Effect of Rainfall on Low-Heat Ground Source Heat Pumps in New Zealand

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ABSTRACT

Low-energy efficient technology that is reliable, cost-effective and has a low environmental footprint has become a key focal point in recent years. Heating and cooling account for a significant share of global energy demand and represent a significant opportunity for improvement. In this study, an alternative approach to contemporary applications of geothermal energy is presented, ground source heat pumps. To qualify the magnitude their opportunity presents, it is first critical to understand the mechanism they exploit and the physical properties that influence their operation and performance. This study will therefore explore, how heat pumps achieve efficiencies over 100%, how efficiency changes with respect to depth and with a focus on the effects of rainfall and moisture content on the thermal balancing of the soil.

1. INTRODUCTION

Ground Source Heat Pumps (GSHP) (also known as Geothermal Heat Pumps) are a combination of two well-established technologies, Heat Pump (HP) and Geothermal Energy Technology (GET). Thermal energy (heat) can provide work directly as process heat or be converted or stored. This is significant because although half of global energy is used for heating, the majority is converted from other forms of energy(IEA 2021)(IEA 2019). None of which have as low of an environmental impact or are as energy efficient as heat pumps(IEA 2021)(IEA 2019). In New Zealand, although electrical energy derives from 80-85% renewable, their share of primary energy is much less at 40%(MIBIE 2022c).

To ameliorate this discrepancy, this study will present GSHP as part of the solution, focusing particularly on the hydrological impacts on performance. To begin with, key principles are outlined, then a summary of the current state of deployment and research into GSHP in New Zealand is conducted. To finish, a deeper dive into the terrestrial and hydrological systems' influence on GSHP performance. The objective of this study is to arrive at a meaningful understanding of rainfall's influence on GSHP performance as well as the provided opportunities to meet key environmental, economic and social policy objectives.

2. GEOTHERMAL ENERGY

The common notion of Geothermal Energy is that of electrical energy production, despite fundamentally being, terrestrially stored heat that is exchanged via GET between the atmosphere and lithosphere (subsurface).

2.1. Variations of Geothermal Energy

Geothermal energy is renewable because it is the product of three different energy production phenomena as depicted in Figure 1(Climo 2014) p.8.. Firstly, the Earth's core retained heat from its formation and propagates frictional heat as well as creates heat from the radioactive decay of elements (Climo 2014, p.2). Secondly, localised volcanic systems propagate high heat flow towards the surface in response to tectonic activity. Lastly, solar energy is absorbed by the earth's surface, the magnitude of which is dependent on surface albedo (heat absorption=1-albedo). It is the latter to which GSHP seek to exploit to improve their performance. This reveals that GSHPs are in fact, solar-powered and therefore renewable.

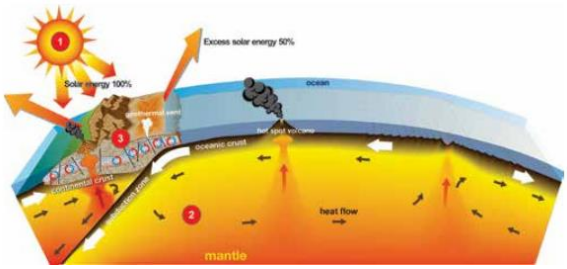


Figure 1 - Sources of Geothermal Energy (1. Volcanic systems; 2. Solar energy; 3. The Earth's core) (Climo 2014) p.8.

1.1. Low-Heat Geothermal Resource

Traditional applications of GET seek to exploit high heat geothermal resources for electricity production (>150°C), hundreds of meters below the surface. Whereas GSHP exploits low heat resources (<150°C) at depths of tens of meters(NZGA 2022). This represents what the New Zealand Geothermal Association (NZGA) describes as, "an underutilized resource in New Zealand." With high heat locations being geographically limited to the Taupō Volcanic zone, low-heat resources, including the solar-powered subsurface, are available throughout New Zealand at varying performance potentials for GHSP (Figure 2).

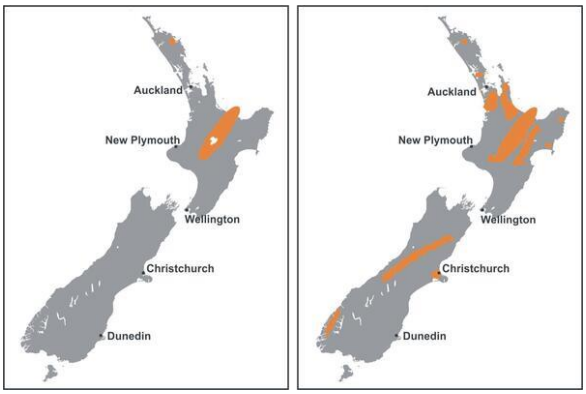


Figure 2 - Areas suitable for electricity generation (left) and direct heat use (right)(GNS 2022)

1.1. Annual Soil Temperature Variations

The temperature and so, heat energy, are much more diurnally and seasonally constant in the subsurface. It is this

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phenomenon that GSHP seeks to exploits. As shown below in Figure 3, The New Zealand Energy Efficiency Conservation Authority (EECA) and GNS Science have shown seasonal variations of soil temperatures at a depth of 1m do not vary significantly from 13°C (EECA 2016 p.9). Dependent on geological features (see 4.1), these effects are more pronounced at lower depths until reaching negligible variances at 5-10m (Sarbu 2014)(Sarbu 2015)(Climo 2014).

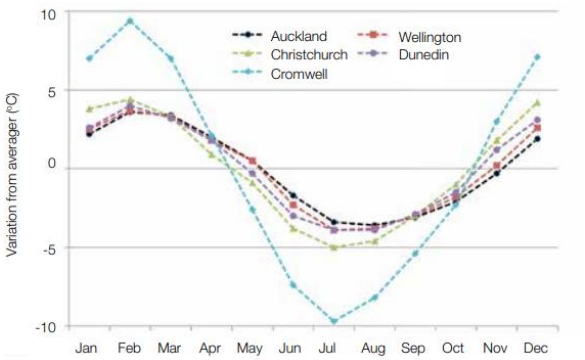


Figure 3 - Soil temperature variation from the annual temperature in 2010 at various locations in New Zealand

3. CARNOT THERMODYNAMIC CYCLE AND HEAT PUMP COEFFICIENT OF PERFORMANCE

A heat engine whose process is reversible is referred to as a reversible heat engine, also known as a Carnot heat engine (Dincer 2018 1.7.11.1)(Chen 2013)(Standards NZ 2022). Thus, GSHP can be pumped bi-directionally using a ground-sourced reverse Carnot thermodynamic cycle (Sarbu 2014). Here, the Carnot heat engine is represented by the temperatures of the two reservoirs, the ground and ambient air. In reverse cycle mode, the heat pump heat engine is the maximum theoretical coefficient of performance (COP) for both cooling and heating modes (Dincer 2018 [77] [78]). COP is the ratio of heating output to energy input (Sarbu 2014)(Sarbu 2015)(Ahmadi 2018)(Standards NZ 2022) and is crucial for the environmental, economic and technical suitability of heat pumps. This means that higher heat sources produce higher COP values as shown in figure 4.

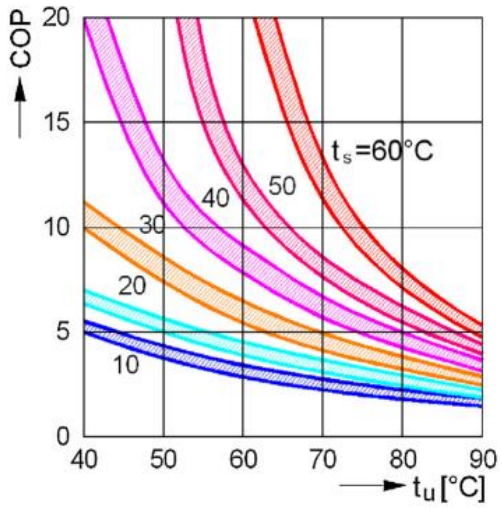


Figure 4 - Efficiency performance of heat pumps with various input temperatures (Sarbu 2014)

This results in heating efficiency improvements via the reduction of the energy required to maintain a fixed temperature. To highlight, a typical air-to-air GSHP has an efficiency of 250% (COP = 2.5), whereas by contrast, conventional heating fuels such as coal, gas-oil and natural gas have efficiencies of 70%, 80% and 80% respectively (Sarbu 2014)(Ahmadi 2018). The GSHP can achieve over 100% efficiency by extracting geothermal energy, this is how, relative to fossil fuels, less energy is required for heating with GSHPs. This is worth noting because increased efficiency and reduced energy result in multiplicative reductions in heating demand and improves heating's Carbon Intensity (CI).

4. CARBON INTENSITY

CI is the levelised carbon emission rate relative to the energy consumed or is otherwise a measure of enviro-climate impact (measured in g CO2 eq/kWh). However, CI has a problem with measurement uncertainty. As direct measurements of emissions are impractical, various estimation methodologies were developed. The most comprehensive and exhaustive of which is Life Cycle Analysis (LCA). This includes not only CI, but multiple environmental impact dimensions.

The International Panel on Climate Change (IPCC) reported aggregated results of a literature review of LCA on CI and found the median for GET is 45. By contrast coal, oil and natural gas are 1001, 840 and 469 respectively (Philippacopoulos 2001 p.982). Other estimates in the literature report 490, 350 and 240 respectively and 15-19 for GSHP GET specifically(Sarbu 2014). This calls attention to the variance and limitations of CI estimations from the various methodologies, delineations and frameworks. Nevertheless, following the implementation of GSHP for heating, a very significant and consistent reduction of CI is shown. Carbon emission reductions from 15% to 77% are reported from the installation of GSHPs in both residential and commercial buildings(Sarbu 2015 pg123). This framework for carbon emission inventorying was developed and then implemented in the Paris accord.

5. THE STATE OF GSHP DEPLOYMENT IN NEW ZEALAND

5.1. Motivations for Deployment

In response to signing the Paris accord of 2015, in 2019 New Zealand had ascended the Zero Carbon Act into Law with the express aim to decarbonise New Zealand(Legislation NZ 2022a). Additionally in 2019, the Healthy Homes Standards introduced mandatory heating and insulation standards, which also include a provision to qualify direct heating by geothermal energy(Legislation NZ 2022b [10B]). Furthermore, the then Ministry for Economic Development (MED), now MBIE, released a strategic energy document with a policy target of achieving 90% renewable electricity generation by 2025, with targets for direct use and geothermal energy(EECA 2011).

These goals are in alignment with GSHP deployment. However, despite the development of GSHP AUS/NZ standards in 2021(Standards NZ 2022) and policies sending clear industry signals, minimal development has occurred in NZ. Perhaps premature to state, but it may have been more effective for the government to directly back GSHP technology to address the lack of industry confidence, rather than simply fund proposals(MBIE 2022a)(MBIE 2022b).

5.2. State of GSHP Industry

The GSHP industry is in its infancy in NZ. At the time of writing, Figure 5 depicts the installations numbering at 130 and include a variety of scales(GNS 2022). This may seem significant with this representation, however, when inspecting installed capacity, the reality of relative energy exploitation paints a very different picture. Total GET installations for power generation, direct use and heat pumps are 1095 MW, 680MW and 1.4MW respectively(GNS 2022). This means that GSHPs currently represent 0.13% peak power capacity compared to that used for electricity generation.

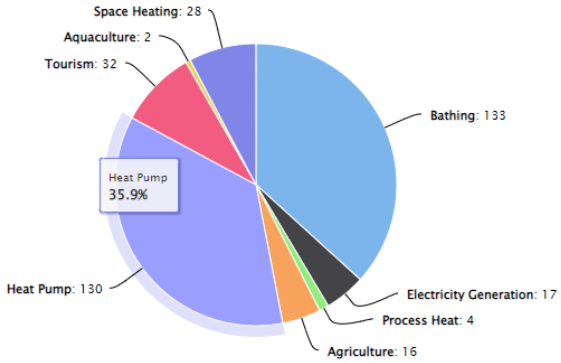


Figure 5 - Number of Geothermal installations in New Zealand as of 15/08/2022. Where an installation fits into two or more categories, the primary category is the one that uses the most geothermal energy.(GNS 2022)

1.1. Potential of GSHP

The literature reports potential cooling energy reductions of 30-50% from GSHP and heating energy reductions of 20-40%(Philippacopoulos 2001). These figures are in agreeance with other findings that suggest a 30-50% reduction potential(Ahmadi 2018, p.1242). To put this in perspective NZ's total residential heating & cooling demand in 2020 was 59 TJ (53 TJ for heating, 91%)(EECA 2022), this means that GSHP has the potential to offset ~18TJ of energy per year. Assuming two million equal residential dwellings in NZ(STATS NZ 2020), that is equivalent to an additional 600 thousand dwellings. In other words, if all residential heating was converted to GSHP, NZ could add over half a million dwellings without any upgrades to its existing energy infrastructure. This represents the mitigation of significant economic and environmental costs.

This is noteworthy for CI's environmental impact, as 18TJ of annual energy from NZ's mostly renewables grid is still responsible for ~500t CO2-e, which is currently valued to the NZ carbon market at $41 123 per year ($83.50 NZU). This CI improvement is in addition to abated emissions from fuel switching. Using the average values reported in 2.3, this equates to a further 1866t CO2-e per year for residential heating alone. Therefore, the total potential emissions abated from switching to GSHP is over 2000t CO2-e per year, more for total heating. Furthermore, additional improvements of 15-20% are possible with more sophisticated power control techniques(Putrayudha 2015), which could further aid the management of the following sections' parameters to qualify optimal geologic and hydrologic characteristics for GHSP.

6. AQUIFERS & RAINFALL EVENTS IMPACT TO GSHP PERFORMANCE

6.1. GSHP Performance & Subsurface Ground Properties

So far, this study has outlined the key basic principles that relate to GSHP performance, it then follows to integrate and relate these principles to soil properties to understand rainfalls' impact on COP. To reiterate, the Carnot heat engine has shown GSHP performance is proportional to the magnitude of geothermal energy. This inferences soil condition, immediately adjacent to the GSHP area, ultimately determines COP. However, GSHP can suffer from a soil thermal imbalance problem from a reduction in heat transfer efficiency(Xu 2022).

6.2. Heat Conductivity

To maintain GSHP performance, thermal conductivity or Heat conductivity (HC) is important(Di Sipio 2017)(Xu 2022)(Mohamed 2015). HC is a measure of heat conduction through the soil and is inversely proportional to heat resistivity. This is key a key factor in determining GSHP efficiency and is highly influenced by geologic variables, soil moisture and temperature variations(Di Sipio 2017) (see section 4.1.4). The HC of the soil and resultant temperature balance, was reported to be primarily dependant on the magnitude of saturation and secondarily, on the flow rate and alluvial path of water(Mohamed 2015). In fact, it was reported that water increases HC five-fold for wet vs dry soil(Mohamed 2015).

6.3. Heat Diffusivity

Where HC concerns the conduction of heat energy, Thermal/Heat Diffusivity (HD) is the measure of heat transfer from cold to hot within the specific soil mineral and is similarly impacted by the presence of water. Heat balance, determined by HD, was reported to improve four-fold when the water level was 200mm above heat pump depth compared to dry conditions(Xu 2022). This reveals that water significantly influences both HD and HC, which in turn influences optimal thermal rebalancing of soil(Xu 2022), a critical factor for GSHP COP. Further revealing that soil moisture levels play a more significant part in the performance of GSHP than air temperature variations(Di Sipio 2017).

6.4. Electrical Conductivity

Electrical conductivity (EC) is another critical factor in GSHP performance. EC values increased in response to increased precipitation and the presence of dissolved chemicals such as calcium (Ca2+), bicarbonate (HCO3), ferrous ion (Fe2+) and silicon dioxide (SiO2)(Okakita 2019, p.360). The concentrations for these chemicals were found to be dependent on the influxes of precipitation to groundwater(Okakita 2019, p.360). Meaning locations with similar features, such as low-residence alluvial aquifers may have strong GHSP COP potentials. Furthermore, this inferences advection as a primary mechanism to which EC, and therefore GSHP COP is influenced.

6.5. Physical Properties of Soil

As mentioned in sections 4.1.1-3 geologic variables are important for HC, HD and EC, all of which are critically important in understanding the effect of rainfall on GSHP performance. Geologic variables additionally include particle size, mineralogical composition, density, porosity, bulk modulus and temperature(Di Sipio 2018). Larger

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particle sizes, such as coarse sand, result in high water velocity, which in turn affects GSHP performance. Whereas by contrast smaller particle sizes, such as loamy sands, has less risk of loss to COP(Di Sipio 2017). Additionally, the presence of certain minerals, like quartz, improves the soil's ability to retain water and so is indirectly responsible for higher HC(Di Sipio 2017).

7. SYNTHESIS CONCLUSION: RAINFALL IMPACT & STATE OF RESEARCH IN NZ

The effect of precipitation on groundwater flow and temperature is an important consideration for the performance of GSHP(Okakita 2019). Rainfall is the best mitigator of the thermal balancing problem GSHP suffer. However, as an alternative, daily pauses in heat extraction were reported to improve soil thermal balance by 33%(Xu 2022). Nevertheless, rainfall improves GSHP COP via increases in TC, HD & HC, additionally, water's latent heat further aids thermal rebalancing via increases in HD and heat capacity(Di Sipio 2017)(Di Sipio 2018). Furthermore, topographic catchment features determine alluvial areas rich in minerals to aid EC. These represent an indication of geologic suitability for GSHP, but would require further research. Critically, optimal maintained moisture content was reported to be >12.5%(Di Sipio 2017).

If a GSHP were to extract heat at a rate the surrounding soil could not maintain via conduction, thermal balance would be lost and the COP value of the GSHP would reduce as a result. As TC, HD and EC are significantly reduced in dry conditions, the performance of the GSHP is most vulnerable to prolonged periods of drought. This is significant because this is exactly what the anthropogenic effects of climate change have been proven by the IPCC to increasingly exacerbate, the very same climate emergency GSHPs offer to help mitigate.

This review has identified existing knowledge in the literature regarding rainfalls' effect on the thermal properties of soil and subsequent performance of GSHP. In Germany(Di Sipio 2017)(Di Sipio 2018), Jordan(Al-Hinti 2017) and NZ(Van Manen 2012) the temperature of the subsurface between 2-10m has been proven to not vary significantly from the average ambient air temperature. The Jordan study focused on air-to-ground temperature fluctuations with respect to soil type but failed to incorporate rainfall(Al-Hinti 2017). The German studies looked specifically at moisture conditions in and out of the lab with various GSHP configurations, but failed to include detailed soil factorisation(Di Sipio 2017)(Di Sipio 2018). These studies also had the additional confounding of subsurface frost line to account for latent heat, which the others did not. Lastly, the NZ study in Wairakei represents the gold standard for current literature on climatic effects on ground temperature and thermal properties in NZ, but was limited to one location and does not include any relation to GSHP(Van Manen 2012). As such this study will focus on filling the knowledge gaps by understanding rainfalls effect on GSHP via alternation of ground physical properties.

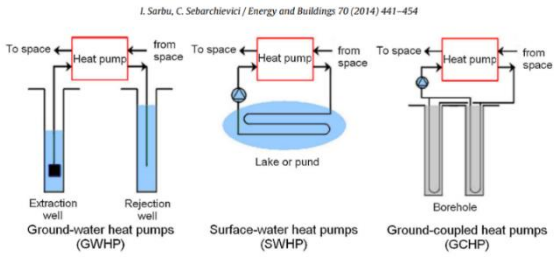


Figure 6 - Typical and most common GSHP configurations (Sarbu 2014)

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