a deep reservoir (>1000 m, 250–300 °C). Several drillings were carried out to depressurize the geothermal aquifers to allow for on-site mining. The geothermal plant was initially developed in 2003 with a 6 MW_e capacity, with successive developments in study phase.

Strong interest has been expressed in geothermal energy due to the region's high fossil fuel prices (maximum retail diesel price around USD 0.94/L [Vukikomoala and Wainibalagi 2019]) and the haphazard nature of the hydrological cycles for the country's hydropower plants (Kuna and Zehner 2015). It was also suggested that small-scale geothermal systems may prove to be beneficial for the development of rapidly growing communities across the country (McCoy-West et al. 2011).

On August 18, 2020, a PNG government press release introduced the country's novel Geothermal Resource Policy. Under the policy, all explorations and developments related to geothermal resources are allowed under governance of the Mineral Resources Authority (via the Mining Act 1992), thus providing a dedicated legislative and regulatory framework for developers. Previously, permit applications for developments of this kind were submitted as mineral exploration campaigns or under various mining legislations, resulting in only two applications having been submitted historically (Australian Geothermal Association 2020).

19.2.3 Geothermal Energy in Vanuatu

The volcanic island group of Vanuatu features many geothermal areas (Fig. 19.6) associated with the New Hebrides Trench—a 1200 km long volcanic arc generated by the eastward subduction of the Australian plate beneath the Pacific plate (Brothelande et al. 2016a). There are nine active volcanoes across the country. The main island, Efate, has 21 known hot springs, 15 on Vanua Lava, 12 on Tanna and 10 on Gaua (Brooks 2015). Other islands are also richly endowed in geothermal activity, providing ample local energy resources.

An Australian geothermal company KUTh (now ReNu Energy), obtained prospecting licenses in 2009 and upon completion of initial geophysical and geochemical explorations proposed to construct a 4 MW geothermal power plant on Efate (at site C in Fig. 19.7) in close proximity to the Takara hot spring (KuTh Energy 2010). Environmental and social impact studies have been completed, highlighting a 'medium' residual risk factor for all impacts and a few potential long-term impacts in the social space—mainly relating to perceived inequalities and the marginalization of vulnerable groups (Geodynamics 2014). However, exploration drilling has not yet commenced due to the high cost of drilling (Richter 2017).

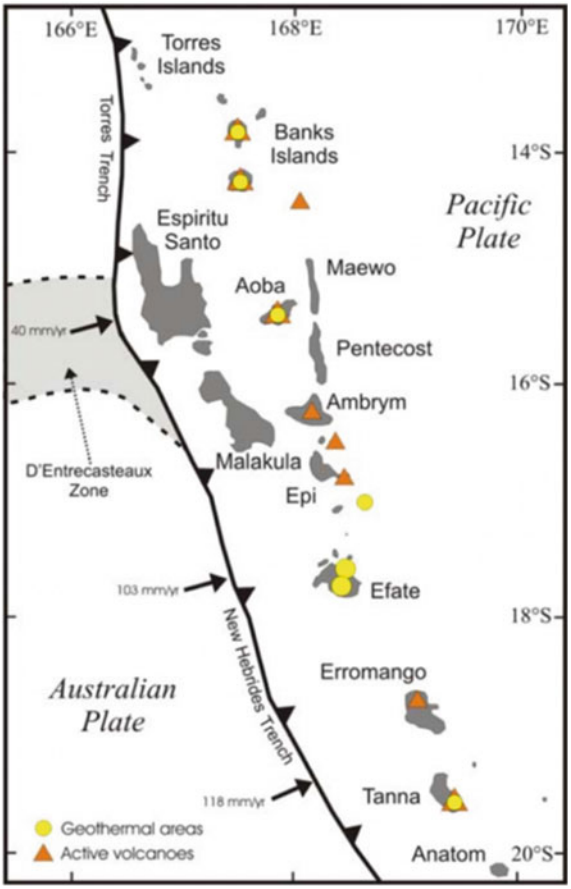

Fig. 19.6 Geothermal areas and active volcanoes in Vanuatu (*Source* McCoy-West et al. 2011)

19.2.3.1 Case Study: Tanna Island

Tanna Island is an excellent example of abundant unexploited heat sources suitable for geothermal developments. Some preliminary resource assessments for Tanna Island have been conducted by the Vanuatu governmental Geology Mines Unit in conjunction with several international laboratories and independent researchers (Bloomberg and Leodoro 2016). These include water sampling studies and the development of hydrothermal models for the region, which describe the behaviour of the geothermal reservoirs. However, more comprehensive geophysical, chemical, and remote sensing assessments are required to understand the exploitability of this resource.

On Tanna all geothermal activities are associated with resurgence processes of the underlying Siwi caldera; a large volcanic crater area formed by a previous major eruption. A study by Brothelande et al. (2016b) has suggested that the high degassing rates of sulphur dioxide in the area may signify high associated levels of basaltic magma intrusion. This process is directly related to the substantial uplifting of important

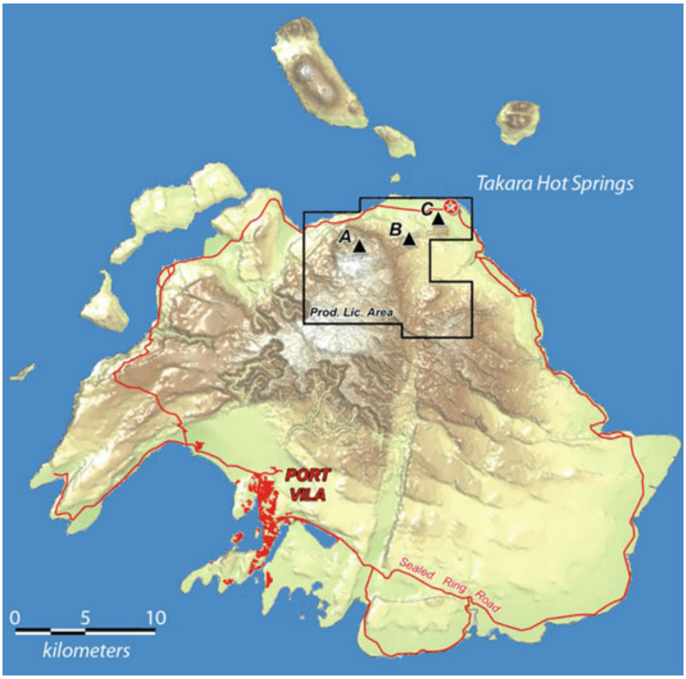

Fig. 19.7 Proposed site of the geothermal power plant near Takara Hot Springs in Efate Vanuatu, at site C. A and B indicate alternative sites for the proposed geothermal installation (*Source* Brooks 2015)

geological features and thus a frequent seismic activity (with first activities recorded by western researchers in 1878 [Patton 1894]).

The caldera zone (Fig. 19.8) also displays an active volcano, Mount Yasur (361 m above sea level). Its continuous eruptions may indicate high-temperature magma-hydrothermal systems (Merle et al. 2013), which are optimal for larger geothermal power plants. These eruptions have also shaped the geological landscape of the area, forming large lava and ash plains with mounds several meters deep.

Ancient magma-driven geological processes have also allowed for the development of the island's rich coral reef terraces, indicating a stark link between its geothermal resources and rich ecological features (Métrich et al. 2011). A study by Merle et al. (2013) has also analyzed various geological features of the area to provide insights on how the caldera zone may change in the long-term through magmatic migration.

As per a study of Bloomberg and Leodoro (2016) water samples from four different geothermal sources in this area indicate high acidic contents and a mix of meteoric and seawater signatures, suggesting various modes of hydrothermal spring recharge. Geothermometry measurements suggest that underground reservoir waters

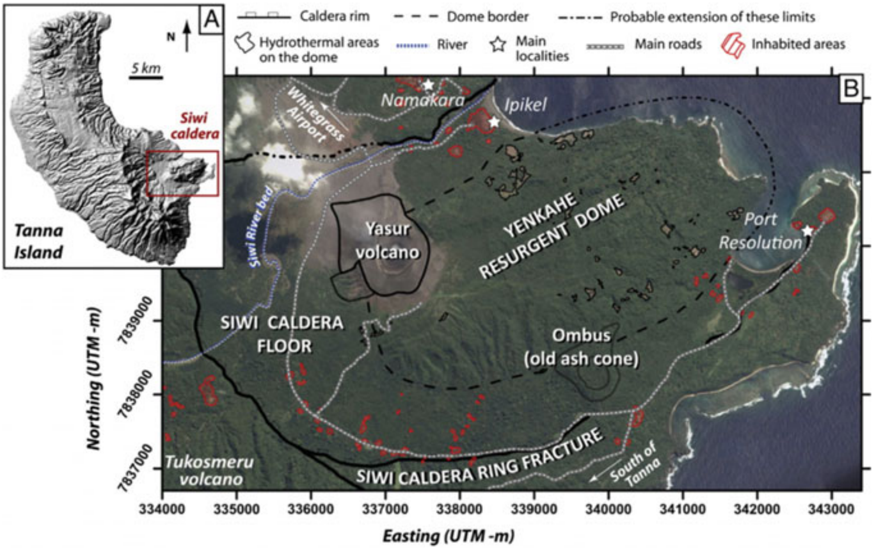

Fig. 19.8 Map of the Siwi caldera area with important surveying features, such as waterways and inhabited areas. Unvegetated areas are marked as surface geothermal features (*Source* Brothelande et al. 2016a)

boil during ascent and some surface hot springs have recorded discharge temperatures of up to 200 °C, thus suggesting the presence of a low-depth high-temperature heat source. This low depth simplifies drilling endeavours and opens up to a wide variety of geothermal applications including Organic Rankine Cycle plants.

Hydrothermal models of Tanna were also developed (Figs. 19.9 and 19.10) in accordance with an electrical conductivity mapping study conducted by Brothelande et al. (2016a) which had previously indicated potential geological facilitators of fluid flow, such as underground faults. The model includes seawater intrusions, meteoric recharge pathways, ascension/descension patterns, fracture zones, and surface spring manifestations. Overall, the understanding of this geothermal source's behaviour, and others that are similar, is crucial to effectively install technologies to provide energy, food, and water services, as explored in the following section.

19.3 Geothermal Solutions

Technologies that employ geothermal heat to provide a wide range of services, including power generation, refrigeration, and desalination, offer opportunity to improve water, energy, and food security. This section provides the reader with an extensive coverage of geothermal approaches to the energy, food, and water nexus, suitable for implementation in the Pacific.

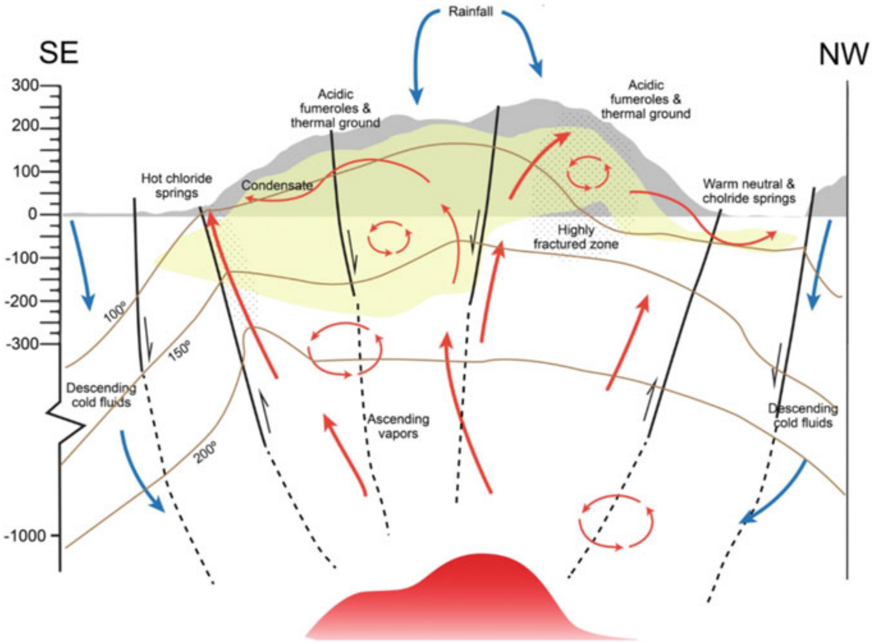

Fig. 19.9 Lateral section of the Siwi caldera (*Source* Bloomberg and Leodoro 2016)

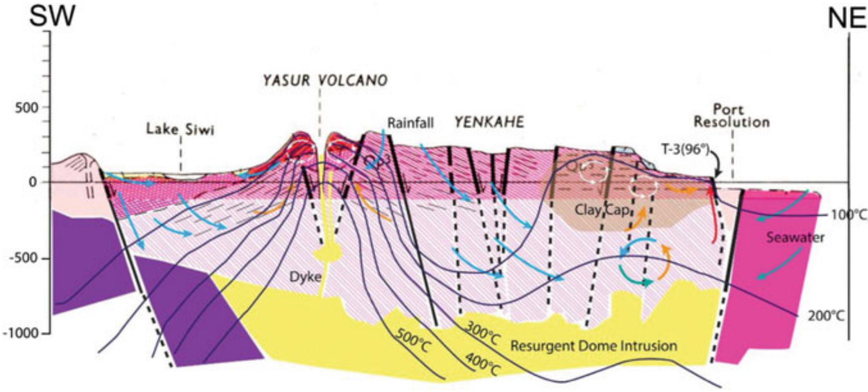

Fig. 19.10 Longitudinal section of the Siwi caldera (*Source* Bloomberg and Leodoro 2016)

19.3.1 Energy

19.3.1.1 Thermosyphons

Thermosyphons are passive thermal management systems based on the natural convection of the working fluid between a hot and a cold source and thus are ideal to displace heat from one location to another. Thermosyphon systems are used in solar hot water units and are also considered for efficient next-generation superconducting machine designs which have cooling loads in excess of the MW range (Yamaguchi et al. 2019). Thermosyphon systems have also been proposed for electricity generation from low-temperature geothermal heat (Li and Liu 2011; Teimouri and Behzadmehr 2019; Eavor 2021). Thermosyphons could be used in PICTs to harvest heat from shallow geothermal reservoirs for either direct-use applications or power generation in small communities, thus being an important technology to enable access to heat and electricity. However, their usefulness has not yet been demonstrated in practical applications in the Pacific.

19.3.1.2 Electricity

Geothermal power plants vary in scope accordingly to their scale and temperature (DiPippo 2015; Bertani 2016). Large high-temperature systems require deep wells and are the most efficient (direct steam flash). These are usually intended for baseload power in widely interconnected electricity grids as they foresee low energy costs. Small low-to-medium temperature systems are less efficient but foresee smaller capital costs and shallower wells. This makes them more suitable for rural communities which may not have access to an electricity grid.

Organic Rankine Cycle (ORC) power plants (Fig. 19.11) operate on an organic working fluid which vaporizes at reasonably low temperatures (low-to-medium enthalpy). These plants accommodate a wide range of temperatures for the geothermal fluid (90–150 °C) and are therefore highly flexible. Alternatively, smaller power solutions could involve the use of underground thermopiles using the Seebeck Effect to convert a temperature gradient into an electric voltage, or nearshore thermosyphon-turbine-generator systems installed in low-tide conditions to exploit the temperature difference between an underground geothermal reservoir and the cooler, overlying seawater.

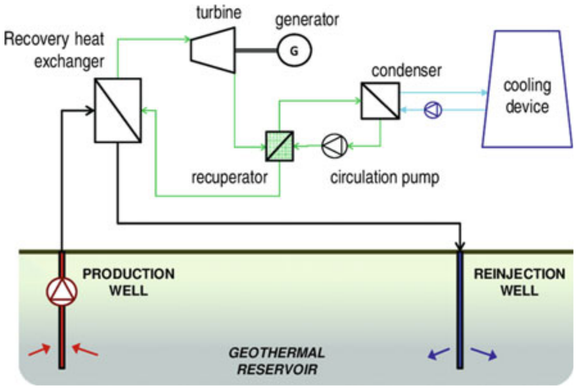

Fig. 19.11 Configuration of an Organic Rankine Cycle plant (©2017 Franco and Vaccaro, CC BY 3.0)

19.3.2 Food

19.3.2.1 Food drying

Food drying is an excellent means of enhancing food product value and creating alternative pathways for food preservation (Chua and Chou 2003). In the Pacific, drying is also used for copra production and the preservation and export of kava, a plant which is used as a beverage with depressant effects utilized in many traditional ceremonies (Lebot et al. 1997). Geothermal drying setups for produce have already been invented in communities living in off-grid areas in both Fiji and Vanuatu. The designs range from gravity-fed geothermal water in between two corrugated iron sheets to dry copra on the top heated surface, to simply exposing the food product to heat from volcanic vents. The latter can contaminate food with sulphur, arsenic, and other noxious compounds present in volcanic gases.

Extrapolating from these local implementations, Fig. 19.12 displays a conceptual design of a low-cost food drying system. This design foresees natural air flow and a multi-tier drying chamber made of bamboo, selected for its versatility, natural abundance in the Pacific, and the augmentation of its structural properties with prolonged heat exposure (McNamara and Prasad 2014; Shangguan et al. 2016). It also presents a variety of node-based construction techniques which render it highly suitable in low-resource environments, where nails and adhesives may be scarce (Schröder 2021). Soil, rock, and ash (perhaps collected by nearby volcanic ash mounds, provided low levels of biotoxicity are ascertained) may be used to fill the interface between the geothermal heat reservoir and the food drying environment to achieve optimal temperatures within the drying chamber. Support structures may also be optimized to facilitate drying of typical products. For example, low-level drainage systems may be integrated in the base heat plate to remove excess water from coconut kernels, thus ensuring optimal dryness within the chamber and minimizing pre-treatment.

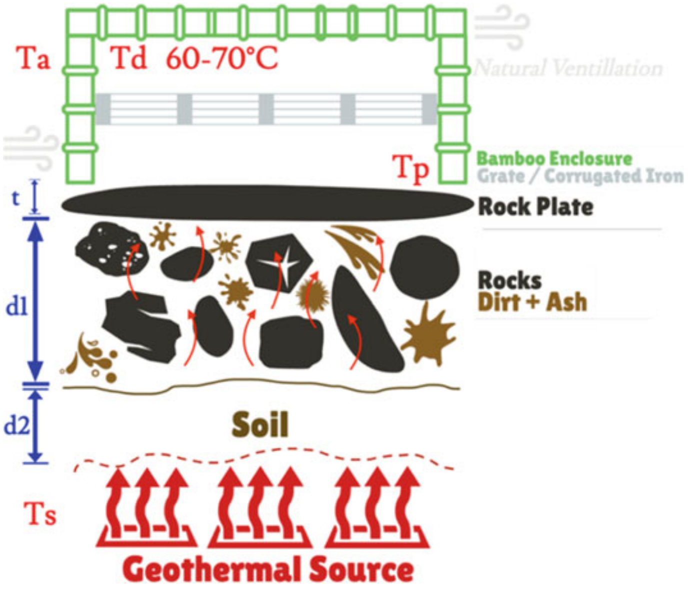

Fig. 19.12 Schematic of a conceptual design for a direct heat use geothermal passive food dryer based on conduction through a dirt, ash, and rock mesh. Uncomplicated architectures and material layouts make the implementation of this design straightforward and within local capacities for rural PICT areas. Relevant material thicknesses (t, d_1, d_2) may be optimized to achieve a drying temperature (T_d) of 60–70 °C and an optimally associate plate temperature (T_p). This optimization depends on the geothermal source temperature (T_s) and ambient temperature (T_a), as well as average ventilation speeds and the thermal properties of the materials involved. Diffusion-based or heat-and-mass-transfer models may be used to model the system's behaviour (Jay et al. 2005; Kumar et al. 2012) to ensure moisture is reduced to below 25% (©Edoardo Santagata)

19.3.2.2 Refrigeration

Remote communities in PICTs have limited means to store food, although customary ways have long been practised for traditional staple crops, such as drying, fermentation, and storage in dedicated huts (Malolo et al. 1999). The proposed geothermal cooling solution is based on replacing electrically driven vapour compression chillers with heat driven sorption chillers (refrigerator/freezer). The technology is highly scalable so that it may service cooling needs for large commercial buildings, including universities, hospitals, hotels, airports, server rooms, and shopping centres. Hot geothermal water as the principal power source is the most energy efficient means of heating and, counterintuitively, cooling. Ab(d)sorption chillers (for high and low temperatures respectively) have so far only found a niche market for camping and off-grid uses. However, they could also be scaled to use the waste heat from large-scale energy applications, such as an ORC plant, to service an adherent cooling load.

This refrigeration technology (Fig. 19.13) is similar to the ubiquitous electrically driven technology, with the main difference consisting of the use of a thermochemical

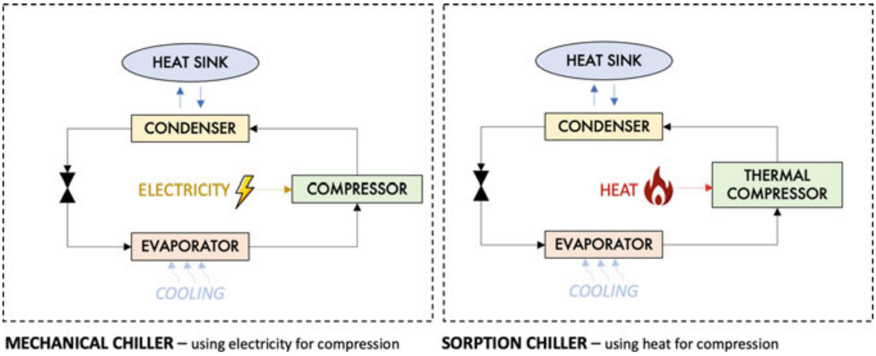

Fig. 19.13 Mechanical chillers versus Sorption chillers (©Edoardo Santagata)

compressor instead of an electric compressor. A small source of electricity is still required for circulating the working fluid, but the pumping power is minor and can be provided by an off-grid photovoltaic (PV) system or a small generator.

Sorption chillers have fewer moving parts and are quieter and more robust than mechanical compressors. This is another reason making them an ideal fit for installation in remote communities, since the need for technical maintenance is reduced. The use of thermal chillers is widespread in tri-generation facilities which supply electricity and use waste heat from a generator to drive absorption chillers for air conditioning settlements in hot climates (Eveloy et al. 2014). Even in cold climates the cooling technology has been used with great effect (Holdmann 2016; Yifru Woldemariam 2019).

19.3.2.3 Greenhouses and Fish Farming

Self-subsistent agriculture and fishing are some of the core foundations of life in many Pacific rural communities. Techniques to enhance these practices via geothermal heat may be beneficial to ensure food security, augment production, and refocus resource utilization practices to facilitate natural resource regeneration (Goldburg and Naylor 2005).

Geothermal heat may be used to ensure stable temperatures for both vegetation and fish; both of which thrive in a range of preferred temperatures. This temperature preferentiality may be used advantageously to farm high-value and high-nutrition species which would otherwise perish in the local environment. This provides new opportunities for both nutrition and small-scale commercial farming and prevents infestations on behalf of non-native species; to which Pacific ecosystems are particularly sensitive due to their condensed nature (Hay and Bells 2007).

Greenhouse heating/cooling may be provided by ground-coupled dual-loop heat pump systems (Fig. 19.14). Cooling occurs by allowing refrigerants in a primary heat pump-driven loop to transfer heat to a secondary underground recirculating

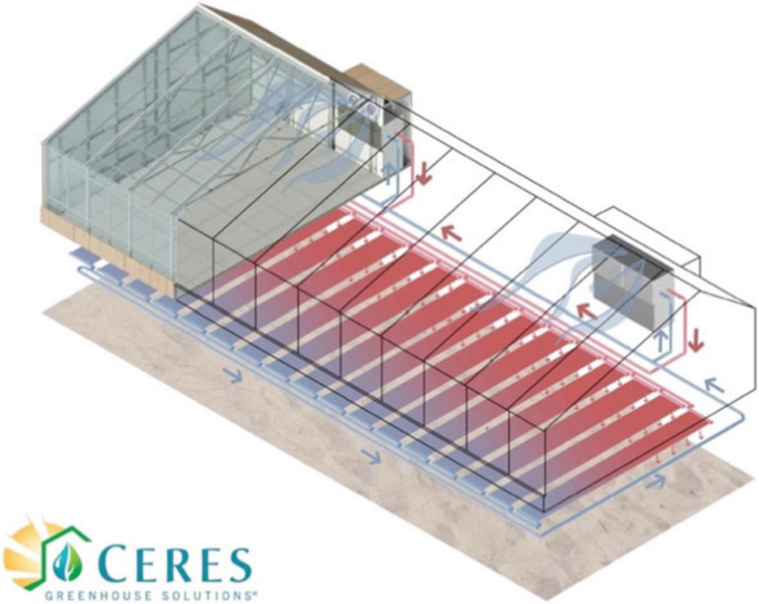

Fig. 19.14 EcoLoop™ design by the company Ceres to provide heating and cooling to greenhouses (*Source* Ceres 2020)

water loop. Conversely, heating on cold days occurs by absorbing heat stored in the underground loop. In colder climates (e.g., New Zealand), a simpler solution may be adopted by excavating 1–3 m trenches to insert earth tubes, which draw air from the external environment, heat it up using the geothermal source, and carry it inside the greenhouse. Geothermal boreholes for soil heating have also successfully been used to improve agricultural outputs in cold climates (Dell et al. 2011). Similar principles may be implemented for the pond bottom of aquaculture facilities with heat transfer via thermosyphons or direct contact with the geothermal reservoir.

19.3.3 Water

19.3.3.1 Desalination

Although most PICTs receive ample rain, water scarcity is still prevalent due to unfavourable groundwater recharge layouts for small islands, rain shadow areas formed by mountains, and insufficient landmass for rainwater capture (as detailed in Chaps. 2 and 5). As such, water is still being shipped to many small islands during drought (Falkland 2002; SPC 2007). Infrastructure to capture rainfall and clean local water supplies is also insufficient, especially on low lying atoll islands (Falkland

2002). Obtaining clean water is therefore one of the highest priorities to improve the standard of living in the region (UN 2021).

Geothermal desalination involves the use of geothermal heat to evaporate salt water to remove the salt and render it potable. This process does not require electricity and therefore can operate safely in off-grid communities. Basic daily potable water access per capita is defined to be 20 L, within a 1 km or 30 min round-trip, and optimal water access is 100–200 L, via multiple taps in each household (WHO 2017).

Thermal distillation can function with a low-temperature heat source and is highly robust. Aristotle (384–322 BC) reported Greek sailors harvesting freshwater from ocean water by thermal distillation (Ross 1931). It constitutes a significant proportion of current freshwater generation through modern Multi-Effect-Distillation (MED) and Multi-Stage Flash (MSF) facilities that use waste heat from power generation as a convenient energy source. In small-scale operations, the most frequent heat source is a wood-fired oven. Modern MED facilities (Fig. 19.15) can run down to a temperature of 55°C and produce freshwater from natural hot groundwater systems at a competitive price, even where geothermal surface manifestations are absent (Christ et al. 2017).

The design specifications for industrial scale freshwater generation are ideal for town water supply and ships, but for remote communities, a single-effect desalination unit would be sufficient as it produces 1000 L/day (Fig. 19.16). This device has very compact dimensions and is based on a plate-type heat exchanger. Many similar devices are available commercially. Commercially available emergency freshwater generators that do not require electricity are also available. These rely on heat to evaporate and recondense water to remove pathogens. A design of this sort may be more suitable for Pacific rural communities with no electricity.

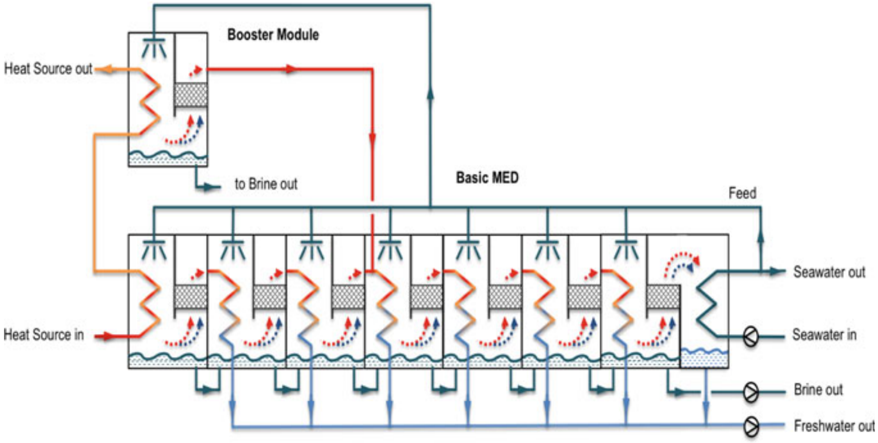

Fig. 19.15 A compact Multi-Effect-Distillation (MED) design uses a cascade of evaporation and condensation chambers where the latent heat of the condensers is used as a heat input for the next distillation step operating at lower temperatures and lower pressures. A patented compact design is shown where a steam booster increases the freshwater yield (©Christ et al. 2015)

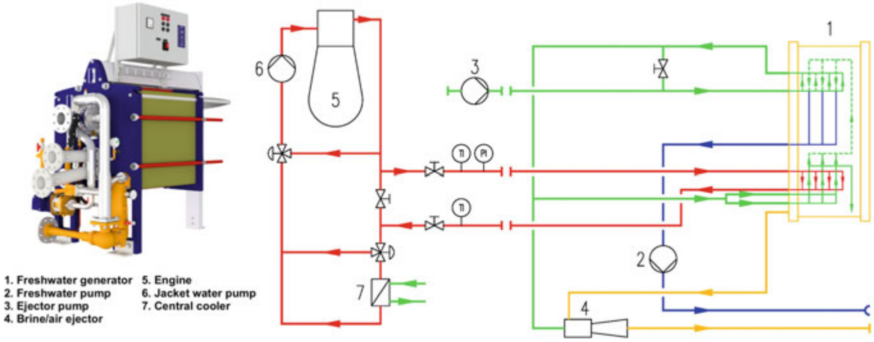

Fig. 19.16 Single effect desalination unit developed by the company Alfa Laval. The plate-type heat exchanger design is titanium-coated and is easy to clean in the event of fouling. A small source of electricity is still required to drive the vacuum and circulation pumps (©Alfa Laval, 2015-2023)

19.3.3.2 Ecotourism

Ecotourism provides the means of establishing income streams which are reliant on the sustainable preservation of local natural resources (Su et al. 2014; Wall 1997). The construction of non-invasive low-cost tourist facilities may help well-placed communities to gain revenue by providing access to natural geothermal baths, saunas, and balneotherapy centres. The use of geothermal water for bathing and curing ailments has also been part of some traditional Maori cultures in New Zealand (Neilson et al. 2010), thus demonstrating a linkage to culture and traditional living practices.

19.3.4 Nexus

The use of indigenous geothermal resources provides the opportunity to achieve interconnected developments which are conducive to water, energy, and food security in the Pacific. The common reliance on geothermal heat to desalinate water, produce energy, and assist with food processing/preservation is at the forefront of achieving the nexus ideal—providing each necessity in a harmonious and interconnected fashion. The robust nature of the presented solutions allows for the integration of processes which improve efficiency (such as geothermal cascading, explored in Sect. 19.4.2) and ensures that PICTs with geothermal resources may maintain the nexus' functionality with more financial and technical independence. The elimination of external dependence for fuel, water, and food imports allows for significant import savings and shields PICTs against the economic and resource stressors experienced by the disruption of shipping supply chains, such as in the case of the COVID-19 pandemic (Kim et al. 2020; Richardson and Hitchins 2021).

19.4 Design Principles for Geothermal Developments

Two key design principles suggested for geothermal developments are integration with nature and society and geothermal cascading. These focus on the establishment of self-sufficient development support cycles (for low levels of development) and efficiency maximization (for higher levels of development).

19.4.1 Integration with Natural and Social Systems

The viability of geothermal projects in PICTs, especially in rural areas, can be greatly enhanced by designing appropriate and sustainable heat-based services as part of a nature-integrated and socially coherent system that focus on robustness, autarky (i.e., self-reliance at a national level), and low social and environmental impacts. Basic requirements to satisfy day-to-day needs, such as food drying to preserve food and desalination to provide potable water, are best met with techniques that draw inspiration from traditional indigenous practices and natural systems. This approach ensures that the resources, materials, and skills required to assemble most projects are readily available (as they are locally sourced and familiar) and independent of the typical developmental project barriers associated with unsuitable financial structures and limited technical capacity (Dornan 2014; Surroop et al. 2018).

Where possible, designing and building using locally grown products (such as bamboo or palms—which can also be dried with geothermal heat to avoid shrinkage, swelling, and contamination), native rocks and minerals, and traditional engineering architectures reduces costs, ensures minimal dependence on external participants, and relieves projects of all problems relevant to the import and installation of replacement parts. In most cases, technologies developed in this manner are also more consistent with the existing technical aptitudes and traditional modes of living of local residents. The additional technical, social, political, and financial complexity introduced by high-tech solutions may result in outcomes in direct contrast with the advocations of energy development projects (Banks 1993; Tisdell 2002; Karekezi et al. 2006).

There is also ample evidence supporting the inclusion of sustainable and culturally relevant approaches within energy project conceptions and operational mechanisms for rural developments, in both an environmental and financial sense (Ferrer-Martí et al. 2012; Ramani 2004; Rehman et al. 2010; Xiaohua and Zhenmin 2002). Traditional economic dynamics, prominent in many PICTs (Rosseau and Taylor 2012), may also be embedded in project cycles to render justice to traditional modes of living and ensure local participation. These take the form of rethinking project operation in the local sociocultural framework as opposed to traditional business-oriented frameworks.

19.4.2 Geothermal Cascading

The concept of cascading thermal recovery in low-to-medium enthalpy geothermal applications has been plentifully discussed in literature and industry (Lindal 1973; Regenauer-Lieb 2011b; Rubio-Maya et al. 2015). The sequencing of cascaded heat systems (Fig. 19.17) is designed to obtain maximum utilization of the harvested geothermal heat to meet a variety of services with optimal efficiency. As such, warmer processes are encountered by the geothermal fluid first and cooler processes last. Services which may function in this regime include electricity production (via the integration of power plants, such as ORC plants), heating, cooling, refrigeration, cattle breeding, incubators, milk pasteurization, greenhouses, fish farming, food processing, industrial drying (including timber drying), water desalination, bathing areas, and saunas.

A few practical examples of these implementations exist, including the famous Unterhaching community network in Germany (38 MWth, 3 MWe). Many development proposals in this fashion also exist, including ones for the Eburru and Barrier communities in Kenya, the Sabalan geothermal region in Iran, the Kozani-8 geothermal well in Albania, and Alkimos city in Western Australia (discontinued due to an unsuccessful bid) (Regenauer-Lieb 2011a; Nevton et al. 2012; Rubio-Maya et al. 2015).

There are various technical and economic barriers to the implementation of these cascading systems, such as high upfront costs, few demonstration projects, and high retrofitting expenses, which are usually more substantial than ones incurred from building interconnected heat systems anew. To some degree, undeveloped rural areas provide an advantage in this case, as little-to-no pre-existing infrastructure exists. Cascading interconnections require extensive planning and well-defined maintenance and fault identification protocols to ensure system functionality, efficiency,

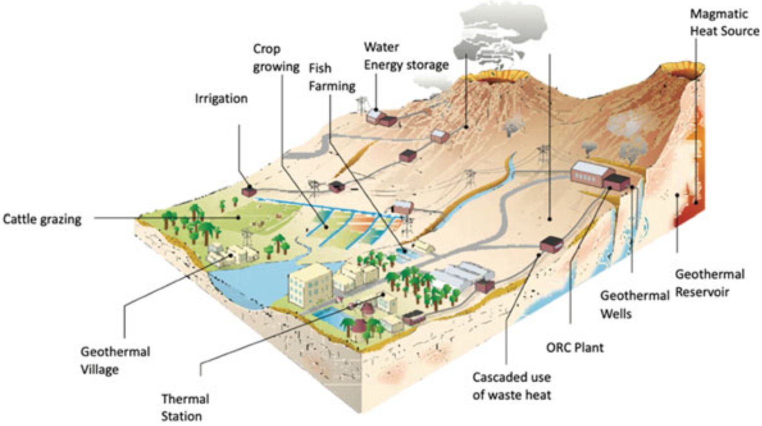

Fig. 19.17 Conceptual diagram of a geothermal village concept (Modified from Varet et al. 2014)

and reliability. If properly arranged, their large upfront cost may provide plentiful returns as well as economic and social benefits in terms of improving water, energy, and food security.

19.5 Application: Geothermal Villages

The following section briefly discusses the idea of a geothermal village and elucidates on a few important sociocultural and technical considerations for geothermal implementations in PICTs. The Tanna Island case study (Sect. 19.2.3.1) is here briefly explored as a proxy for rural PICT developments. While the viability of developments in Tanna in the long-term is still to be assessed, geothermal solutions for energy, food, and water are a clear opportunity given the local context.

19.5.1 Case Study: Tanna Island

The idea of a geothermal village is to establish an integrated communal system of energy and material flows, where societal activities take place in harmony with naturally present geothermal resources. The interconnected nexus approach of water, energy, and food security is highly suited to this. In Tanna, this has a particular significance given the need to provide services such as desalination and sufficiently high temperature cooking systems (with 73 °C being a good target to extinguish most microbial agents [Kawabata et al. 1983]). Given the limited technical capacity present on the island, these systems would foresee low levels of sophistication and minimal intrusion, as per the first design principle introduced in this chapter. This ensures that communities with little technical background residing in isolated regions can operate and maintain them. All systems within a geothermal village should be designed and arranged from a holistic perspective, taking into account all the particularities of the local people, resources, and environment to prevent cultural and environmental spoilages. Some examples of robust designs have already been presented throughout Sect. 19.3, such as conduction-based food dryers.

In Tanna, various communities with separate forms of governance are spread across the caldera area, from Port Resolution to Sulphur Bay, with an estimated population of roughly 1500 people. These communities display some limited infrastructure (small schools, dispensaries, aid posts) and have reasonable road accessibility. Energy poverty is widespread and typically small lighting loads and smartphone charging are serviced by small diesel or petrol generators or PV systems.

Most locals live subsistence-based lifestyles centred on fishing and agriculture (with main cultures involving coconut, kava, breadfruit, and cassava), which would greatly benefit from geothermal implementations. Most communities share similar sociocultural elements, such as the use of the Kastom Ekonomi (a cashless traditional economy based on hierarchies, relationships, and trade, but does not apply for the payment of school fees, kerosene, and other products such as tea and sugar) and the respect of Tabu Land (i.e., sacred areas, burial grounds) (MacClancy 1981; Rousseau and Taylor 2012). Another common cultural aspect is the presence of cargo cults, a millenarian belief system centred around the fetishization of western technologies as a result of interactions with military forces during the Second World War (Sherry 2017; Lindstrom 2019).

Geothermal resources in this area are abundant (Sect. 19.2.3.1). However, they are not entirely riskless, as these communities have suffered health impacts due to the volcanic fluorine content in surface waters (Cronin and Sharp 2002). Agriculture and PV system performance have also suffered due to frequent toxic ash rains, killing crops and soiling solar panels (VGMD 2021).

As per the National Energy Road Map (NERM) outlined by the Vanuatu government, there is an ongoing national effort to provide energy solutions to off-grid communities (Republic of Vanuatu 2016). Funding sources employed to achieve this are typically utilities, private companies, NGOs, the world bank, local governmental funds, and international development partners. Opportunities for project proposals in the geothermal space are present (Dornan 2015, Wolf et al. 2016, Keeley and Keeley 2017).

19.5.2 Other PICTs

To ensure the applicability of geothermal solutions to other PICTs, sociocultural and economic contexts need to be explored in depth. For example, cargo cults in particular are widespread throughout the rural Pacific, and in PNG infrastructure vandalism and psychosomatic health detriments have been recorded as a response to development (Bettison 1978). Countries like Fiji also amortize the costs of diesel to the population via extensive subsidy programs (Chap. 3) which cover up the high cost of importing fuel to the region, thus potentially restricting funding to other economic sectors and affecting the financial superiority of geothermal solutions (ITP 2014).

19.6 Conclusions

Geothermal energy derived from natural hot springs or deep hot aquifers has an enormous potential to provide energy, food, and water solutions, often in an interconnected or nexus approach. It can provide a clean and reliable baseload energy capacity, represents a state-of-the-art renewable approach that has not yet reached its potential in the Pacific, and provides a wide variety of food and water security improvements. Its natural abundance in the Pacific also renders it a resilient and convenient option to expand energy systems and provide sustainable and appropriate development options to many PICTs. This is especially the case for isolated and rural communities with abundant heat sources. Furthermore, the implementation of geothermal facilities in a nature-integrated fashion supports a culture that embraces heat as a valuable commodity. This follows the example of other Pacific cultures where its use has been historically beneficial and central to daily life (Neilson et al. 2010).

In some Pacific countries, like Vanuatu, geothermal energy may present a cheap solution for electricity generation due to the high fuel cost of diesel gensets (Castlerock Consulting 2011). However, the core innovation in terms of extending energy, food, and water access in a riskless and cost-effective fashion lies in direct heat use facilities. The advantages of these facilities are threefold. Firstly, they allow comparatively low-cost demonstrations of the use of geothermal power for hot spring areas that are too low in temperature to be suitable (without deep drilling) for electricity production. This is especially important in PICTs where financial capabilities are limited. Secondly, they can be used to explore and test reservoirs further in order to reduce the financial risk of drilling deeper. This is important to support the larger capital investment of intermediate-to-large power plants. Thirdly, they provide a wide range of options in terms of waste heat use, which may be cascaded to other services such as chilling and desalination, as per the ideal geothermal village architectures (Varet et al. 2014). Providing reliable and clean geothermal energy with cascading benefits for water and food security is truly an exciting prospect for development in the Pacific.

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