Rotorua Geothermal Home Heat Investigation

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EXECUTIVE SUMMARY

Rotorua has the worst winter-time air quality in the North Island with the city regularly exceeding the National Environmental Standards for Air Quality.

60% of this air pollution is attributed to home heating practices and to improve air quality in the Rotorua Urban Airshed, it is estimated that as many as 7,650 homes may have to change their home heating methods (Environment Bay of Plenty, 2010).

Geothermal home heating offers a low running cost, clean, renewable and reliable alterative home heating solution.

A significant geothermal resource is present in Rotorua and this includes:

- The Rotorua Geothermal Field, which is generated by relatively shallow volcanic activity, heating the surrounding earth, rock and fluids
- Heat flowing from the hot interior of the earth, to the surface along a natural temperature gradient by means of conduction.
- Solar radiation absorbed by the earth's surface and stored in rock, earth and water.

A range of these geothermal resources could contribute much more to the future clean energy supply for Rotorua.

Careful management of the Rotorua Geothermal Field is required to prevent effects on surface geothermal features. Low impact technologies such as downhole heat exchangers can provide geothermal energy with little or no effect on surface geothermal features. Some additional direct take of geothermal fluids may also be possible from the Rotorua Geothermal Field if they are located and managed appropriately.

Geothermal heat pumps access geothermal resources that are available without the presence of volcanic activity, and will have no effect on the Rotorua Geothermal Field.

Technologies that access geothermal resources to provide home heating carry higher initial capital costs compared with conventional heating systems. Costs could range from ~$21,000 to $80,000 per household, depending on the technology used. In addition, retrofitted space heating systems will be required in the majority of existing homes, and these costs could range from $16,000 to $18,000. These capital costs could be substantially reduced on a per household basis if multi-user systems are used.

The typical New Zealand household uses electricity and/or a wood burner to heat one or two rooms in the house. Given the high capital cost / low running cost characteristics of geothermal technologies, it makes little economic sense to use geothermal energy in this way. Geothermal home heating is much more suited to providing a "whole of home" heating solution, often including the supply of domestic hot water, and should be considered in this context.

This is the key barrier to greater use of geothermal technologies for home heating. In New Zealand, less than 5% of homes have central heating, where in many countries this is considered a basic necessity. New Zealanders have lower expectations of indoor comfort in winter and a cultural norm of single room heating, and this effects willingness to invest in home heating technologies.

Other barriers include low levels of customer awareness and understanding, a lack of skilled technology specific experts and installers, issues around ownership and access to geothermal resources, the process to secure and maintain resource consents, other regulatory barriers and a relatively mild climate (short heating and cooling seasons).

For these reasons, widespread uptake of geothermal technologies in the residential home heating market in the Rotorua Urban Airshed is not expected in the near term, and therefore at present, geothermal home heating is unlikely to provide a feasible alternative to current heating practices.

Facilitating a change in home heating practices requires investment in reducing these barriers.

Improving the thermal performance of the residential building stock will assist with any future home heating systems, and can also provide an immediate benefit by reducing the energy required from current, solid fuel burning systems, in turn reducing the air particulate loading.

The development and support of pilot projects across the various geothermal technologies would assist with providing real-time data and raising awareness, supporting individuals to consider and take up geothermal home heating.

Additional incentives are likely required to encourage the use of geothermal home heating. Means of providing incentives should be further investigated, such as identifying sources of funding from public or private organisations.

There is a cost to achieving cleaner air and healthier homes. The Rotorua Urban Airshed is one of the few places in the world with such impressive geothermal resources available that can deliver this result, but investment in reducing barriers to the use of this technology is required.

If longer term superior energy use solutions are seen as a community objective to not only improve air quality but also overall energy use effectiveness of the city of Rotorua, then geothermal energy in the broadest sense should be a central focus of planning for this outcome.

GLOSSORY OF UNITS USED IN THIS REPORT

Unit (symbols)	Unit	Comments
km^2	square kilometre	area
m^2	square metre	area
ppm	parts per million	concentration
US$/kWh	US dollar per kilowatt hour	cost
€	Euro	currency
$	dollar	currency, NZ dollars unless otherwise stated
kWh/yr	kilowatt hours per year	energy
PJ/yr	petajoule per year	energy
TJ	terajoule	energy
bar (g)	bar (gauge)	gauge pressure
$kWh/m^2/yr$	kilowatt hour per square metre per year	heat demand density (expressed in area)
MWh/m/yr	megawatt hour per metre and year	heat demand density (expressed in length)
m	metre	length
km	kilometre	length
mm	millimetre	length
kg/s	kilogram per second	mass flow rate
tonne/yr	tonnes per year	mass rate (tonne meaning 1000 kg)
tonne/day	tonnes per day	mass rate (tonne meaning 1000 kg)
MW	megawatt	power
kW	kilowatt	power
bar	bar	pressure
MJ/m^2	megajoule per square metre	solar radiation (in this report)
kJ/kg	kilojoule per kilogram	specific enthalpy – energy per unit mass
W/m^2	watt per square metre	surface irradiance (in this report)
°C	degree Celsius	temperature
ΔT	delta temperature	temperature difference
W/(m*K)	watt per metre Kelvin	thermal conductivity
L/s	litres per second	volume flow rate
L/min	litre per minute	volume flow rate

1.0 INTRODUCTION

Rotorua has the worst winter-time air quality in the North Island with the city regularly exceeding the National Environmental Standards for Air Quality. 60% of this air pollution is attributed to home heating (Environment Bay of Plenty, 2010).

The Rotorua Urban Airshed boundary is identified to be within the green line on Figure 1.

50% of Rotorua residents use wood burners, open fires or multi-burners as their main source of heating. 72% of households in the Rotorua Urban Airshed use older technology solid fuel burners that are generally past their effective life span (Environment Bay of Plenty, 2010).

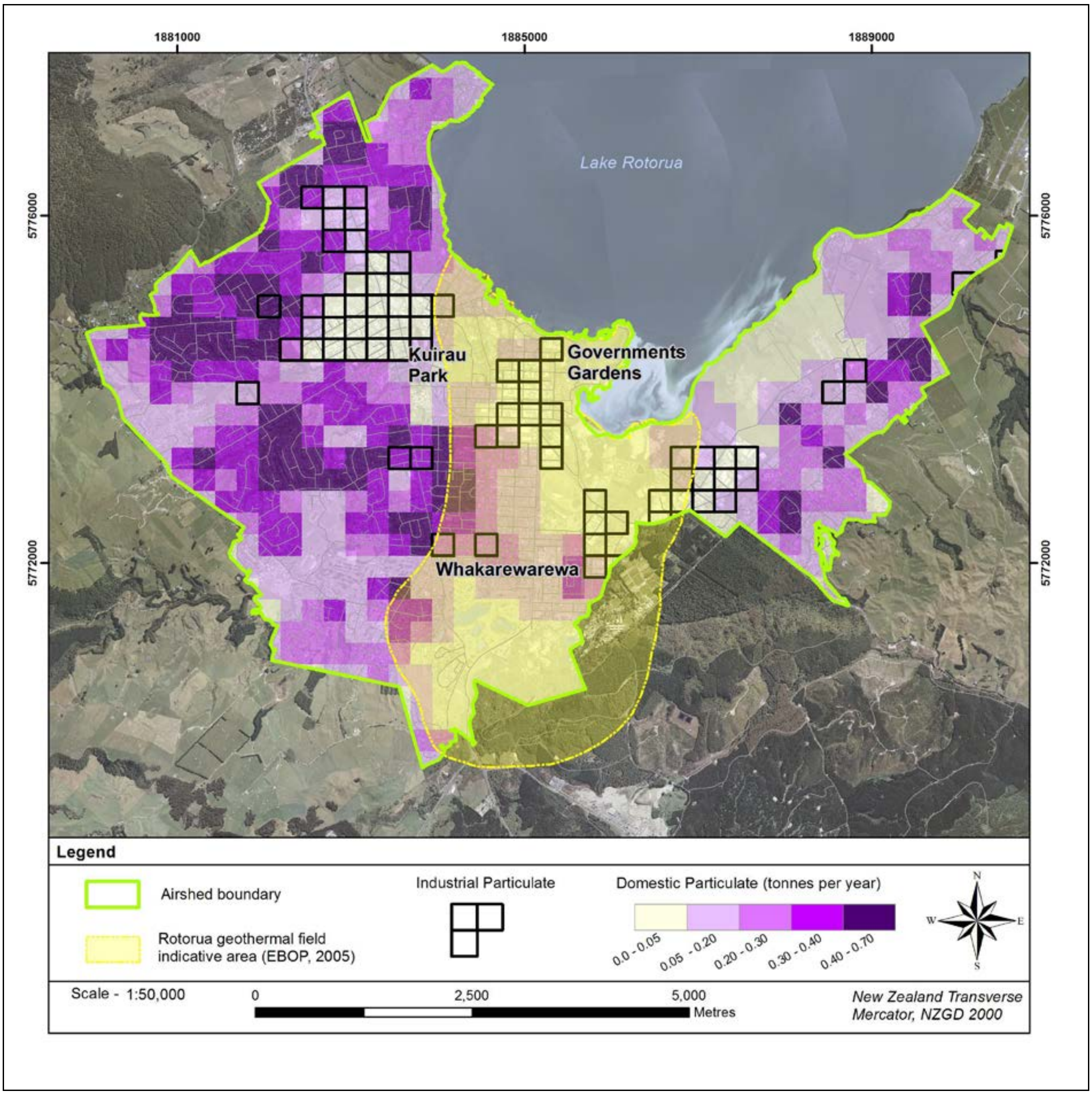

Figure 1 Rotorua Urban Airshed Area and Air Quality Measurements (data sourced from Bay of Plenty Regional Council).

To improve the air quality in the Rotorua Urban Airshed, it is estimated that as many as 7,650 homes may have to change their home heating methods (Environment Bay of Plenty, 2010).

There are a variety of alternative heating solutions to consider, including compliant solid fuel burners, air source heat pumps and others.

The Bay of Plenty Regional Council ("BOPRC") has requested this report to consider the feasibility of geothermal home heating as an alternative to current home heating practices.

In this report we broadly consider geothermal energy to include all underground water, ground water and the ground at whatever temperature, as well as surface and lake waters. This is much broader than the conventional geothermal energy definition that one would usually consider where fluids and the ground would be hotter than the prevailing ambient environment.

The high temperature geothermal resource in Rotorua is one of the areas greatest assets. This taonga has been used for generations for heating, bathing, cooking and tourism and these uses continue. In modern times, Rotorua's geothermal assets attract three million tourists a year, and support a wide variety of business and industry.

There are, however, historical issues associated with the direct use of geothermal fluids in Rotorua.

In earlier times the geothermal field had been accessed and developed an in ad hoc fashion, with over 900 shallow wells drilled for residential, commercial and industrial heating purposes, with approximately 430 in operation at peak use. While utilization may have been cost effective for individual home and business owners, it was not efficient, and typically resulted in wastage of geothermal heat (NZGA, 2012).

In the late 1970s significant changes to surface geothermal features were seen at Whakarewarewa in response to increasing fluid extraction.

The Government responded by embarking on a programme of compulsory well closures within 1.5 km of the Pohutu Geyser and the implementation of a field management regime. Since the completion of the programme, the water level in the main production aquifer has recovered and the natural surface features are recovering.

This report will consider the feasibility of various uses of geothermal energy for home heating in the Rotorua Urban Airshed, such as downhole heat exchangers, multi-use schemes, and geothermal heat pumps, as a means to address air quality issues created by current home heating methods.

2.0 PROJECT SCOPE

This report is a desktop study of proven geothermal technologies for domestic home heating and existing information about the Rotorua geothermal resource as it relates to the Rotorua Urban Airshed. This scope does not provide for any detailed investigations of geothermal resource development capacity or the use of geothermal energy for commercial or industrial purposes.

2.1 Objectives

The following objectives for this study have been identified:

- Summarise information available on the range of geothermal resources in Rotorua.

- Investigate technological adaptations for retrofitting existing private homes with a form of geothermal heating.
- Investigate cost effectiveness and feasibility of using these technologies for domestic home heating in Rotorua.

2.2 Methodology

The following approach has been taken in the preparation of this report:

- Investigate current heat demand requirements within the Rotorua Urban Airshed, the distribution of measured air quality and the availability of geothermal resources.
- Complete a literature review to identify other studies, information and data that is publicly available relating to geothermal home heating in New Zealand and material that might be relevant internationally.
- Review appropriate existing technologies in New Zealand and internationally and consider their feasibility and appropriateness for use in Rotorua; in particular, consider cost effectiveness.
- Identify and investigate relevant case studies that show the successful use of various technologies in settings and applications similar to what may be appropriate for Rotorua;
- Compile findings into a draft report for presentation to BOPRC.
- Receive comments from BOPRC, prepare and deliver a final report.

3.0 ROTORUA URBAN AIRSHED – HEAT DEMAND

From 2006 data, the Rotorua Urban Airshed has a total population of 57,840 people living in 17,200 dwellings (Statistics NZ, 2006).

Rotorua has the worst winter-time air quality in the North Island with the city regularly exceeding the National Environmental Standards for Air Quality.

Solid fuel burning for home heating significantly contributes to the amount of particles (PM10) in the air (Iremonger & Graham, 2006). The distribution of heating methods used by each household for heating their main living area is presented in Table 1. As each household may have more than one heating method in the living areas, these figures do not total 100%.

Table 1 Distribution of heating methods for living areas in Rotorua households.

Fuel type	
Open fire	5%
Wood burner	43%
Multi-fuel burner	2%
Gas (reticulated)	19%
Gas (bottled)	25%
Geothermal	5%
Electricity	33%

Table 1 shows that 50% of homes in the Rotorua Urban Airshed heat their main living areas by solid fuel burners (open fire, wood burner or multi-fuel burner).

The effective life span of a solid fuel burner is about 10 to 15 years. After this they are less efficient and produce more pollution than newer, cleaner burning designs.

The majority of wood burners (72%) within the Rotorua Urban Airshed are outdated and no longer comply with requirements introduced by the Ministry for the Environment. The age distribution of wood burners currently in use is shown in Figure 2.

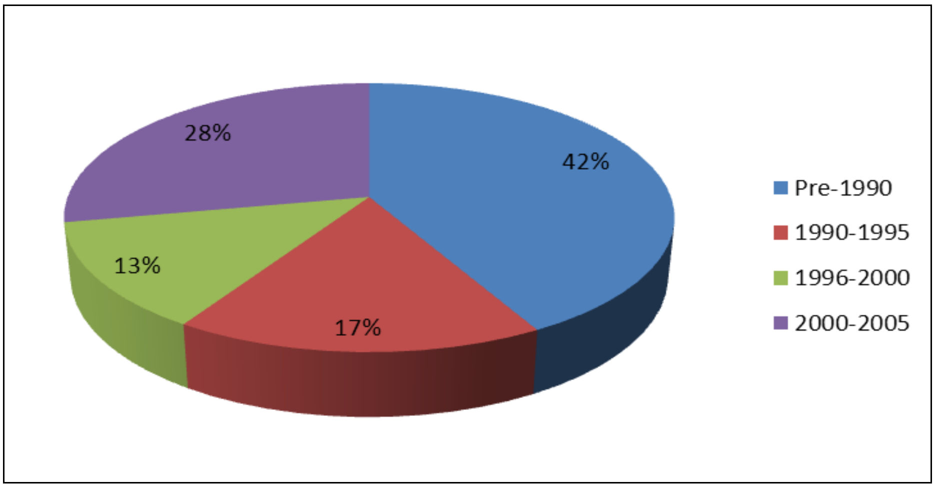

Figure 2 The age distribution of wood burners in the Rotorua Urban Airshed (Iremonger & Graham, 2006).

The central and western parts of Rotorua use the most energy for heating and the eastern parts and the outskirts of the city use less (Jonsson & Nielsen, 2006).. The use of firewood stoves is evenly spread, but the largest concentration of firewood stoves can be found in the urban parts of the city (Jonsson & Nielsen, 2006).

The Household Energy End-use Study (HEEP) (Isaacs, et al., 2010) quantified energy use in New Zealand houses based on monitoring and end-uses in a national sample of 400 houses. Based on this data, space heating consumes an average 34% of total household energy use. HEEP found that the average total energy use (all fuels) per household was 11,410 kWh/yr (Standard Error 420 kWh/yr). The HEEP breakdown of New Zealand household energy consumption by end-use is given in Figure 3.

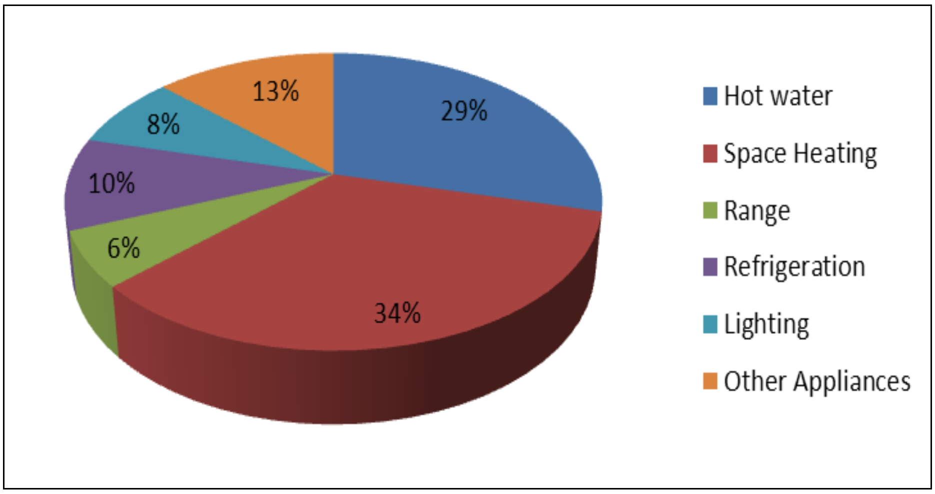

Figure 3 Total energy use by end-use. Source HEEP.

It can be seen that the largest use of energy is for space heating at 34%, followed by hot water at 29%.

The average annual energy demand for space heating and hot water in the Rotorua Urban Airshed can be calculated based on the numbers above, with space heating and hot water per household calculated at 3,880 kWh/yr and 3,310 kWh/yr respectively.

With 17,200 dwellings in the area the total energy demand for space heating is estimated at 0.24 PJ/yr, and the total energy demand for hot water is estimated at 0.20 PJ/yr.

In summary, the key points to note from this data:

- Outdated (less efficient, more polluting) solid fuel burners are the most common form of domestic heating in the Rotorua Urban Airshed.
- Solid fuel burners are the primary contributor to air quality problems in the Rotorua Urban Airshed.
- Space heating accounts for the highest proportion of household energy demand.
- Space heating and hot water collectively account for 63% of total energy use for an average household.
- The total energy demand for space heating and hot water in private homes in the Rotorua Urban Airshed is estimated at 0.24 PJ/yr and 0.20 PJ/yr respectively.

3.1 Heating Degree Days

Based on the average maximum and minimum temperatures for a specific location, heating degree days (HDD) are able to be calculated. This enables a heat demand comparison to be made between specific locations across different countries. HDD are used for calculations that relate to the heating of buildings relative to a "base temperature", and provide a measure of how much (in degrees), and for how long (in days), the outside temperature was below that base temperature. It uses Hitchings formula:

$$Average\ degree\ days\ per\ day = \frac{(t_{base} - t_{mean})}{1 - e^{-k(t_{base} - t_{mean})}}$$

Where:

t_{base} is the base temperature
t_{mean} is the mean outside air temperature

k is a constant (0.71 is typically used in the UK)

Using 18°C as a base temperature (the temperature below which buildings should be heated according to World Health Organisation guidelines) the HDD values for various locations are presented in Table 2.

Table 2 HDD Comparisons.

City	HDD
Rotorua	2004
Auckland	1201
Christchurch	2576
Klamath Falls, USA	4076
Reykjavik, Iceland	4484
Madrid, Spain	2050
Vicenza, Italy	2091

Table 2 shows that Rotorua (2004) is actually closer to Christchurch (2576) in terms of HDD than it is to Auckland (1201).

Places like Klamath Falls, USA and Reykjavik, Iceland use significant quantities of geothermal energy for space heating. The HDD values for these places are more than double the HDD in Rotorua.

Madrid, Spain has a similar HDD as Rotorua. It is interesting to note that Madrid is planning a geothermal multi-user heating system. They will use geothermal resources at 75°C at a depth of 1,500 to1,800 m to supply 5,000 dwellings with heating, cooling and hot water. The investment is estimated at €11 million. The project is one of six renewable energy projects of interest within the Madrid Regional Government's Renewable Energy Cluster, which is seeking to advance renewable energy projects in the region (Lxrichter, 2010).

4.0 GEOLOGY AND THE GEOTHERMAL RESOURCE

This Section provides some background on the geology and the geothermal resource in the Rotorua Urban Airshed and beyond.

4.1 Geology

The Rotorua basin was formed from the caldera of the Mamaku rhyolitic eruption 220,000 years B.P (Wilson, et al., 1995).

Subsequent Caldera basin infilling with rhyolite domes, rhyolite lava flows and lake deposits is described by Wood (1992). Lake deposits are found as high as 90 m above the present lake level from earlier damming at the northern outlet of Lake Rotorua (Gordon, 2005).

The most important shallow formations in the Rotorua basin relevant to geothermal resources are, from oldest to youngest: the Mamaku Ignimbrite, the Rotorua City Rhyolite Domes and the Rotorua Basin Sediments.

Rhyolite domes underlie the northwestern part of the city, outcropping in the northwest as the Pukeroa dome.

Mamaku ignimbrite occurs in the east and south of the geothermal field, but its thickness is not well known because to date drilling has penetrated less than 60 m into the ignimbrite.

Both the ignimbrite and rhyolites are overlain by lake sediments derived from a mix of muddy breccias, siltstones, pumice sand, and diatomites in various states of consolidation. Generally between 50 and 100 m of lake sediments overlay the ignimbrite or rhyolites below, while up to 200 m of sediments have been found in the Ngapuna area and in the southwestern side of Kuirau Park. Figure 4 is a summary shallow/surface geological map of the Rotorua Urban Airshed.

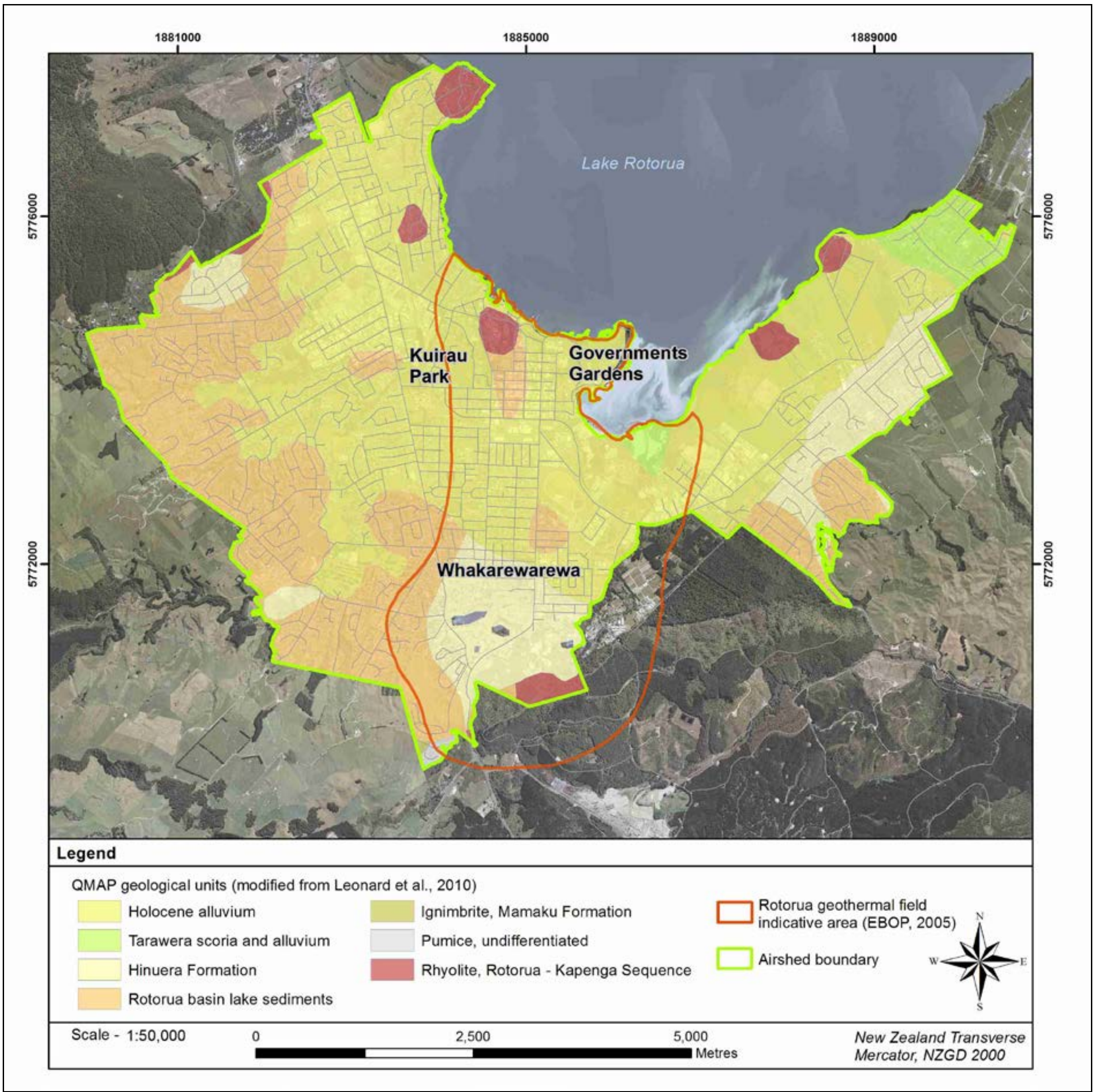

Figure 4 Geology of the Rotorua area.

A number of faults play an important part in channelling geothermal fluids. Lloyd (1975) identified and named a number of faults (Puarenga, Whakarewarewa and Pohaturoa faults) associated with hot spring alignments at Whakarewarewa. Further work by Simpson (1985) defined the Roto-a-Tamaheke and Ngapuna faults further to the east.

Wood (1985) developed the concept of the Inner Caldera Boundary Fault (ICBF) to account for the abrupt change in elevation of the top of the Mamaku Ignimbrite in the area south of Sala Street towards Whakarewarewa.

Wood (1992) postulated the presence of the Kuirau Fault located in Kuirau Park.

Gordon (2005) created a simple block diagram to assist with visualisation of the major geological and structural features of the field (Figure 5). The diagram is looking south towards Whakarewarewa.

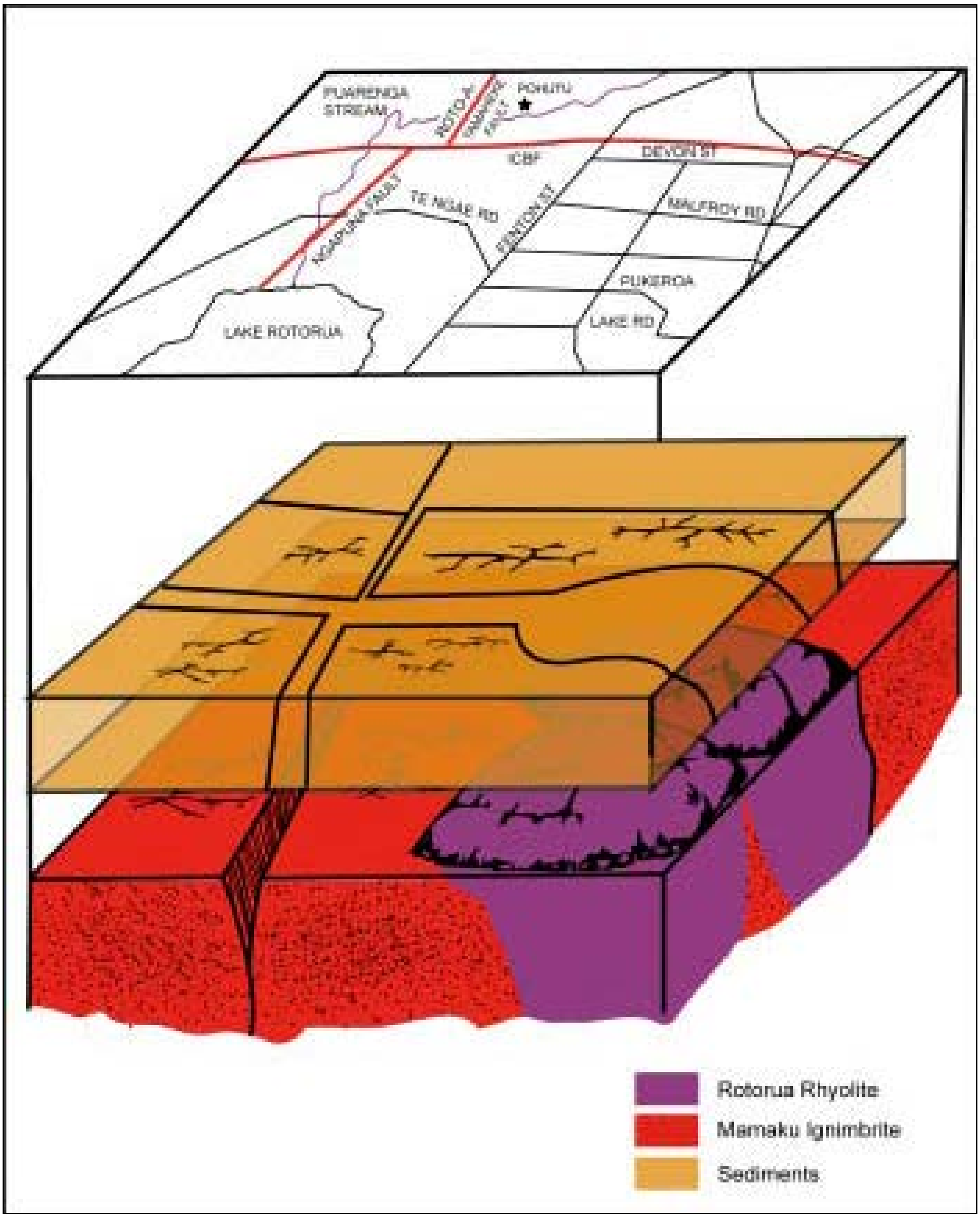

Figure 5 Block diagram showing the major geological and structural features of the field (Gordon, 2005).

4.2 Geothermal Resources

Geothermal energy is thermal energy stored in the earth at whatever temperature it might be encountered. This energy is generated in three different ways:

1. Heat generated by relatively shallow volcanic activity, heating the surrounding earth, rock and fluids.
2. Heat flowing from the hot interior of the earth, to the surface along a natural temperature gradient by means of conduction.
3. Solar radiation absorbed by the earth's surface and stored in rock, earth and water.

4.2.1 The Rotorua Geothermal field

Rotorua is a volcanically active region where magmas are present close to the surface. Heat from the magma is transferred to the surrounding rocks which in turn transfer heat to circulating (convecting) fluids.

The Rotorua geothermal system is located in the south part of the Rotorua Caldera. Geophysical and geochemical investigations of the field indicate that it has an area of 18 to 28 km^2 at about 500 m depth. About a third of the area and over half the heat and mass flux occur beneath the southern end of Lake Rotorua. Aquifer pressure beneath much of Rotorua City is controlled by the lake level, being relatively uniform due to the high permeability in the rhyolitic host rocks.

In the Rotorua Geothermal Field the rhyolitic host rocks comprise viable source of hot water within the Rotorua Urban Airshed.

The Faults identified in the area enable hot fluid to up flow from deeper regions. Two main up flow zones have been identified (Figure 6): The main one is below the Whakarewarewa geyser area with a smaller one centred below Kurirau Park on the west side of the north rhyolite dome (Allis & Lumb, 1992).

Typical chemical composition of Rotorua's geothermal fluid is listed in Table 3.

Table 3 Typical composition of geothermal fluids (Hodder, 2010).

Component	Rotorua (ppm)
Cl^-	560
Na^+	485
SiO_2	490
K^+	58.5
HBO_2^-	21.6
HCO_3^-	167
SO_4^{2-}	88
Ca^{2+}	1.2
Li^+	4.7
F^-	64
NH_3	0.2

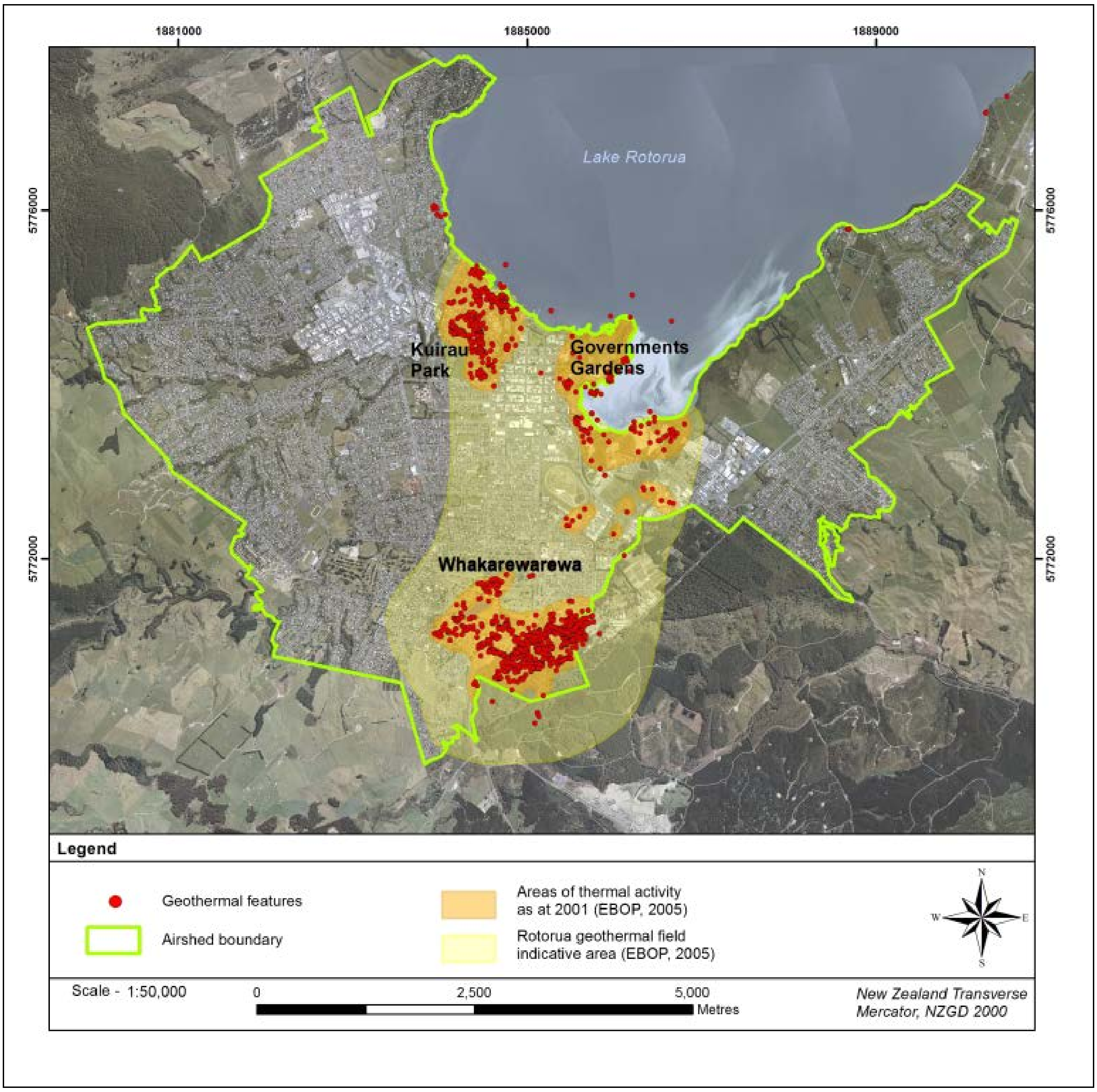

Figure 6 Rotorua's thermal area plotted with the Airshed boundary.

The outflow from the Rotorua Geothermal Field is towards Lake Rotorua, which also acts as the main cold water pressure control of the field (Allis & Lumb, 1992). Although information on the field's permeability is limited, Burnell (1992) estimated the out flow rate of the field (100 m aquifer, 3 km wide, 2 bar pressure drop) to be 120 kg/s, which would be about a quarter of the predicted up flow of 400 kg/s at Whakarewarewa.

Geothermal wells in Rotorua are typically drilled to about 100 m deep, ranging from about 45 to 190 m. Aquifer temperatures vary from about 125°C to 175°C (Andersson, 1998).

The main target depth for drilling is the upper 40 m of the rhyolitic domes, which comprise pumiceous, brecciated and fractured rhyolite with good permeability. Below this depth, rock is weakly fractured and less productive (Wood, 1992).

The natural heat flux at Rotorua is suggested to be 430 ± 30 MW (Allis & Lumb, 1992). Calculations based on the total measured Cl flux from surface streams into Lake Rotorua correspond to a thermal output from the field of 470 ± 50 MW (Glover 2003).

4.2.2 Geothermal Gradients and Solar Radiation

Volcanic activity (Figure 7) has created the Rotorua Geothermal Field as it is thought of conventionally, but there are other geothermal resources available that might be able to be accessed for home heating.

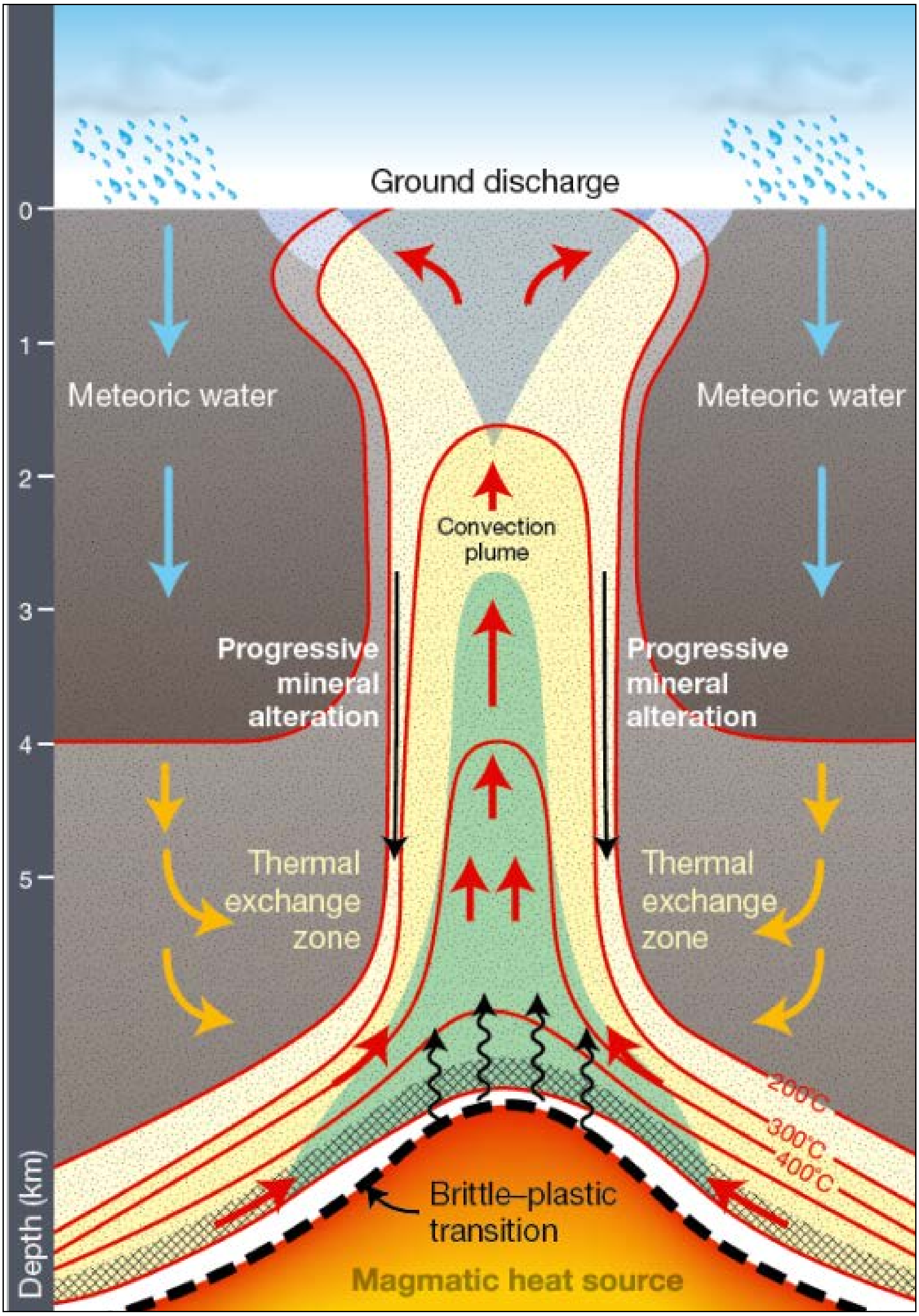

Figure 7 Geothermal energy generated in the Earth is slowly, continually conducting to the surface.

A natural geothermal gradient (the rate at which temperature increases with depth) is created by heat from the inner core of the Earth being slowly conducted to the surface. This occurs irrespective of the presence of volcanic activity.

The inner core of the Earth from seismological studies is believed to have a temperature similar to the Sun's surface at approximately 5,430°C (Alfè, et al., 2002)

The natural geothermal gradient varies from place to place. Outside the Rotorua geothermal field there are very few wells deeper than 100 m so a temperature gradient has not been accurately measured but can be estimated to be about 3°C/100 m, which is the estimated geothermal gradient for the rest of New Zealand outside of hot geothermal areas.

Solar energy also contributes to accessible geothermal energy. The surface of the Earth is hit by solar radiation, with about half of this being absorbed and stored in the ground and water bodies (Figure 8).

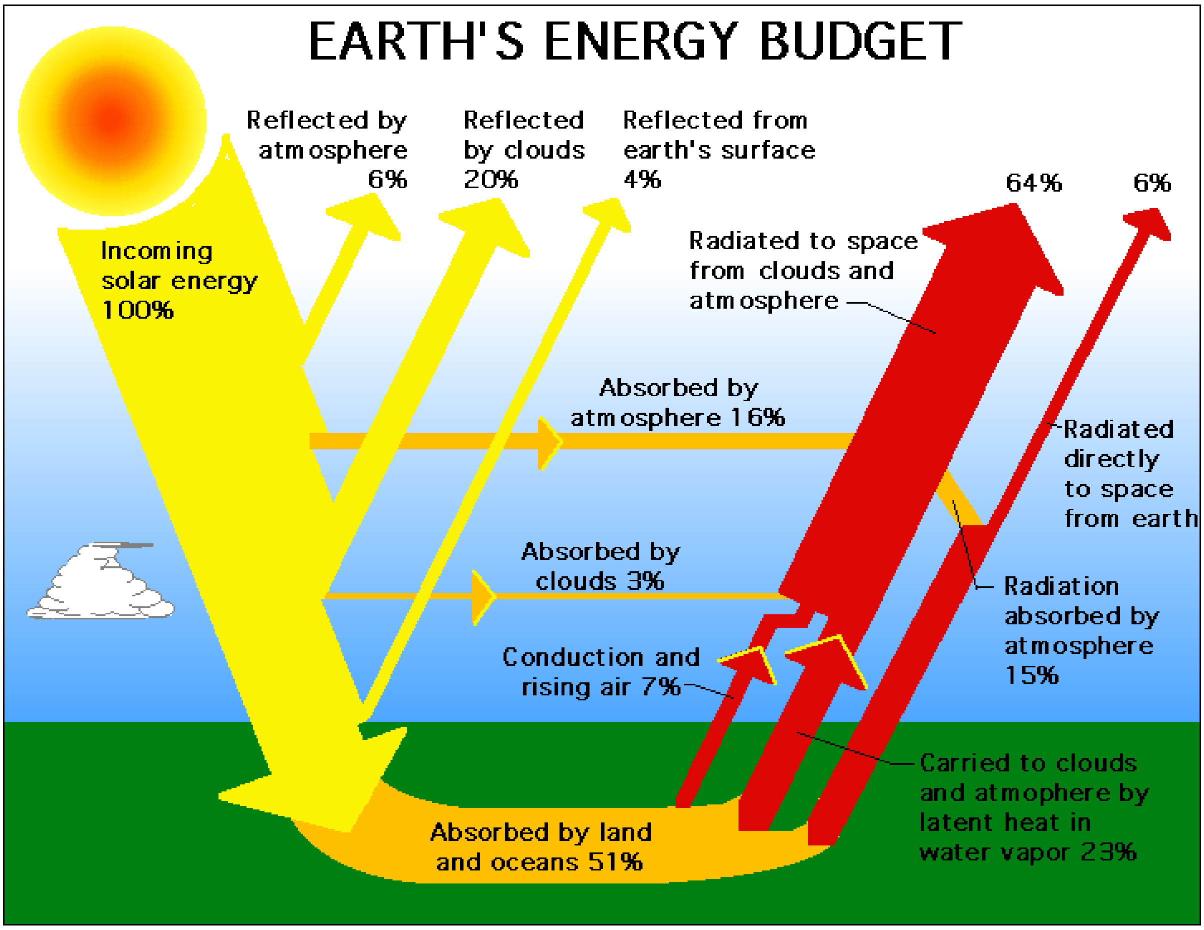

Figure 8 Earth's energy interaction with the sun.
Source: http://asd-www.larc.nasa.gov/erbe/components2.gif

The annual average horizontal surface irradiance is approximately 170 W/m^2. However, the flux changes from place to place. NIWA measured daily global solar radiation at the Rotorua airport weather station. The mean yearly daily global radiation was 14.1 MJ/m^2. This was based on 21 years of data. From this a mean annual global solar insolation (irradiance) can be calculated to be 164 W/m^2. This is similar to values of 160 and 165 W/m^2 that de Vos & Fortuin (2010) reports for Rotorua.

This combination of the natural temperature gradient and solar energy ensures that ground temperatures remain relatively constant throughout the year, even at shallow depths. Certainly there is much less variability than occurs in ambient air temperature.

Seasonal variations of the ground temperature due to seasonal change in the ambient air temperature have been studied by van Manen & Wallin (2012) at a shallow bore installation at Wairakei, Taupo.

An almost constant temperature at 14.3°C, 1 to 2°C higher than the mean ambient air temperature at this site was recorded at the bottom of a bore at 7.39 m.

Based on NIWA's temperature measurements (ambient air and soil) at the Rotorua Airport weather station and the Wairakei test bore an estimated shallow ground temperature profile have been created for Rotorua (Figure 9) in areas that are not influenced by the Rotorua Geothermal System.

The figure plots temperature on the vertical axis and depth on the horizontal axis. The temperature at 6 to 8 m depth has been fixed at 12.5°C (NIWA's average soil temperature). This can be compared to the Rotorua average ambient air temperature of 12.8°C also measured by NIWA. The seasonal energy exchange which results in the associated change in ground temperature with depth is plotted for four selected months.

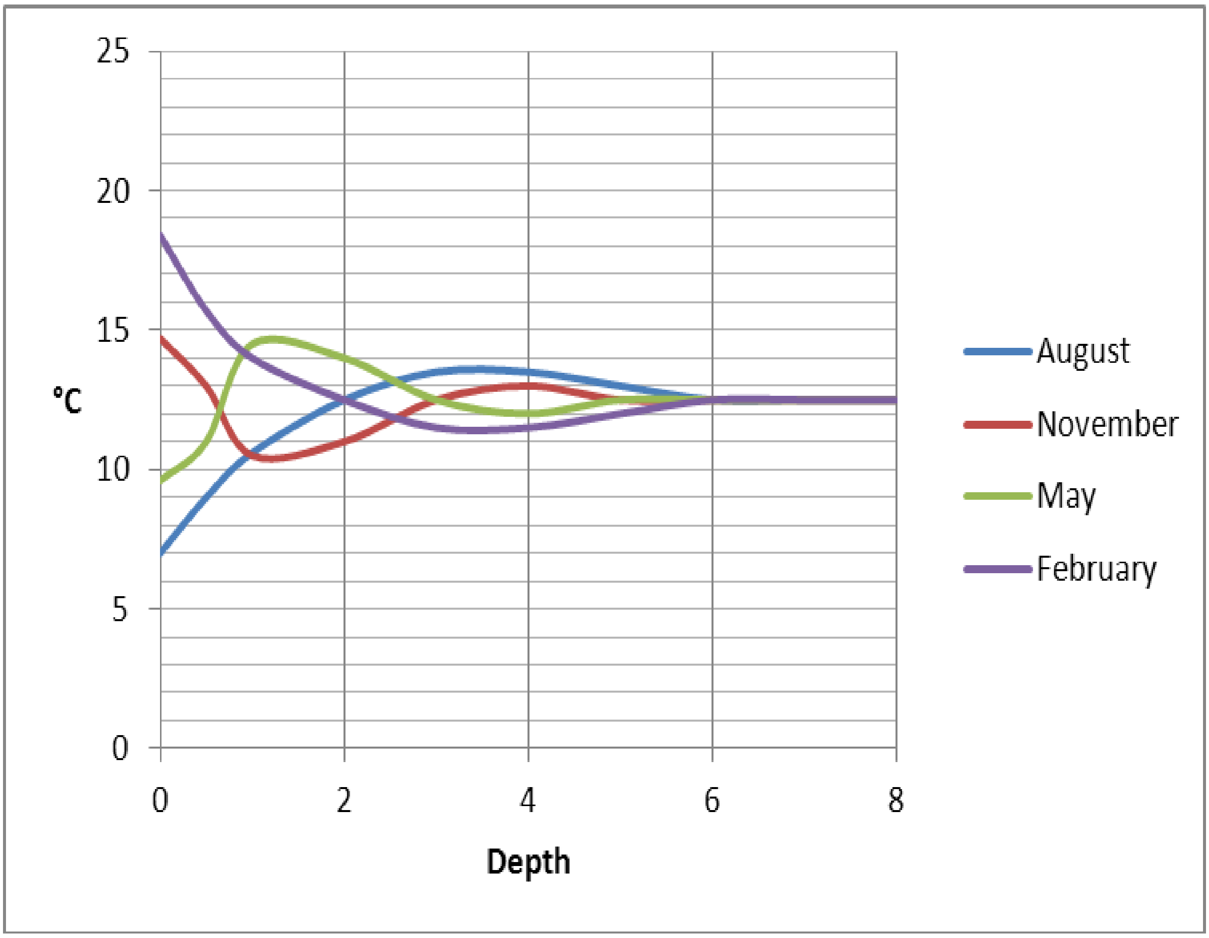

Figure 9 Estimated temperature profile for non geothermal Rotorua ground with depth plotted for four selected months.

4.2.3 Ground

The shallow temperature conditions in the ground, generated by the natural thermal gradient and stored solar energy, create an environment that enable space heating and cooling using heat pump technology. More information on the technology is provided in Section 5.3.

Heat transfer capability from the ground depends on the soil and rock type. Soil thermal properties are strongly influenced by water content. In general, an increase in the water content results in higher thermal conductivity which results in higher heat transfer rates to or from the ground.

Thermal conductivity for common soil and rocks in the Rotorua Urban Airshed are presented in Table 4. Note that as thermal conductivity for specific rock at a given location varies according to its mineral content, porosity, pore fluid and anisotropy, a table of thermal conductivity according to rock type cannot provide this site specific information.

Table 4 Generic Thermal Conductivity of Different Soil and Rock Types

Soil / Rock Type	Indicative Thermal Conductivity (W/(m*K))
Soil	
Sand, dry	0.15-0.25
Sand, moist	0.25-2
Sand, saturated	2-4
Loam	0.25-2
Clay, dry to moist	0.15-1.8
Clay, saturated	0.6-2.5
Igneous rocks	
Granite	1.9-5.2
Andesite	1.9-4.7
Basalt	1.4-4.8
Gabbro	1.6-3.6
Pumice	0.6-0.9
Rhyolite	1.3-1.7

4.2.4 Ground water

Groundwater temperature is controlled by the natural thermal gradient and aquifer flow conditions. Groundwater has potential for heat storage capacity by providing temperatures that remain relatively constant all year round. The thermal capacity of a particular groundwater resource is dependent on the volume of water present, depth and rate of natural recharge. In Rotorua, groundwater temperatures are typically around 10^o to 12^oC.

The hydrogeology of the Rotorua area can be described as a permeable pumiceous surface tephra layer that allows easy penetration of rainwater recharge to the deeper rhyolite and ignimbrite aquifers. These aquifers are essentially unconfined and yield high volumes of groundwater that discharge to spring fed streams or directly to the lake.

The hydrochemistry of groundwater in the Rotorua area is characterised by much lower concentrations of Ca, Mg and SO_4, and higher concentrations of PO_4-P and SiO_2 than other groundwaters in New Zealand. This chemical signature reflects the volcanic origin of the aquifer lithology. The aquifers in the Rotorua area have large water storage capacity with long residence times (Morgenstern, et al., 2004).

Rainfall recharge to groundwater in the groundwater catchment of Lake Rotorua is estimated at approximately 17,300 L/s. A calibrated steady-state groundwater flow model estimates that approximately 11,000 L/s of this flow discharges into streams and then into the lake and the balance flows directly to Lake Rotorua through the lake bed (White, et al., n.d.)

There are several ways in which groundwater can be used to provide heating and cooling solutions and these are detailed in Section 5.3.

4.2.5 Lake water

Lake Rotorua is a relatively shallow lake, with a mean depth of 11 m and a maximum depth of 45 m. It has a surface area of 80.8 km^2 and a catchment area of 507.8 km^2. The water temperature varies through the year generally between about 10°C and 22°C, see Figure 10.

Similar to ground and groundwater, Lake Rotorua is a large thermal mass that has the potential to be harnessed for heating and cooling purposes. Further information on the technology is provided in Section 5.3.

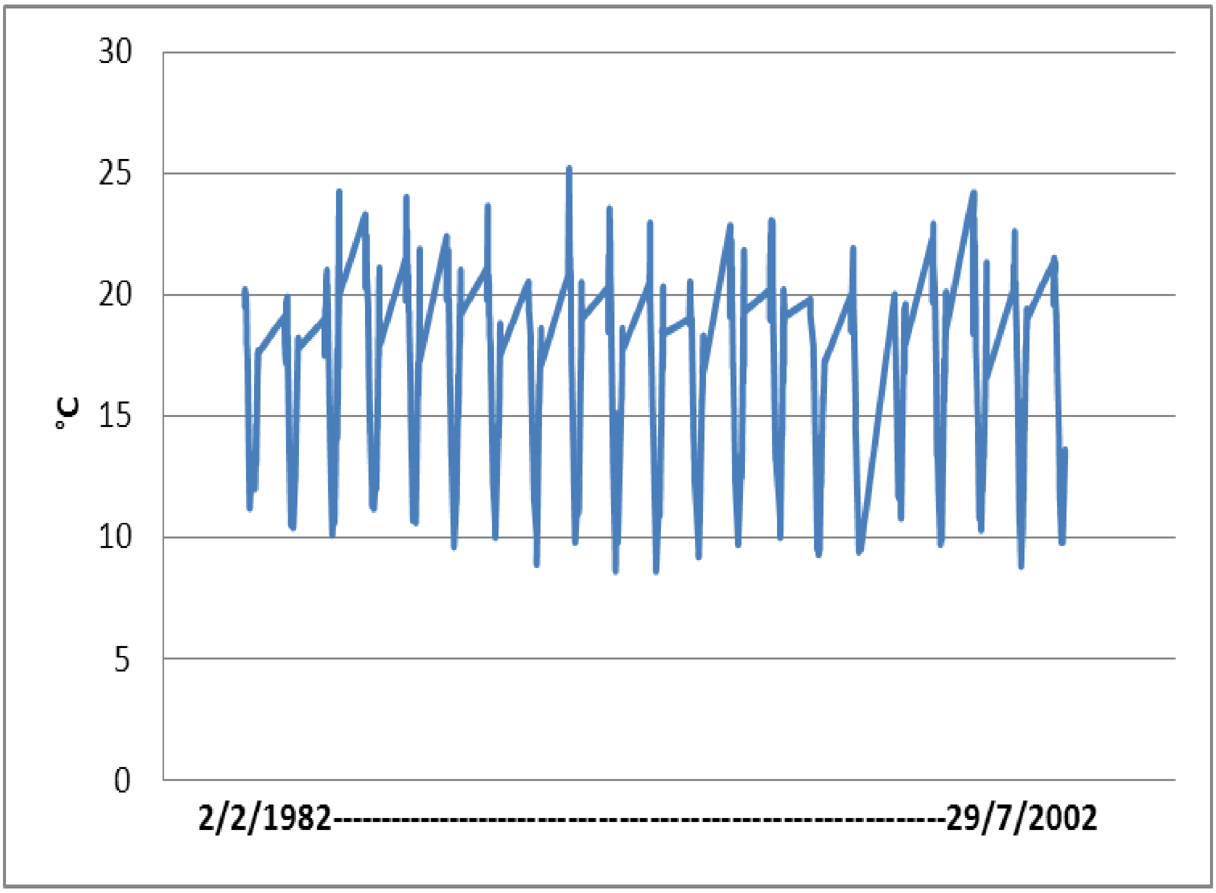

Figure 10 Water temperature Lake Rotorua between 1982 and 2002 (data sourced from Rotorua Lakes Database).

4.3 Conventional Geothermal Use in Rotorua

Rotorua has a long history of using the geothermal field for heating.

Overall use of the field has been assessed by White (2009) to be 585 TJ. He identified 140 production bore sites, 86 injection bore sites and 42 downhole heat exchangers. Most of the bores were drilled to 90 to120 m depth tapping water around 150°C.

White calculated the total take to be 1,675 TJ (3,658,000 tonne/yr at about 458 kJ/kg) with an additional 20 TJ from downhole heat exchangers. 967 TJ (3,180,000 tonne/yr at around 73°C (304 kJ/kg)) is injected back into the field and 145 TJ is discharged at the surface.

Current use of the geothermal resource includes various tourist attractions, domestic and commercial heating and hot water supplies, swimming pools and mineral baths and hospital and large hotel air conditioning. About 69% of the geothermal fluid take is for commercial use, 26% for domestic use and 5% for municipal use

19 scenarios were designed and modelled to assess how increased use of the Rotorua Geothermal field would impact on the surface geothermal features, ((Burnell, 2005). The scenarios were modelled for 30 years from 2005 and the results showed that:

- Increased production in the Central Business District and along Fenton St would adversely impact the outflow at Kuirau Park.
- New production and injection within 1 km of Pohutu Geyser would result in an adverse impact on the Whakarewarewa area.
- New production and injection of about 500 tonne/day can be added to a zone between 1 km and 1.5 km from Pohutu Geyser with an impact on surface outflow of less than 1% of the recovery between 1986 and 1990.
- Increased use of downhole heat exchangers by up to 1,280 kW within the 1.5 km zone would have a negligible impact on surface features.

A careful balance is therefore necessary to ensure that any new use of the field does not adversely affect surface geothermal features and further, that parts of the field are already close to maximum use.

For example, from these results it can be calculated that another 15 to 20 downhole heat exchangers (each supplying approximately 8 homes) could be installed within 1.5 km of the Pohutu Geyser with negligible impact, however no direct take developments within the 1 km zone should be added, and between 1 km to 1.5 km of the Pohutu Geyser there may be potential for some new direct take.

At the time of writing, there are no known examples in the Rotorua Urban Airshed of the use of non-conventional geothermal resources being those provided by the natural temperature gradient and stored solar energy. The potential to use these resources is abundant, and will not result in adverse impacts on surface geothermal features.

5.0 TECHNOLOGIES FOR ACCESSING GEOTHERMAL ENERGY

The geothermal resource within the Rotorua Urban Airshed as defined in this report is substantial, and can be accessed using a number of different technologies.

In this section, a variety of different technological solutions for accessing geothermal energy are presented. Information provided on preliminary cost estimates is based, as much as possible, on local labour, services, and equipment costs obtained from interviews with local installers. If this could not be obtained then cost estimates are based on overseas experience, and reasoned estimates for Rotorua.

5.1 Direct Take

Geothermal direct use has a long history in Rotorua, pre-dating European settlement. The earliest were for bathing, washing and cooking using suitable natural features. Today it normally involves drilling a well to bring geothermal fluid to the surface where heat is extracted.

Modern direct take systems generally involve three basic elements:

- A production system that brings geothermal fluid up through a well to the surface.
- A heat exchanger.
- A disposal system where the cooled water is injected back into the reservoir or discharged.

For the production system, a well is typically drilled to between 90 and 120m in the Rotorua Geothermal Field.

According to Wells & Lichti (1985) approximately 10% of the wells in Rotorua are high pressure bores (3.5 to 7.0 bar(g) at 150 to 170°C), which naturally discharge and can supply sufficient bore fluid to heat 40 to 90 homes with the other being lower pressure bores in the range 0.5 to 2.5 bar(g) (110 to 140°C) that can provide fluid for heating 4 to 12 homes each.

Andersson (1998) has classified production wells in Rotorua as either self-starting, self-sustaining, or pumped.

Self-starting wells will, when shutdown, maintain pressure and temperature sufficient to flow again when the wellhead valve is opened.

Self-sustaining wells once shut down do not flow of their own accord when subsequently opened. Flow is induced by introducing compressed air or gas into the well. Once a flow has been established, the flow from the well will then continue without further assistance. The majority of wells in Rotorua are of this type.

Wells that need pumping can use downhole pumps. Common types of downhole pumps are line-shaft or submersible (see Figure 11 a&b).

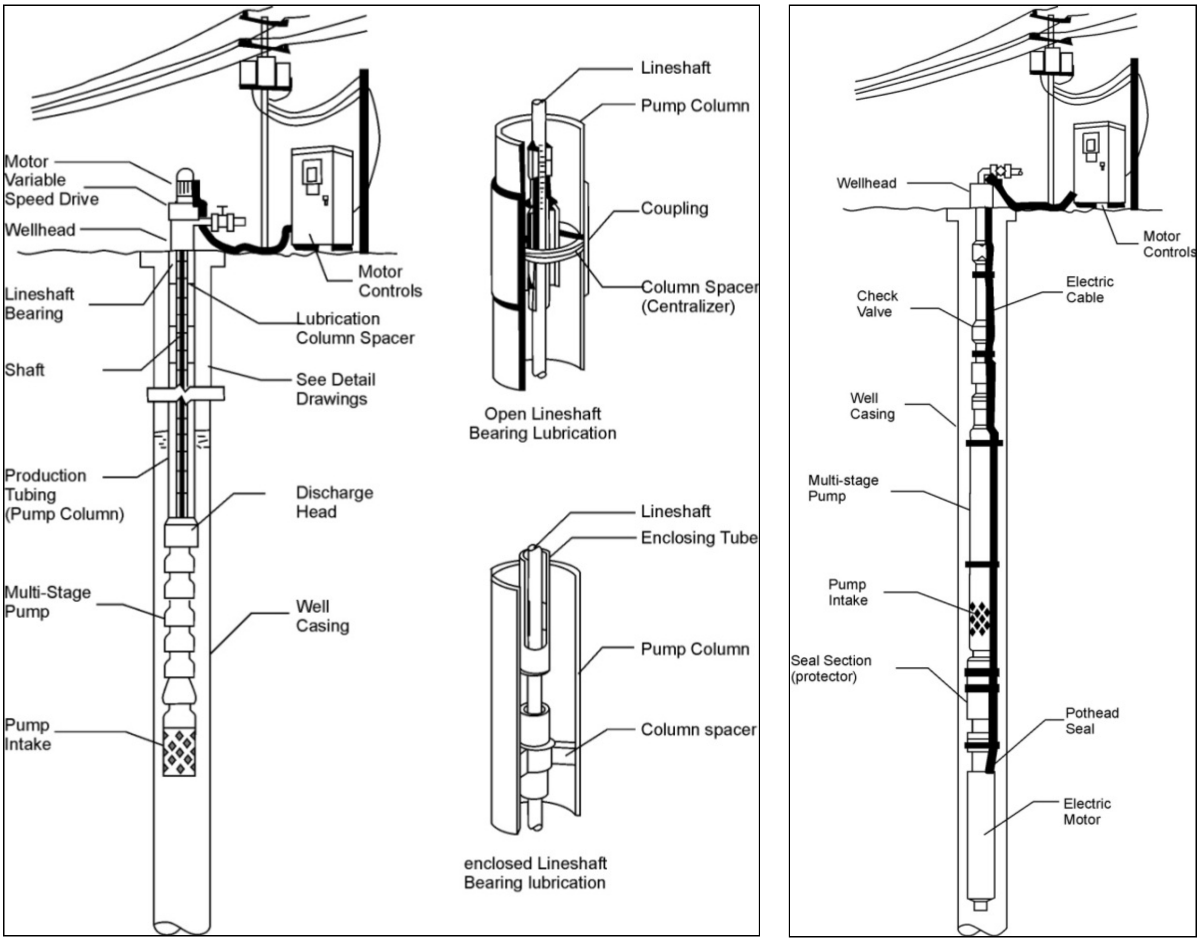

Figure 11a & b Line-shaft and submersible pumps.

Even in wells that are self-sustaining the use of downhole pumping may be considered. Downhole pumping can be used to increase well production, and by suppressing boiling in the wellbore and keeping non-condensable gases dissolved problems associated with scaling can be reduced. The economic advantage of higher flow rates from pumping may offset the cost of installation and maintenance of downhole pumps.

Recovery by natural pressure or air injection to start has the advantage that little hardware is required down the borehole, which reduces the cost and complexity of equipment installation and maintenance.

In most cases, a primary heat exchanger is connected to the production system which isolates the geothermal fluid from a buildings heating system.

In some older direct take systems, a heat exchanger was not used and the geothermal fluid was circulated directly within the building heating system. This approach is not recommended. Geothermal fluids contain chemicals (see Section 4.2.1 for Rotorua specific chemistry) that interact with pipes and fittings potentially causing scaling and corrosion.

A large proportion of the low pressure domestic bores in Rotorua suffer from calcite scaling and require regular maintenance for the effects of calcite deposition (Brown, 1985). The central and western sections of the field seem to be particularly affected. Threshold antiscalants can be used to control the calcite deposition.

The primary heat exchangers can be constructed from materials resistant to corrosion and designed for easy servicing to remove scale.

The heat exchanger transfers heat from the geothermal fluid into a secondary working fluid, which is usually water. The working fluid is then used to heat the building and may also be used for domestic hot water supply.

The two most common types for geothermal heating applications are plate heat exchangers and shell and tube heat exchangers.

Plate heat exchangers (Figure 12a) are common in smaller installations and are relatively low-pressure / low temperature devices. Current maximum design ratings are for temperatures of about 150°C and pressures of about 20 bar. They are constructed from a series of plates with gaskets between, with geothermal fluid circulating down one face of each plate, transferring heat to the process fluid circulating against the opposite face. The benefit of these systems is that plates are easy to remove to clean any build-up of mineral deposits (scaling).

Shell-and-tube heat exchangers (Figure 12b) are common for industrial geothermal applications. These systems can be more difficult to clean with fouling a common problem. They also require greater approach temperatures ("difference between incoming and outgoing fluid temperature") and are physically larger in size.

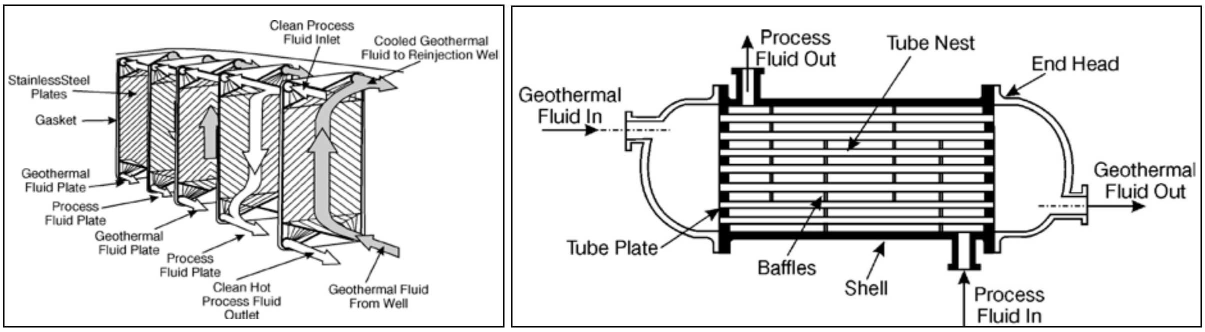

Figure 12a & b Plate heat exchanger and Shell and tube heat exchanger.

The final component to direct take systems is the injection of geothermal fluid back into the subsurface reservoir through a second well drilled for that purpose. The position of injection relative to the production needs to be far enough apart to limit or prevent thermal breakthrough (i.e. the injection fluid cooling the production fluid), yet close enough to keep the reservoir charged (pressure and fluid). As an example, the Rotorua Hospital's production and injection wells are located 210 m apart (Steins & Zarrouk, 2011).

Based on data from (Steins & Zarrouk, 2011) a single set of production and injection wells, producing an average of 130°C water at 500 tonne/day and extracting a ΔT of 30°C (i.e. injecting the spent water at 100°C), would provide up to 0.8 MW. This is enough for heating about 58 average family homes (3 bed room house, 149 m^2). This arrangement would suit a small multi-use scheme (see Section 5.4).

5.1.1 Installation Costs

Direct use systems require the drilling of a production well and an injection well, unless existing bores can be used. Wells cost about $350 per metre to drill and case. A fairly standard geothermal well in Rotorua of 100 m, plus an injection well of roughly the same depth, could be expected to cost approximately $70,000.

A plate heat exchanger for residential applications costs approximately $2,000.

Other costs associated with a production system (e.g. pipes) are estimated at around $8,000.

Total system cost for a production system and heat exchanger can therefore be estimated at $80,000, although this can vary significantly depending on local conditions and design requirements.

5.2 Downhole Heat Exchangers

Downhole heat exchangers ("DHE") eliminate the problem of producing and disposing of geothermal fluid as only heat is taken from the well.

The DHE consists of a system of pipes or tubes suspended in the geothermal well through which a fluid is pumped to extract heat from the underground resource.

There are a number of installed examples of DHE's in the Rotorua Urban Airshed, such as the Alpin Motel in Sala Street.

These systems offer substantial economic savings over surface heat exchanger direct take systems, in large part because only one well is required. The thermal delivery from a DHE is much reduced relative to a fluid discharge system.

In Rotorua, a well drilled into the deeper Rhyolite aquifer (about 100-200 m) would access temperatures between 125°C to 175°C (Andersson, 1998) and have would usually be expected to encounter good permeability.

In a typical installation, the well would be drilled with a diameter of 250 to 400 mm, with a 200 or 300 mm casing. A promoter casing to enhance convection maximising heat transfer from the geothermal fluid to the process fluid circulating within the downhole heat exchanger is an enhancement installed in some systems (Figure 13).

Typically, a loop of 20 to 75 mm diameter pipe would be installed within the casing.

The pipe material used has to be chosen to withstand the local geothermal conditions. Piping has traditionally been carbon steel (Labour, 2005).

Recent experimental work in the USA has shown that a cross-linked polyethylene (PEX) pipe can successfully be used. This eliminates the corrosion and pitting problems associated with metal pipes, especially at the airwater interface (Lund, 2009).

The Alpin Motel has recently improved their system by replacing some of the metal piping with corrosion-resistant plastic fusiotherm piping.

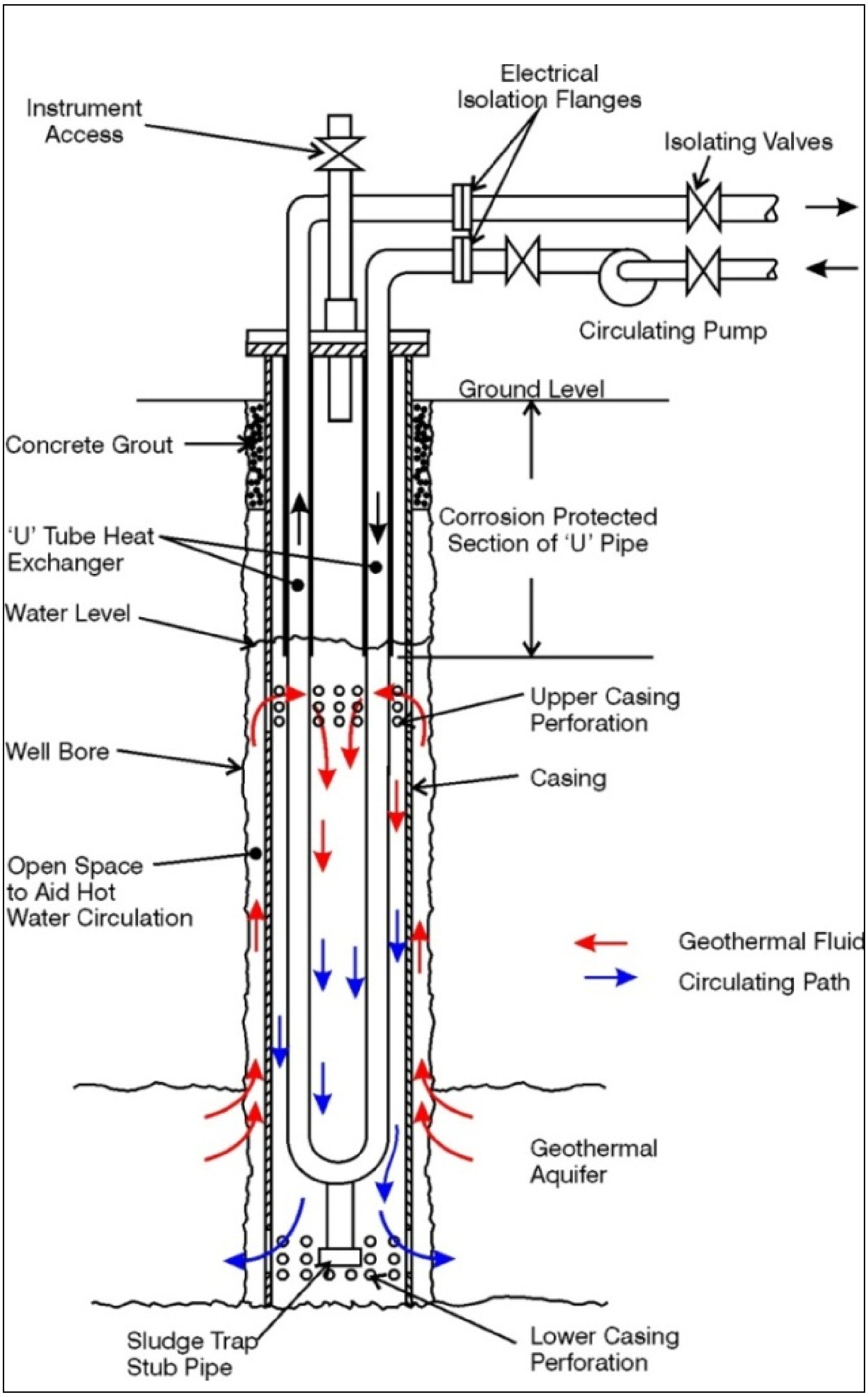

Figure 13 Typical downhole heat exchanger

Experiments to determine the performance characteristics of a small DHE fitted to an existing geothermal well in Rotorua (RR679) is described in Freeston & Dunstall, (1992). The well was located at the Ministry of Works site in Te Ngae Road. It was 100 mm diameter, steel cased, with a drilled depth of 123 m. The bore bottom temperature was about 160°C. It was demonstrated that a downhole heat exchanger retrofitted to an existing geothermal well has the potential to provide heating for about 8 Rotorua homes.

The Alpin Motel and Conference Centre, located on Sala Street, Rotorua, has a 130 m deep DHE. At the time of drilling (October 2009) the bottom temperature was 185°C. As energy was being extracted the temperature dropped and became stable at 77°C. The decline in temperature was most likely due to poor permeability within the geothermal aquifer in that location. The DHE currently supplies about 41 kW.

A DHE in Rotorua might supply 1.0 to 1.4 L/s with a 10 to 20°C temperature difference (ΔT) between the flows in the two legs. Using 1.2 L/s and 15°C ΔT, this would produce 75 kW which could supply about six to eight average sized homes in a small multi-use system (see Section 5.4).

5.2.1 Installation Costs

DHE require the drilling of a single well, unless an existing bore can be used. Average costs are about $350 per metre to drill and case a geothermal well with a standard geothermal well in Rotorua of about 100 m costing approximately $35,000. Installation of the DHE loop and circulation pump is estimated at approximately $15,000.

Total system cost is therefore estimated at $50,000, although this can vary significantly depending on local conditions and design requirements.

5.3 Geothermal Heat Pumps

Geothermal heat pumps (also called ground source heat pumps or geo-exchange systems) are an effective method of heating and cooling buildings. They work by using normal ground, ground water or surface water as a heat source, accessing geothermal energy provided by the natural temperature gradient and/or stored solar energy. This means they can be used almost anywhere. GHPs can run “in reverse” to provide cooling. Heat is extracted from the building and discharged to the ground, ground water or surface water as a heat sink.

The focus of this report is on geothermal home heating to address winter air quality issues in the Rotorua Urban Airshed, and therefore the cooling capabilities of GHPs will not receive any additional consideration, other than noting this as an additional benefit.

Ground based GHP system performance depends on local geological and/or hydrological conditions, such as the composition and properties of soil and rock or the flow, depth or composition of groundwater. For example, different soil types have different heat transfer rates, which in turn will determine the amount of piping required to meet heating demand.

GHPs work using the same principle as air source heat pumps by pumping heat from a lower temperature heat source to the higher temperature space or use that requires the heat. In an air source heat pump, an external fan and coil unit absorbs heat from air outside the building. A GHP is designed to access geothermal energy, absorbing heat from the ground, ground water or surface water.

GHPs achieve this through the use of a ground loop. The ground loop is formed by a network of pipes located underground and outside the building footprint (Figure 14). Depending on the energy load and particulars of the site, the ground loops may be installed in either a vertical or horizontal configuration and as open or closed systems. A closed loop system circulates a working fluid through buried or submerged pipes, while an open loop system uses ground water or surface water directly.

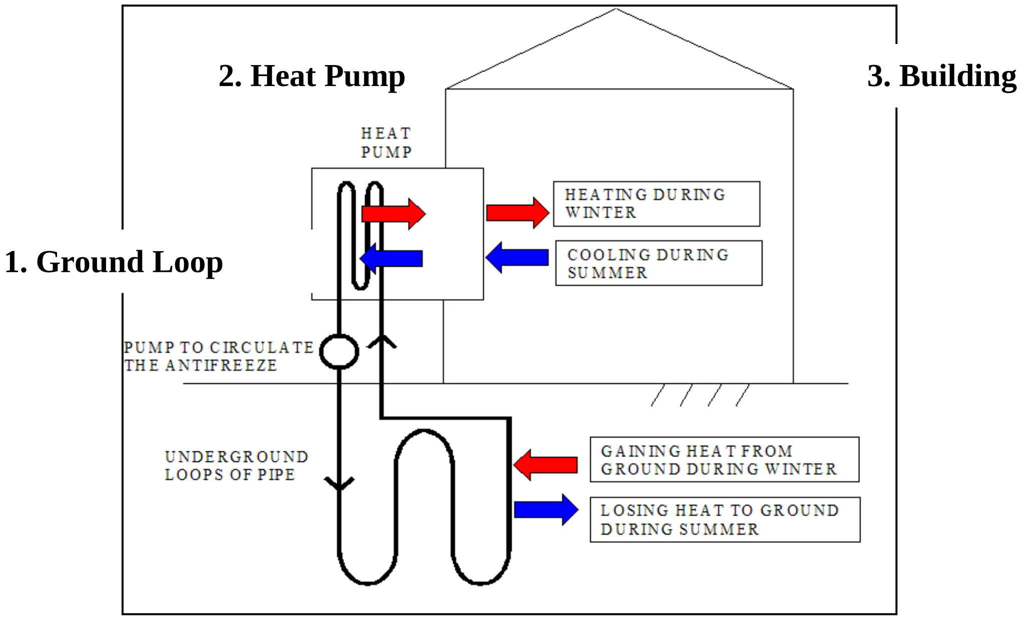

Figure 14 Geothermal heat pump systems.

As discussed in Section 4.2, the temperature of ground, ground water and surface water remains fairly constant throughout the year. This is an advantage that GHP's have over air-source systems which must cope with substantial seasonal variations in air temperature. A slightly elevated shallow ground temperature can be advantageous to the performance of a geothermal heat pump, however the heat pump will need to be appropriately designed, which may include using a refrigerant with a higher boiling point than what would be used for standard ground temperatures.

There are two generic types of geothermal heat pumps:

- Closed loop
- Open loop.

These are discussed in the next two sections.

5.3.1 Closed Loop Systems

Closed loop systems operate by circulating a working fluid (water + antifreeze) through a network of polyethylene pipes (20 to 30 mm in diameter). This pipe network is buried in the ground, or submerged in water. The working fluid never leaves the pipe network, but flows around the loop collecting heat as it circulates. The only interaction with the environment is the transfer of heat through the pipe walls. There are a variety of configurations, including horizontal, vertical and DX systems.

For a horizontal closed loop installation (Figure 15), pipes are buried about 1.0 to 2.0 m deep and laid in a horizontal grid pattern. Depending on soil conditions, the land area required to provide heat for a standard Rotorua home would be between 600 m^2 and 1,800 m^2 (based on calculations using RETScreen4-1).

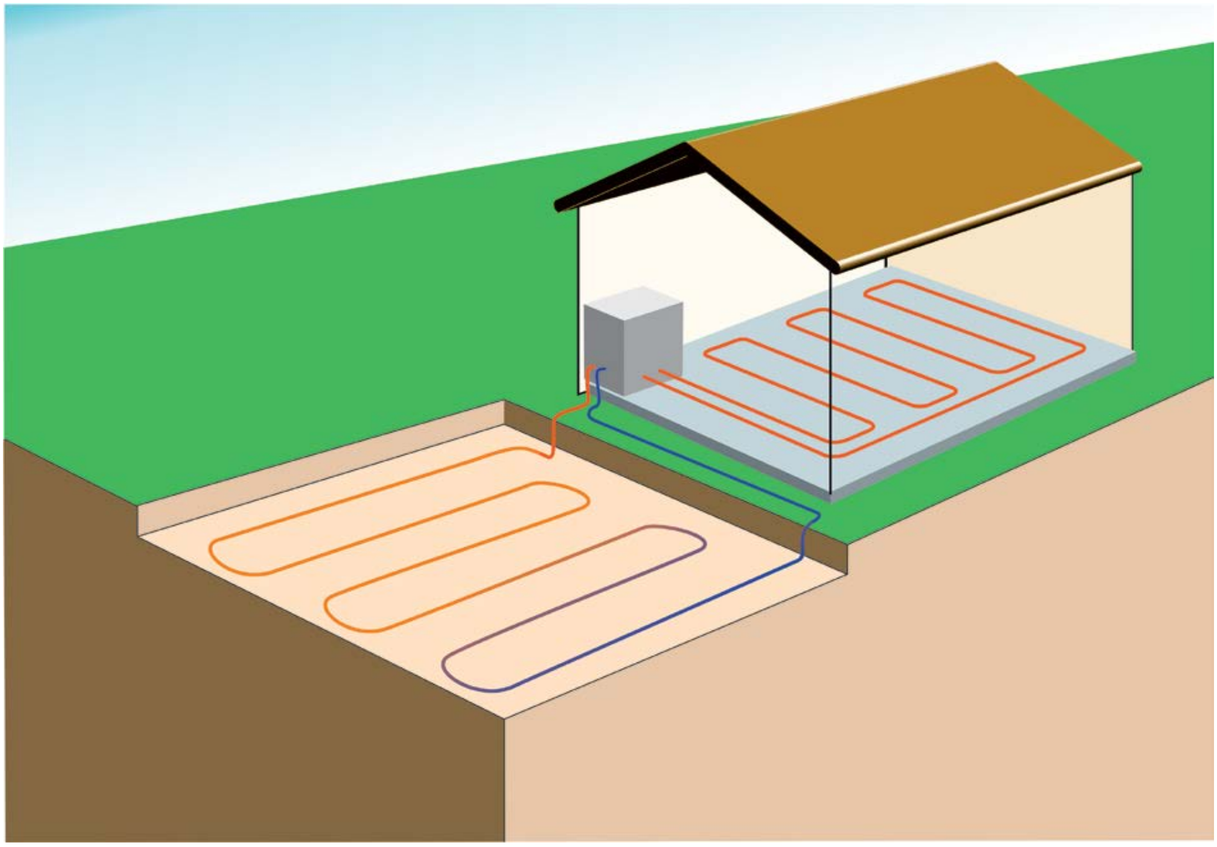

Figure 15 Horizontal, closed loop geothermal heat pump system.

An alternative horizontal loop configuration is a “slinky” loop, where coils of pipe are placed vertically in trenches or horizontally in shallow excavations. The coiled nature of the pipes mean there is more installed pipe length over the same area compared with a straight pipe system.

Another alternative is direct-exchange (DX) systems. Rather than a water based working fluid, DX systems circulate a refrigerant directly through the ground loop. This reduces the number of heat exchangers required and may provide an efficiency advantage. These systems have been restricted in some countries as they use copper pipes containing refrigerant in direct contact with the soil. External corrosion of the copper can be a problem causing refrigerant leakage. A copper based loop system would likely have a limited life in the Rotorua soils.

In a vertical closed loop configuration (Figure 16), a 100 to 150 mm diameter hole is drilled to between 50 and 100 m deep. A loop of pipe is inserted and the hole backfilled with a grout mixture that provides good thermal contact between the pipe, grout and soil to maximize heat transfer. A working fluid is then circulated through the pipe to absorb heat from the ground. Approximately 3 to 5 kW of heat can be extracted per hole, with each hole spaced approximately 5 to 10 m apart. The exact depth and number of holes needed for a project depends on the thermal conductivity of the ground, subsurface conditions and heat demand. A typical Rotorua home outside of the geothermal field would require about three vertical holes. Care must be taken not to extract more heat than can be naturally replaced. An experienced installer is able to calculate appropriate vertical loop depth and the number of holes required.

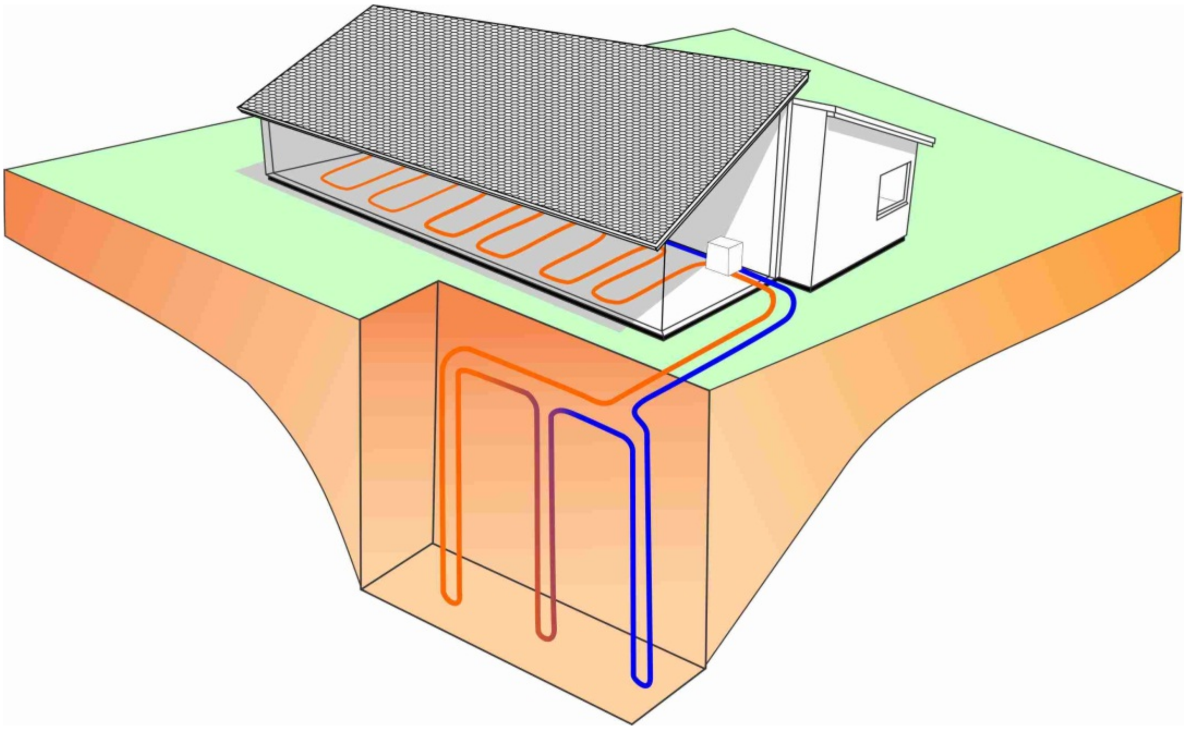

Figure 16 Vertical, closed loop geothermal heat pump system.

In a submerged coil installation (Figure 17), the loop is submerged in a surface water body to extract stored energy. Pipes are laid on the bottom of the lake or watercourse, weighted to hold them in place. A working fluid is circulated through the loop to extract heat energy from the water body.

Submerged coil installations generally require a body of water with a minimum depth of 3 m. The minimum surface area of the water body is calculated based on heat load requirements. As a general rule, in an enclosed water body (i.e. dam or pond) 50 m2 of water surface is required per kilowatt of capacity. The closed loop placed within the water body consists of either HDPE pipe or a plate heat exchanger constructed of stainless steel for freshwater applications. Either construction method is less expensive than earth-based loops.

Figure 17 Closed water loops using HDPE pipes or a stainless steel plate heat exchanger.

5.3.2 Open Loop Systems

Where closed loop systems circulate a fluid within a pipe, open loop systems operate by the direct take of surface water or groundwater.

Water is taken from an aquifer (groundwater), lake, stream, river or ocean (surface water) and pumped through a heat pump before being discharged. This water flow is used to transfer heat, in the same way that working fluid is used to exchange heat in a closed loop system.

There are a variety of configurations for open loop systems, including ground water, single well and drainage field, two well, standing column well and surface water systems. Figure 18 shows a double well system.

Open loop systems have minimal environmental impact, as the only change in water discharged from the heat pump unit is a small change in temperature.

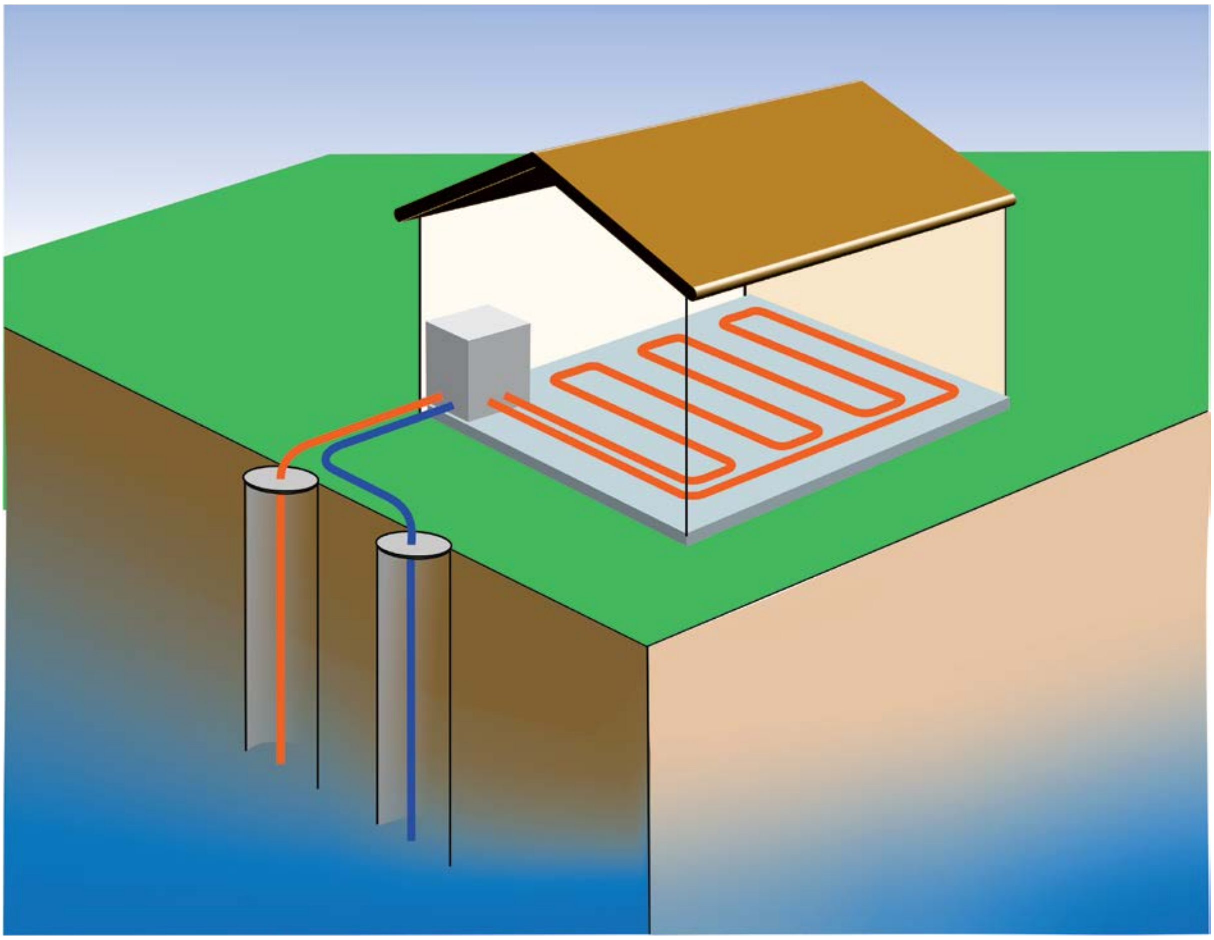

Figure 18 Double well open loop system.

For open loop systems, approximately 2.3 to 3.5 L/min of flow per kW is required; however, this depends on the water temperature and pump load required.

For a single home with a 12 kW load (about 149 m^2 of floor area), 23 to 35 L/min of flow would be required. This type of unit may be cost effective if a suitable well or river/pond source exists. Even domestic wells can be used to supply the needed water.

Standing column wells have been used in some areas, where water is extracted from the bottom of the well and returned to the top of the well. These require deep wells, up to 450 m deep, to maximize the heat transfer and prevent mixing of the return water with the bottom supply water.

There are a number of geothermal heat pump installations in New Zealand of the types described in Section 5.3. A copy of several case studies prepared to illustrate these can be found on the GNS Science website http://www.gns.cri.nz/Home/Learning/Science-Topics/Earth-Energy/Case-Studies.

At the time of writing, there are no known examples in the Rotorua Urban Airshed of the use of any of the geothermal heat pump systems described in Section 5.3.

5.3.3 Installation Costs

The installation cost of a geothermal heat pump will depend on the type, configuration and geological conditions specific to the site, such as availability of groundwater or surface water, soil and rock thermal conditions, site access, existing landscaping or vegetation, etc.

Table 5 presents estimated costs for typical geothermal heat pump installations in New Zealand for an average 3 bedroom home of approximately 150 m^2 with an approximate maximum heat demand of 15 kW and an average annual energy usage of 10,000 kWh. These costs are based on interviews with New Zealand installers and will vary depending on the specifics of a given installation.

Table 5 Indicative capital costs* for ground/water heat pump systems.

System type	Ground coil costs ($)	Heat pump (15 kW) costs ($)	Total system costs ($/kW)
Horizontal	19,000-30,000	6,000-10,000	25,000-40,000
Vertical	24,000-70,000	6,000-10,000	30,000-80,000
Submerged	15,000-22,000	6,000-10,000	21,000-32,000
Open (ground water)	19,000-40,000	6,000-10,000	25,000-50,000

*costs include installation and commissioning but exclude the buildings heating distribution system

5.4 Multi-User Systems

One of the benefits of geothermal home heating is the lower operational cost; however installation costs are high compared with other heating solutions.

Multi-user systems present an opportunity to spread installation costs across multiple households, and are particularly suitable where a geothermal heating solution produces more heat than a single household could realistically use.

In Rotorua a direct take system and a downhole heat exchanger system (as described in section 5.1 and 5.2) could provide multiple households with heat energy and may be suitable to consider for multi-user systems.

A typical geothermal heat pump system on the other hand may be less suitable for multi-user systems. The type of geothermal resource being accessed is widely available, and it is cheaper to access it where it will be used to avoid a costly distribution system. An exception to this is if a large surface water resource is available for distribution, from which individual geothermal heat pumps could access and supply heat to homes within the distribution network. An existing example of this type of system is seawater distribution in Stockholm, Sweden, which is used primarily for cooling commercial buildings in the central business district.

Multi-user systems work by circulating heated water through a ring main that encircles a network of homes to be heated (Community Energy Scotland Limited, 2011). The main carries heated water past each building (Figure 19) with each building drawing heat from it. This heat is then used for both the living space (radiators or under floor heating pipes) and can also be used for domestic hot water (hot water storage tanks).

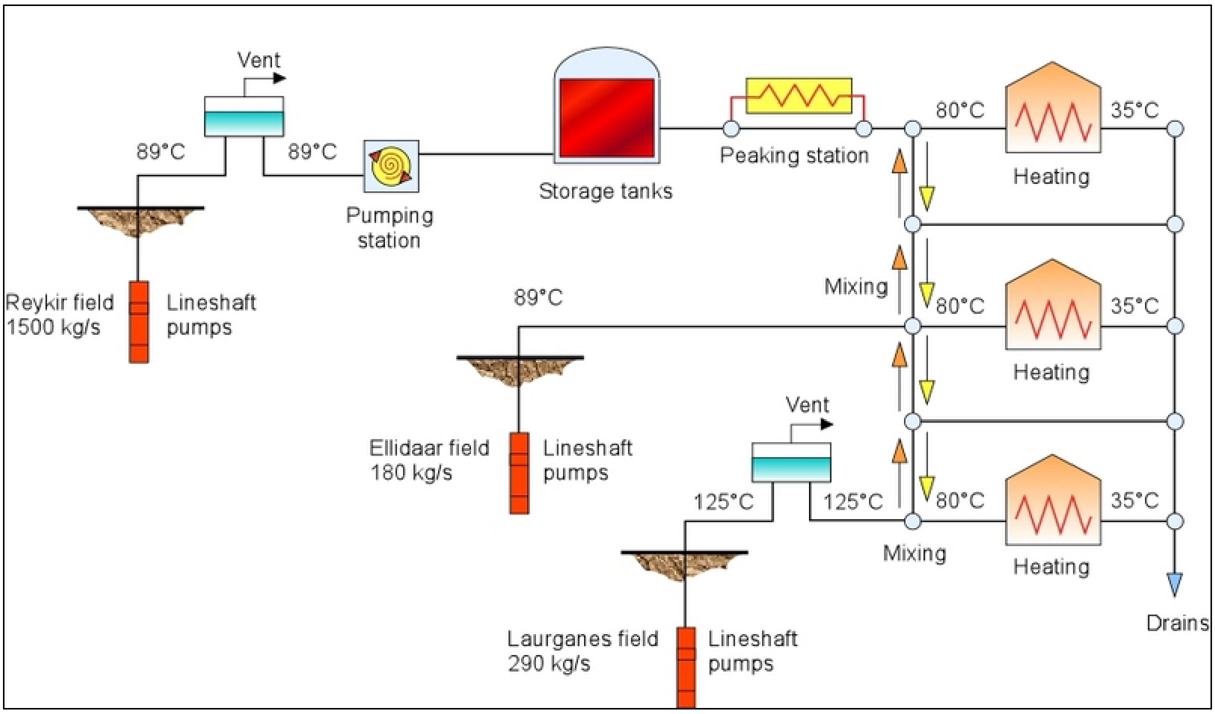

Figure 19 Simplified flow diagram of the geothermal multi-use system of Reykjavik. (Gudmundsson, 1988).

For new developments, multi-use systems can be installed in a similar way to other services such as potable water, gas, etc., with water for energy use becoming a utility. Design considerations, such as an evaluation of total building heat demand and the clustering of buildings can be done in such a way to maximise the efficiency of a multi-user scheme.

To achieve a financially viable multi-user system, a high thermal load density is required. International studies have shown that at least 55 dwellings per hectare are necessary for financial viability of a residential only scheme; this equates to a heat density of at least 3,000 kW per km^2 (UK Local Government, 2011). Zinko, et al. (2008) study heat distribution in areas with low heat demand density and came to the conclusion that heat density of 10 kWh/m^2/yr or with line heat demand of 0.3 MWh/m/yr can be economically served by multi-use. More detailed market analysis is required in Rotorua to determine expected and required residential uptake rates within specific areas (i.e. achievable load density). It is likely that higher energy users (e.g. office buildings, rest homes, etc.) may be required as part of a residential multi-user scheme in Rotorua in order to achieve economic load density.

A typical model for multi-user systems is for an organisation to own and operate the system as a utility, with individual users paying to access it.

In this model, the utility owner confirms the market conditions (i.e. pricing, predicted up-take and use) and technical issues to determine the feasibility of the installation of a multi-user system for a particular location. Following confirmation of feasibility and detailed design, the heat source is established and the distribution network installed.

A one-off connection fee may be charged to each new user of the system at time of connection. This fee covers the individual heat exchanger and heat meter installation for each connected building. With heat meters customers' heating bills are based on the actual level of heat consumed as determined by the meter reading. Heat meters measure flow rate and return temperature to calculate energy consumption. The utility owner pays the cost of connection to the system and recoups this investment through a monthly energy bill. This has been an effective means of attracting new customers as initial capital costs can be significantly reduced for users connecting to the system (Connecting to district heating, 2004).

There are a variety of billing models possible that are designed to cover maintenance costs, recoup installation costs, and in some cases provide a profit to the system owner, if a profit-based model is being used.

In one example from the UK, fees are set based on what it actually costs to produce the heat (UK Bristol Council, n.d.). Users pay a weekly heating and service charge prepayment which is calculated on the expected annual energy costs for running the multi-user system. Annually, prepayments are compared against actual running costs and any under or over charging resolved through refunds or an additional bill, as required. The community's multi-use system was first developed, owned and operated by the provincial government. The system has since been sold and is now owned by a publicly traded company. The system has grown since its beginnings and continues to incorporate new customers whilst investing in new technologies to improve efficiency and reduce emissions. Local jobs have been created and it is estimated that 70% of each dollar spent on energy from the multi-use system stays in the community, as compared to 10% of the money spent on oil heating (Connecting to district heating, 2004).

5.4.1 Installation Costs

The benefit of multi-user systems is that capital costs are shared by multiple users, significantly reducing installation costs per user. In examples presented in Section 5.1, a single set of production and injection wells in the Rotorua geothermal field may cost $80,000 but could provide up to 800 kW. This is enough to heat about 58 average family homes (3 bed room house, 150 m^2). From Section 5.2 a single DHE in Rotorua could supply up to 8 homes with geothermal heating. As noted in section 5.4, geothermal heat pump systems are unlikely to provide heat for more than one house. An open loop system using Lake Rotorua as the heat source might be feasible, but would need to be further investigated to determine whether any benefits of this approach exist, given the availability of volcanic geothermal resources in the area.

Regardless of the method of producing heat, multi-user systems generally consist of:

1. The heat transfer system
2. The heat distribution system
3. The consumer system

These systems are described and costed separately below.

Heat transfer system

If using direct take to supply a multi-user system with isolation of the geothermal fluid from a buildings heating system there are two approaches:

- Indirect system – use of a central heat exchanger facility that heats water for distribution to consumers;
- Direct system - geothermal fluid is delivered directly to the consumer and an individual heat exchanger (or exchangers) is located at each house – or users' site.

Due to the economy of scale, there is a point at which the cost of the central equipment is less than the sum of the costs for individual equipment at each user. Additionally a central system should be able to be designed so that it is more efficient. Use of the central heat exchanger approach (indirect system) allows the elimination of corrosion and scaling problems in the distribution lines and would be the preferred alternative for a larger system.

Estimated costs for the two types of systems are presented in Table 6 based on the example of a geothermal well producing 0.8 MW, (Steins & Zarrouk 2011).

Table 6 System Cost.

Item	**Direct System**	**Centralised System for 58 houses**
Heat exchanger	$2,000	$50,000
Circulation pumps	$2,500	$30,000
Other	$2,000	$50,000
Total System Cost	$6,500	$130,000
Total cost per house/user	$6,500	$2,241

It can be seen that the economics of a system of this size favour centralized systems.

Distribution system

The pipes transporting either geothermal fluid or hot water must be designed for the purpose. Design considerations include pipe material, chemical composition, size, installation method, head loss, pumping requirements, temperature, insulation, pipe expansion and service taps (Rafferty, 1998).

The installation of the distribution system in an existing built up area is a complex process with laying pipes under and around existing infrastructure.

Based on discussions with local suppliers and overseas information, a distribution system for the 0.8 MW / 58 house example is estimated at $240,000 and a distribution system for the DHE example of 6 to 8 houses is estimated at $105,000

Consumer system

To connect each house to the distribution system, a consumer branch pipe line is required. An estimated cost for the pipe line is $50 / metre – for a house requiring 40 m of pipe (20 m from the distribution system plus the return pipe) a cost of $2,000 is estimated.

A circulation pump is required to draw from the distribution system, with an estimated cost of $2,500.

The cost to retrofitting the building to enable use of the supplied heat for home heating is discussed in Section 6.2.5.

5.5 Hybrid Systems

All geothermal home heating technologies have the potential to be supplemented by other energy sources. These hybrid systems combine different energy sources with geothermal home heating providing greater cost effectiveness and/or greater energy efficiency.

Hybrid systems are designed with one energy source (i.e. geothermal) supplying the bulk of energy demand, with an alternative energy source (e.g. solar, wood, gas or electricity) available to boost heating capacity.

For example, a geothermal home heating system might be designed to meet 80 to 90% of the peak home heating demand, or, in other words, designed to adequately heat the home for all but the coldest days in winter. During those coldest days a supplementary heating system is used to top up heat as required.

The benefits achieved with this approach vary, depending on the type of hybrid system used. Hybrid systems can reduce capital installation costs. For example, a capital intensive direct take geothermal home heating system can be scaled back in terms of size and expense, and supplemented by heating systems that are less capital intensive, such as electric heating.

Some hybrid system options are presented below, however given the variety of combinations possible and the complexity of considering all of these options, this report will not consider hybrid systems in any detail. Rather, it is the intention here to highlight the potential use of hybrid systems and the way technology is expected to evolve.

Combined Heat and Power Plant (CHP)

A CHP plant generates electricity and usable heat simultaneously in the same process. It makes more efficient use of the geothermal resource by cascading the temperature (energy use), which in turn improves the economics of the entire system. Low temperature power generation on its own is often not economical below 150°C, as net plant efficiency becomes too low. There are a number of CHP examples in the U.S., especially those using a low-temperature resource, started as multi-use projects (GHC Bulletin, 2005). In some examples, the electric power plant was added later, presenting an economical prospect as the well and pumping systems were already in place. All that was required was to take some temperature off the top for power generation, while still providing enough temperature (energy) for the multi-use system to function effectively.

Base load and Booster system

A boosted system is one that uses a combination of heat supplied at a lower temperature and a fuel fired or heat pump system to boost the temperature when needed.

Such a multi-use system would provide water at lower temperatures to each building in the multi-use system. Each building would then have a heat pump or fossil fuel system to boost the temperature when needed. In this way, a lower temperature resource may become viable for use, and the overall impact on the primary geothermal resource can be reduced, as less heat is required from it.

Geothermal heat pumps + solar

Hybrid geothermal heat pump systems couple conventional ground-loop heat pump equipment with supplemental heat extraction systems, such as solar panels.

In some heat pump systems, the annual amount of heat extracted from and injected to the ground are not balanced. If the system is only used for heating, an annual imbalance in ground load can lead to lower heat pump entry temperatures (EFT), to a point where equipment capacity may be compromised. This imbalance requires either a very large ground loop heat exchanger or some mechanism for assisting the system by supplementing the heat deficit. Because the cost of installing a large ground loop heat exchanger may be excessive, a hybrid system can be used. For example, a solar collector can inject additional heat into the ground loop for buildings that have a dominant heat load (Figure 20).

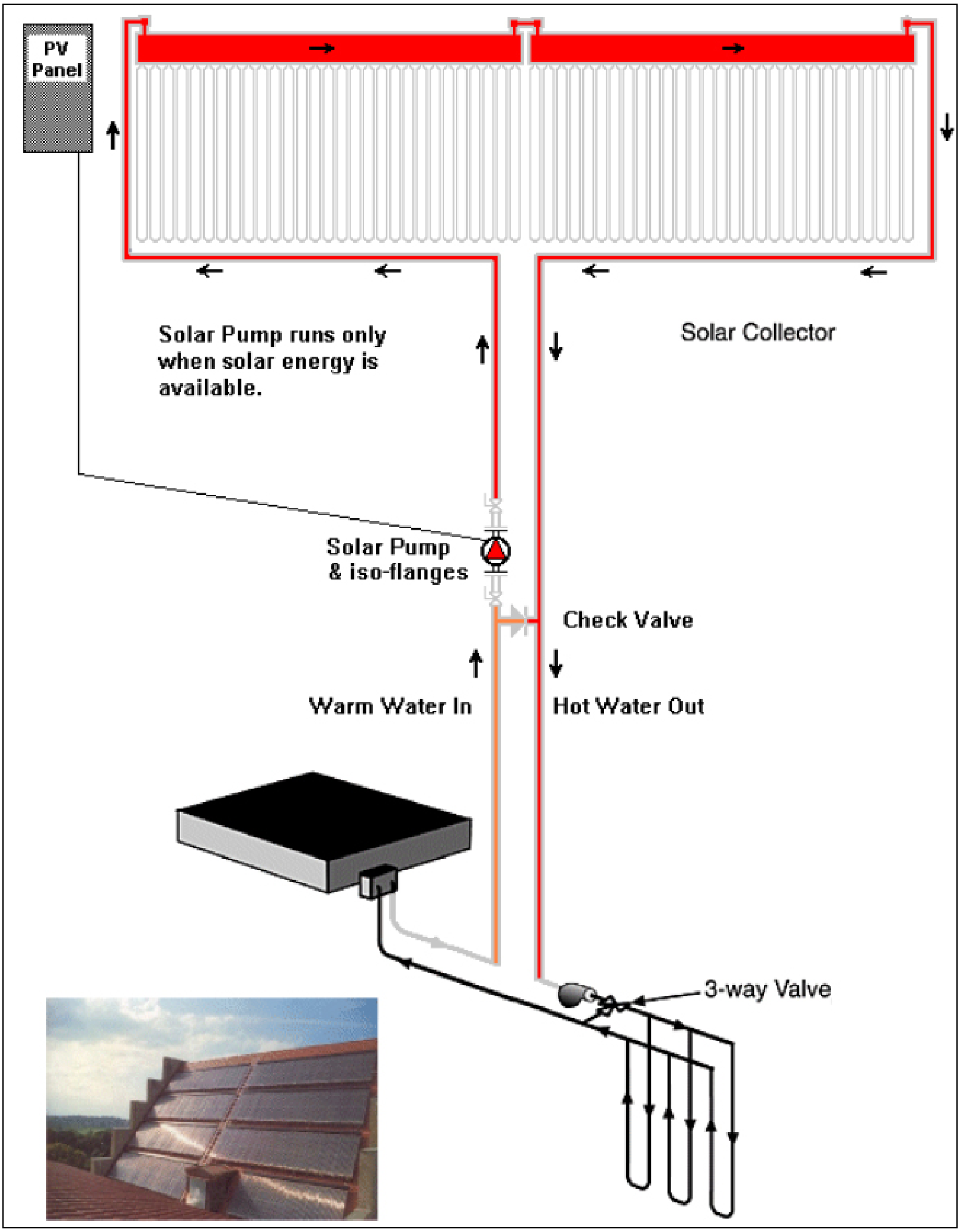

Figure 20 Diagram of a hybrid GHP system with supplemental solar thermal collector (IGSHPA, 2012).

The design and operation of hybrid geothermal heat pump/solar systems is complex, as each component must be carefully designed and sized to provide complimentary operation. This is discussed to identify the sort of technology combinations that are being considered in other countries. It is not suggested that these be considered for use in Rotorua at this time.

6.0 TECHNOLOGIES FOR HEATING WITH GEOTHERMAL ENERGY

Heating systems using geothermal supplied energy are presented below. Any heating system, however, should start with a consideration of the thermal performance of the building.

6.1 Building Thermal Performance

The envelope insulation of a building determines its thermal performance with the envelope formed of floors, external walls, glazing and ceilings adjacent to external spaces.

The use of insulation in New Zealand homes was codified in April 1978 following the introduction of NZS4218P– The housing and small building energy efficiency standard (provisional). This standard (2009 requirement for Zone 2 from NZS4218 which includes Rotorua) now provides levels of insulation for floors (R1.3), walls (R1.9), glazing and skylights (R0.26) and roof/ceilings (R2.9) (Burgess, 2011).

Over one third of the current housing stock has been constructed since insulation standards were introduced, with a further 40% of houses having some insulation retrofitted, primarily in ceilings. This suggests that at least 0.5 million houses in New Zealand still have no, or only partial/substandard, ceiling insulation, with greater numbers lacking wall and floor insulation (Ministry for the Envrionment, 2005).

This issue has led to the development of the Warm up New Zealand: Heat Smart programme, run by the Energy Efficiency and Conservation Authority. The programme started on 1 July, 2009 and aims to retrofit more than 188,500 New Zealand homes.

In 2011, a survey was conducted of people's energy uses, demands and needs in Auckland, Tauranga, Rotorua, Christchurch and Dunedin (Dowdy & Becker, 2011). Results on questions regarding insulation upgrades in respondent's house in Rotorua showed that 62.0% of survey respondents had fully installed ceiling insulation, 35.1% underlay carpet, 59.1% draught stopping, 21.3% thermal-lined curtains, 19.2% wall insulation,18.1% under floor insulation and 32.6% double-glazing.

Retrofitting a home with any form of capital intensive heating, including geothermal, without addressing inadequacies in the building's thermal performance, will not achieve a desirable outcome. It is recommended that envelope insulation forms the initial phase of any home heat retrofitting or improvement programme.

6.2 Space Heating Systems

In New Zealand, only 5% of homes have central heating. A strong tradition exists of individual room heating, although expectations are developing for a greater level of home heating based on people's exposure to warmer conditions experienced elsewhere in the world (Ministry for the Envrionment, 2005).

The benefit of central heating is that all parts of the home are heated evenly, providing a healthier and more comfortable environment in all rooms, where single room heating often leaves bedrooms, bathrooms and other areas of the home at best uncomfortable, and at worst unhealthy.

Like most renewable energy systems, geothermal home heating is characterised by high initial capital cost with low running cost. As such, compared with other fuels such as electricity, geothermal home heating is a suitable means of providing central heating.

Providing geothermal home heating to houses in the Rotorua Urban Airshed will require a retrofit to existing buildings heating systems. However, if a central heating system is already installed, it is likely that this can be converted.

Rooms and buildings can be heated by passing a geothermal heated working fluid through heat convectors located in each heating space. The main types of heat convectors used for space heating are a) forced air, b) finned tube convector, c) radiator, and d) under floor panel. These are shown in (Figure 21).

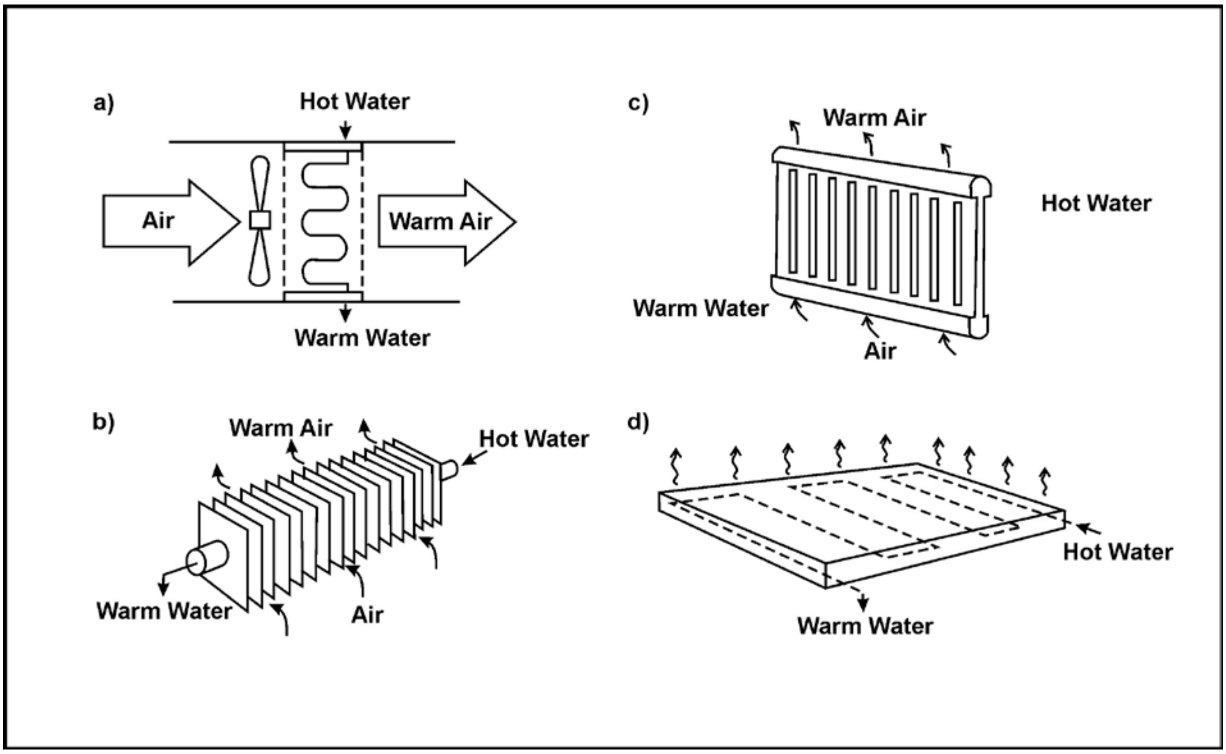

Figure 21 Space Heating Components.

6.2.1 Forced Air

Forced air systems blow cold air over finned hot water coils, creating warm air. This warmed air is then distributed to the home by ductwork to room vents.

These units can operate with working fluids at temperatures as low as 55°C, but work more efficiently with temperatures above 70°C.

6.2.2 Finned tube convectors

This system consists of a length of ‘finned’ pipe. The fins increase the surface area of the piping to improve heat transfer from the hot water to air by means of convection.

The primary function of finned tube convectors is to provide a curtain of warm, rising air between occupants in the home and the colder surface of a window or exterior wall. A small percentage of heat output is radiant, but this is typically less than 10% of net output. The net effect on the mean radiant temperature in a room is almost nil.

Units can be installed with or without a sheet metal cover. With the cover, units are installed at a low level along a wall; without the cover they can be concealed in an architectural enclosure, recessed into floors or areas where the units won't be subject to damage or corrosion.

Finned tube convectors require working fluids above 60°C, with temperatures above 70°C preferred. The efficiency of the unit can be increased to use lower temperature water by placing a fan behind the unit to help circulate the air.

6.2.3 Radiators

Radiators are typically mounted on internal walls in each room to be heated. They are ideal as a retrofit solution for existing properties where under floor heating is not an option because installation is relatively straight forward and non-invasive.

Radiators deliver heat in the form of radiant energy: the energy from a radiator travels through the air without heating the air until it strikes a solid object. The object is warmed, which in turn warms the surrounding air. A radiator's primary function is to affect the mean radiant temperature, or the average surface temperature of the surfaces surrounding your body.

Optimal working fluid temperatures to support radiator systems are typically above 60°C.

6.2.4 Under floor panels

Under floor panels work by the circulation of warmed water through piping installed under, or within the floor.

Under floor panels provide even, uniform heat and do not generate drafts. They operate at lower temperatures than other heating systems, with working fluids at temperatures as low as 38°C

While perhaps the preferred method of heating overall, the main disadvantage with under floor panels is the difficulty of retrofitting. In reality, retrofitting with under floor panels is unlikely to be feasible in the majority of existing homes.

Under floor distribution systems are recommended in new builds.

6.2.5 Installation Costs

The most common central heating retrofit system in New Zealand is radiators, as they offer a practical compromise between ease of installation and efficient and effective operation.

Forced air systems can also be considered, however they require higher working fluid temperatures to operate effectively.

Table 7 identifies the cost of retrofitting an average 3 bedroom house of 150m^2 with a 15 kW geothermal central heating system estimated from discussions with local installers and from local examples.

Table 7 Cost Comparison for Central Space Heating Systems

	Forced Air	Radiators
Installation cost	$13,000-$18,000	$6,000-$14,000

7.0 COMPARISON WITH OTHER HOME HEATING SOLUTIONS

New Zealand homes are traditionally heated individually, often with a single heat source in one room of the house. This is in contrast to a number of other nations where central heating is well established, as is reticulated heat delivered via district heating schemes with households taking heat from the reticulation system.

A typical New Zealand household uses electricity and/or a wood burner to heat one or two rooms in the house (Doody & Becker, 2011). The lounge is most commonly heated, although some households heat bedrooms (particularly those occupied by young families and elderly residents) in the interest of maintaining their health and wellbeing.

Individual household central heating systems have penetrated the NZ market to a small degree, and as New Zealanders seek higher levels of comfort and become more interested in healthy, warm homes, central heating uptake will increase.

Consumer NZ (2012) completed a survey to compare costs of heating homes with different fuels and different heating arrangements. This data is tabulated in Table 8. The data for the geothermal heat pump in the table is a calculated number added to the Consumer data.

Table 8 Home heating costs 2012 (cents per kWh delivered).

Fuel/heating option	Single room	Central Heating
Fire wood	6-14	
Wood pellets	14-27	14-27
Electricity	23-37	
Air source heat pump	13-18	
LPG	20-27	18-23
Natural gas	14-26	13-23
Diesel		17-19
Geothermal Heat-pump [1]		6-9

1 – Calculated using a COP of approximately 4 for a GHP – Not Consumer NZ data.

Geothermal heat pumps have a capital / running cost position with high up front capital loading and low running cost. They feature in nations where household central heating is established and where longer term paybacks for environmentally friendly energy solutions are embraced. They are not expected to be an energy solution that would displace the single heated room approach for an individual dwelling, as is common in New Zealand. For example: an oil-column heater can cost as little as $50 to buy and runs at around 25 cents per kWh for the heat delivered to the house; a wood burner will cost around $4,000 to install and 10 cents per kWh for heat delivered; a geothermal heat pump will cost $20,000 to $80,000 to install and about 8 cents per kWh for heat delivered to the house.

Table 9 considers the cost to install a central heating system for a range of technologies including geothermal heat pumps and geothermal energy use from the Rotorua Geothermal Field. The two systems that use energy from the Rotorua Geothermal Field are multi user systems because of the capital intensive nature of the installations and the quantity of energy delivered from the individual wells.

The following assumptions have been made in developing the data in the table:

- Retrofitting the house to central heating using radiators is included in the capital cost.
- The households are the shareholders in the multi-user systems, splitting the common capital costs equally.
- For the multi-user systems, 100% of the houses close to the production site will connect to the system.

Table 9 Individual household installation costs* for central heating systems.

Fuel	Capital cost (per house)	Number of Households
Wood pellets	$22,000-$32,000	1
LPG	$13,000-$14,500	1
Natural gas	$13,000-$14,500	1
Diesel	$16,000-$17,500	1
Direct geothermal take (58 shareholders)	$23,983	58
Down hole heat exchanger (6 shareholders)	$25,833	6
GHP (Submerged)	$36,500	1
GHP (horizontal, closed loop)	$42,000	1

* costs are based on a 3 bedroom home of approximately 150 m2 with an approximate heat demand of 15 kW and an average annual energy usage of 10,000 kWh

In order to get a feel for the benefit that multi user geothermal systems have achieved in other nations, data from the U.S. is detailed in table 10. This shows the average unit cost for energy for various individual residential energy supply types against a geothermal multi-user district heating system (Hildigunnur H. Thorsteinsson, 2010).

Table 10 Cost data for individual residential energy sources and geothermal multi-user systems.

Fuel source	Price 2007 US$/kWh
Electricity	0.11
Propane	0.07
Kerosene	0.07
No. 2 heating oil	0.05
Natural gas	0.04
Geothermal district heating	0.03 – 0.12

8.0 OPPORTUNITIES AND BARRIERS

In 2010 the Ministry of Economic Development released a report identifying barriers to geothermal development in New Zealand (Ministry of Economic Development, 2010). These are summarised below:

- limited access to information;
- low levels of customer awareness and understanding;
- lack of skilled technology specific experts and installers;
- issues around ownership and access to geothermal resources;
- the process to secure and maintain resource consents and other regulatory barriers;
- relatively low population density;
- New Zealand's relatively mild climate (short heating and cooling seasons);
- A lower level of comfort demanded by New Zealand householders relative to some overseas countries.

These barriers apply equally to any process of retrofitting homes in Rotorua with a form of geothermal heat whether it will be ground source heat pump or more conventional geothermal use.

9.0 SOCIAL DYNAMICS

New Zealand has a comparatively mild climate, a history of single room heating, minimal investment in home heating and generally lower expectations of levels of indoor comfort in winter compared with other countries.

Against this backdrop, social dynamics are a key determinant in any shift in home heating practices that can benefit air quality in the Rotorua Urban Airshed.

Research on people's energy choices by Doody & Becker (2011) identified that decisions consumers make about how to heat their homes are entrenched in a social process. People triangulate public information and expert advice with anecdotal evidence and experiences of family and friends. This essentially means that consumers need to see the technology in action before they will commit to the alternative themselves.

Doody & Becker (2011) surveyed some Rotorua residents, identifying that a third of respondents (33.6%) to the survey had considered changing the main method of heating used in their house. Those in Rotorua who were contemplating changing were most commonly thinking about installing air source heat pumps (65.9%). Other options include enclosed wood-burners (11.4%), central heating gas (2.3%), gas heaters (4.5%) and other (15.9%). Geothermal was not specifically identified as a choice in the survey, so is likely a component of the "Other" option.

An interesting result is the 66% response rate for air source heat pumps. Due to the particulars of the ambient Rotorua environment, corrosion issues have resulted in premature failure of many of these heating systems. It could be concluded that air source heat pumps present an attractive choice for consumers because they offer an easy retrofit option for single room heating, despite this choice being poorly suited to the Rotorua environment.

Further studies have shown that the extent to which people can adopt new home heating technologies and their willingness to do so is influenced by how easily new technologies can be integrated into their homes and the related costs of such a retrofit (ORC, 2006). New Zealanders have a short term view on home ownership; the rate at which the average New Zealander moves house is about every 6 to 7 years. This provides a time window in which they will wish to recoup expenditure through short pay back periods. Additionally, owners of rental properties have little incentive to bear the costs of a more expensive installation that provides lower on going heating costs for tenants.

In work conducted around the adoption of solar energy systems, interviewees were supportive of financial incentives and subsidies, and these were important in encouraging the uptake of solar systems (see Scotts & Saville-Smith, 2007); however, such initiatives may not be as successful for technologies such as geothermal heating systems that incur higher outlay costs (see NZBCSD, 2008; ORC, 2006). For instance, a number of interviewees while keen to upgrade their properties observed that they would not recoup the cost of retrofitting their home in the property resale value and, therefore, suggested it was unviable to undertake such projects.

These dynamics present an impediment to the implementation of longer term environmentally superior heating systems in the residential environment. Lower operating costs and environmental benefits do not appear, on their own, sufficient to encourage wide spread uptake of these technologies.

If the environmental benefits of such systems are assessed as significant, then an agency needs to manage the uptake process. Intervention will likely need to include show casing the technology, raising awareness in the target community, providing ways to get the investment to occur and assisting to get operating systems in place.

If multi-user systems are to be encouraged, then work to draw operating groups together would need to be undertaken because in most situations, it is unlikely that groups will form by themselves. Securing buy in from enough home owners within a discrete areas of the Rotorua Urban Airshed to produce economically viable multi-user systems may prove challenging. Grouped residential structures around social constructs such as marae, papakainga or kaumatua housing, military or other institutionally provided housing, or state housing, may provide a key opportunity. In these situations, it is possible that the required structures to support multi-user systems are already in place. Opportunities to work with and support these groups should be explored.

10.0 REGULATORY AND POLICY CONSIDERATIONS

The Rotorua Geothermal Field is managed under the Resource Management Act 1991 through the Rotorua Geothermal Regional Plan which became operative on 1 July, 1999.

The Rotorua Geothermal Regional Plan seeks to ensure that the Rotorua geothermal resource retains its values and potentials, while:

- protecting geothermal surface features, and
- protecting tikanga Maori, and
- identifying and, as practicable, enhancing available geothermal resource, and
- providing for the allocation of that resource for present and future efficient use, and
- managing and controlling all adverse effects on the field, and
- providing for efficient cost effective administration.

At the time of writing it is understood that the Rotorua Geothermal Regional Plan is under review.

It is the intent of this report to acknowledge this on-going review process, and to identify this review as a key opportunity to facilitate appropriate use of geothermal resources generally within the district and the Rotorua Urban Airshed. Some key opportunities are:

- To conduct a review of the implications of existing rules structures on geothermal heat pumps.
- To conduct a review of existing restrictions on the geothermal field with consideration of modern technologies and increased knowledge of the geothermal resource.
- To consider a prioritisation of allocation where use of the geothermal resource can directly contribute to positive environmental impacts such as improved air quality.

11.0 CASE STUDIES

Space heating with geothermal energy is one of the most common and widespread direct uses of geothermal resources internationally. Space heating comprises over 37% of the total direct geothermal use worldwide. If geothermal heat pumps are included, space heating accounts for more than 50% of all geothermal non-electric uses (Bloomquist, n.d.).

Space heating is also one of the oldest direct uses of geothermal, and as early as the 14th century the inhabitants of the French village of Chaudes-Aigues Cantal were enjoying the benefits of geothermal space heating delivered to them via a district heating network that is still in operation today. In the U.S., many cities in the west enjoy direct geothermal use space heating, many dating from the early 1900’s.

The development of geothermal multi-user systems (or district heating), led by Iceland, has been one of the fastest growing segments of the geothermal space heating industry and now accounts for over 75% of all space heating provided from geothermal resources worldwide. Many countries, including Turkey, Hungary, Romania, France, Poland, China, Sweden and Denmark are developing this use of geothermal resources.

At the present time approximately 50,000 geothermal heat pumps are installed in the United States annually with a total capacity of approximately 600,000 kW. Geothermal heat pumps are also popular in many European countries with Sweden, Switzerland, Germany and

France being some of the leaders. Geothermal heat pumps are also an important component of some district heating systems.

Listed in Appendix B are some case studies that showcase some of the ways geothermal resources have been applied for space heating in New Zealand and overseas.

12.0 CONCLUSIONS AND RECOMMENDATIONS

Geothermal home heating can contribute to addressing winter-time air quality issues associated with existing home heating practices in the Rotorua Urban Airshed by offering a clean, renewable alternative.

The geothermal resource is abundant in Rotorua including the conventional geothermal resource, ground energy, energy in groundwater and Lake Rotorua. A range of these sources could contribute much more to the future clean energy supply for Rotorua.

At present the least cost geothermal solutions are identified as multi user conventional geothermal systems. Careful management of the Rotorua Geothermal Field is required to prevent effects on important surface geothermal features with low impact technologies such as downhole heat exchangers which can provide geothermal energy with little or no effect on surface geothermal features. Some additional direct take of geothermal fluids may also be possible from the Rotorua Geothermal Field if they are located and managed appropriately. The non-conventional geothermal heating solutions are more expensive than the conventional.

Geothermal home heating requires high initial capital investment compared with other heating solutions, however this is offset by much lower operating costs. For this reason, geothermal home heating is an effective way of providing residential central heating, but is not considered feasible for lower energy demand applications, such as heating a single room.

In New Zealand less than 5% of homes have central heating and the traditional approach to home heating is low capital investment, single room heating with lower expectations of indoor comfort in winter. In many other countries central heating is considered a basic necessity.

For this reason, widespread uptake of geothermal technologies in the residential home heating market in the Rotorua Urban Airshed is not expected in the near term, and therefore at present, geothermal home heating is unlikely to provide a feasible alternative to current heating practices.

There are, however, a range of opportunities that can assist to change this.

The development and support of pilot projects across the various geothermal technologies will assist with providing real-time data and raising awareness, supporting individuals to consider and take up geothermal home heating.

Upfront capital costs may be reduced by developing multi-user systems where a high density of users can be secured. In addition, geothermal home heating can provide domestic hot water for little or no additional cost, which can improve overall economics and attractiveness to consumers.

Improving the thermal performance of the residential building stock will assist with any future home heating systems, and can also provide an immediate benefit by reducing the energy required from current, solid fuel burning systems, in turn reducing the air particulate loading. There is a Government incentive package already in place for this to occur.

Additional incentives are likely required to encourage the use of geothermal home heating. Means of providing incentives should be further investigated, such as identifying sources of funding from public or private organisations.

There is a cost to achieving cleaner air and healthier homes. The Rotorua Urban Airshed is one of the few places in the world with such impressive geothermal resources available that can deliver this result, but investment in reducing barriers to the use of this technology is required.

If longer term superior energy use solutions are seen as a community objective to not only improve air quality but also overall energy use effectiveness of the city of Rotorua, then geothermal energy in the broadest sense should be a central focus of planning for this outcome.

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APPENDIX A COST SUMMARY

Individual User

System	Resource	Production	Retrofitting the house	Cost per house hold
DHE	Volcanic	$50,000	$10,000	$60,000
GHP – Closed	Soil (Horizontal)	$32,000	$10,000	$42,000
GHP – Closed	Soil (Vertical)	$55,000	$10,000	$65,000
GHP - Closed	Surface water – Lake Rotorua	$26,500	$10,000	$36,500
GHP – Open	Groundwater	$37,500	$10,000	$47,500

Multiple -user

System	Resource	Production	Transmission, distribution and retrofitting house	Total cost multi-user system	Cost per house hold
Direct take (58 houses, with centralised heat transmission)	Volcanic	$80,000	$1,311,000	$1,391,000	$23,983
DHE (6 houses)	Volcanic	$50,000	$105,000	$155,000	$25,833

APPENDIX B WEB BASED INFORMATION

Direct take

- Hospital heating (Rotorua, NZ) (http://www.hera.org.nz/Category? Action=View &Category_id=767)
- District heating (Ankara, Turkey) (http://geoheat.oit.edu/bulletin/bull22-2/art3.pdf)
- District heating (Phili, South Dakota, U.S.) (http://geoheat.oit.edu/bulletin/bull24-2/art6.pdf)
- District heating (Vicenza, Italy) (http://geoheat.oit.edu/pdf/bulletin/bi076.pdf)
- District heating (Reykjavik, Iceland) (http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-06-09.pdf)

Downhole Heat Exchangers

- The Alpin Motel (Rotorua, NZ) (http://www.gns.cri.nz/Home/Learning/Science-Topics/Earth-Energy/Case-Studies)
- Space and hotwater heating (Taupo, NZ) (http://www.gns.cri.nz/Home/Learning/Science-Topics/Earth-Energy/Case-Studies)
- Space and hotwater heating (Klamath Falls, U.S) (http://www.geothermal-energy.org/pdf/IGAstandard/EGC/szeged/O-7-08.pdf)

Geothermal heat pumps

- Closed loop, horizontal GHP (Kapiti Coast, NZ) (http://www.gns.cri.nz/ Home/Learning /Science-Topics/Earth-Energy/Case-Studies)
- Closed loop, vertical GHP (Queenstown, NZ) (http://www.gns.cri.nz/ Home/Learning /Science-Topics/Earth-Energy/ Case-Studies
- Closed loop, submerged GHP (Wairakei Intl Golf Club, NZ) (http://www.gns.cri.nz/Home/ Learning/Science-Topics/Earth-Energy/Case-Studies)
- Open loop, groundwater GHP (Christchurch, NZ) (http://www.gns.cri.nz/Home/ Learning/Science-Topics/Earth-Energy/Case-Studies)
- District heating, using GHP as base load (Lund, Sweden) (http://www.energy-cities.eu /db/lund_139_en.pdf)

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