CAN THE REYKJAVÍK DISTRICT HEATING SYSTEM (DHS) BE USED AS A MODEL FOR A ROTORUA DHS? A COMPARATIVE STUDY

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ABSTRACT

The Rotorua geothermal field is managed by the Bay of Plenty Regional Council under the Resource Management Act and provisions of the Bay of Plenty Regional Policy Statement and the Rotorua Geothermal Regional Plan. The latter is currently being reviewed as is required every ten years by the Resource Management Act 1991. Feedback during initial community engagement stages of the review included questions around the potential for a district heating system (DHS) in Rotorua based on the experience of the Reykjavík DHS. This paper presents a high-level desktop study comparing the Rotorua and Reykjavík geothermal fields. Aspects such as historic background, current development model for the fields, statistics of use, funding, costs, government input and administration of the field are discussed. The Reykjavík DHS was a pioneer engineering work which changed the way Icelanders lived. It evolved over decades of trial and error and significant governmental support. The Icelandic DHS suited perfectly a country with heat demand year-round and abundant geothermal resources, but a limited variety of other indigenous heating and energy options. Incommensurable differences between Reykjavík and Rotorua cities and access to the geothermal resource make the Icelandic DHS unsuitable for Rotorua. Some obstacles are technical, and while these could be overcome, solutions would be complex and costly, possibly making the system economically infeasible. Several other issues for a Rotorua DHS were greatly simplified with the Reykjavík municipality offering the utility service. The geothermal resource in Rotorua could be more efficiently and equitably utilised for residential space heating. However it is expected that better results would be achieved by fine-tuning the Rotorua Geothermal Regional Plan according to the local settings than replicating the Reykjavík DHS in Rotorua.

1. INTRODUCTION

The Rotorua geothermal field is managed by the Bay of Plenty Regional Council (BOPRC) under the Resource Management Act 1991 (RMA), the Bay of Plenty Regional Policy Statement (RPS) and the Rotorua Geothermal Regional Plan (RGRP) (BOPRC, 2010). The RGRP became operative in 2009 and is currently under review (Doorman and Barber, 2017). In 2019 the Bay of Plenty Regional Council held a number of hui and workshops to gain input from key stakeholders and the wider public. One of the issues raised in discussions about current and future uses was whether Rotorua City could have a large-scale district heating system (DHS), similar to the Reykjavík DHS. Specific questions were raised around the capacity of the field to support increased direct use for home heating and whether an efficient heating system could provide an economically attractive scheme for the city.

Bay of Plenty Regional Council and Rotorua Lakes Council have researched home heating options previously [e.g. Rotorua geothermal home heat investigation (Bendall and Lind, 2012) and Scoping study for the opportunities of a geothermal district heating scheme in Rotorua (Boyles et al., 2013)]. Building on this work a high-level desktop study was carried out to compare the Rotorua and Reykjavík geothermal fields and aspects related to its historic and current use, environmental impacts, funding, costs, government input and administration of the field.

2. DISTRICT HEATING SYSTEMS OVERVIEW

District heating systems, or DHS, offer an effective and equitable use of a limited natural resource (Boyles et al., 2013). Hot water in a DHS is a utility used for space and water heating. The implementation of the system is characterised by a high capital cost and low running cost (Sipilä et al., 2011).

2.1 Basic requirements for a DHS

According to Boyles et al. (2013) and Bendall and Lind (2012), the main requirements for the establishment and efficient operation of a DHS are: (i) Technical feasibility; (ii) economic feasibility (iii) centrally heated dwellings with high thermal performance. A good DHS economics is achieved in places with a long heating season and a high thermal load density (>3 MW/km^2; Bendall and Lind, 2012).

2.2 Components of the DHS

A DHS consists fundamentally of three components: the hot water production system, the transport system and the distribution system, including pumping stations and deaeration and storage tanks (Bendall and Lind, 2012, Karlsson, 1982). Each of these individual systems is tailored to the local conditions (e.g. geothermal resource, the city layout and the heat demand profile). Population growth and average house size changes are key factors that can significantly increase the heat demand of the DHS through time (Karlsson, 1982).

The distribution system is considered the most important part for the successful operation and proper functioning of the DHS (Karlsson, 1982). It is often the most expensive part of the system, typically ~35% to 75% of the capital cost of a DHS (Lund, 2014). Most of the capital cost of the distribution system is related to the installation of the pipe system and not its size or capacity. In low heat density areas, fluids need to travel over long distances to reach the houses but only a small volume of hot water would be required per distance travelled. This is the main rationale behind the requirement of a high heat demand density to make a DHS economically feasible. Smaller pipes have greater heat losses too which reduces the system efficiency.

3. COMPARATIVE STUDY

3.1 Background

Rotorua has a warm, temperate climate, with ~13 ℃ annual average temperatures (~8 ℃ in the winter and ~18 ℃ in the summer). Reykjavík has a lower annual average temperature (~5 ℃), with average temperature of ~11 ℃ in the summer and ~-0.2 ℃ in the winter. Heating degree days (HDD) is a measurement of the demand of energy required to heat a building in a specific location, based on how much and for how long the outside temperature was below a base temperature. Rotorua City has 2004 HDD while Reykjavík has 4484 HDD (Bendall and Lind, 2012), which means that the overall demand for space heating in Reykjavík is more than twice Rotorua's heating demand.

A heat demand density of ~10 MW/km^2 is used for the calculation of the economics of large-scale DHS in Iceland (Liya, 1984). This value is over three times the threshold value considered for the economic feasibility of a DHS in Rotorua (3 MW/km^2, Bendall and Lind, 2012). Most of the Reykjavík city has a high heat demand density that is covered by the DHS. Boyles et al. (2013) identified three zones along Fenton Street with heat demand density over the 3 MW/km^2. However, none of the outer residential suburbs of Rotorua (e.g. Lynmore, Hillcrest) achieved heat demand density above 3 MW/km^2.

3.1.1 Iceland and Reykjavík

The Reykjavík municipality was a pioneer in the development of district heating systems. However, it took around 30 years to connect all the houses to the system (from 1943 until 1970s). The main historical, geographical and geo-political aspects that led to the successful use of geothermal energy for space heating in Iceland are[1]: (i) year-round space heating season; (ii) large and widespread geothermal resources; (iii) limited alternative fuel resources (e.g. oil, coal); (iv) dependence on international fuel suppliers[2]; (v) large central government funding and support to harness geothermal energy.

Historically geothermal water from flowing springs had been used for bathing and laundry. However, it was the harnessing of the geothermal energy that changed the way Icelanders lived – from a poor country, with rudimentary heating practices and heavily polluted urban atmosphere to a developed country with widely available geothermal heating alternative and clean atmosphere.

3.1.2 Rotorua

Rotorua City was built on top of a significant but limited geothermal resource. It has experienced several historical periods of geothermal use and development (Scott, 2019): (i) the traditional use by Māori (for hundreds of years); (ii) the establishment of Rotorua as a European-style spa destination by the New Zealand government (1880s); (iii) rapid growth of direct heat use in the 1960s and 1970s; (iv) well closures in the 1980s; (v) partial field recovery since the 1990s.

Unlike Reykjavík, the interests of several sectors of the society need to be considered by the regulatory agency when allocating geothermal resources in Rotorua: (i) traditional use (e.g. cooking, ceremonial use); (ii) tourism (e.g. balneology, geothermal attractions); (iii) Rotorua residents (e.g. space heating); (iv) scientific community (research)

3.2 Geological setting and overview of the geothermal fields

3.2.1 Geological setting

New Zealand and Iceland have very different geological settings, which result in geothermal fields with different characteristics (Table 1). Iceland lies within the Mid-Atlantic Ocean Ridge (MAR) and on top of a geological hotspot, the Iceland mantle plume. The location of Iceland within the MAR results in a country with intense volcanic and tectonic activity, while the Iceland mantle plume enhances the volcanism already caused by plate separation. Volcanism occurs predominantly within its central, geologically younger zone, which is flanked by relatively older, cooler rocks.

New Zealand is located within the southern Circum-Pacific belt. The country sits in the plate boundary zone of the Australian and Pacific plates. The Taupō Volcanic Zone (TVZ) represents the southernmost, continental portion of the Tonga-Kermadec arc system associated with the Australian and Oceanic plate subduction zone. The TVZ is a rifted continental volcanic arc, with its central segment generating profuse silicic volcanism and exceptionally active hydrothermal fields (Wilson and Rowland, 2016).

Table 1 – Geological and geothermal backgrounds.

GEOLOGY, GEO-THERMAL FIELDS	ICELAND	NEW ZEALAND
Geological setting	• Mid-Atlantic Ocean Ridge • Iceland mantle plume	Taupō volcanic zone (rifted volcanic arc)
Heat source geothermal fields	• Low-T: Abnormally hot crust • High-T: Magmatic intrusions	• Low-T: Areas of young volcanism (North Island) • High-T: Magmatic intrusions • Rotorua: Quasi-magmatic intrusions at ~2.5 km depth
Number of fields	• Low-T: ~250 • High-T: >20	• <220 °C: ~114 • >220 °C: ~15 (Rotorua)

3.2.2 Geothermal fields

Geothermal fields in New Zealand and Iceland have different classification systems. In both systems the main criteria are reservoir temperature and surface expression. In both countries geysers, fumaroles, boiling springs, mud pots and pools and steaming ground are surface features typical of high-temperature fields. Low-temperature fields have a much lower range of surface features, typically warm and hot springs, with little or no alteration around the springs.

High-temperature geothermal fields in Iceland have reservoir temperatures >250 °C within the first 1000 m depth; low-temperature geothermal fields reach ~150 °C

[1] Compiled from Jonasson and Thordarson (2007) and Gunnlaugsson and Ívarsson (2010)

[2] Fuel prices and availability are dependent on geopolitical affairs (e.g. 1970s oil crisis), which Iceland has little influence over.

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within the first 1000 m depth (Björnsson, 2010). In New Zealand of the 129 identified geothermal areas, 114 have reservoir temperatures <220 °C and 15 are >220 °C, including Rotorua (depth not specified; NZGA website).

In Iceland water resources (including geothermal) are sustained by the high level of precipitation. Groundwater flow and recharge is controlled by the country topography and structural framework (Gunnlaugsson et al., 2000). The Rotorua geothermal field (reservoir and its surface features) is affected by short and long term changes in the rainfall pattern and the Rotorua lake water level. Some surface features are particularly vulnerable to short term rainfall variations, while longer term changes in the rainfall pattern may affect the deep reservoir (Ratouis et al., 2017).

3.3 Geothermal fields: natural state, exploitation and its impacts on the surface features and reservoirs

3.3.1 Geothermal fields

The Rotorua field has reservoir temperatures of around 180-200 °C at ~200 m depth (Table 2). It is considered that higher reservoir temperatures would be reached at greater depths (Scott, 2019). The high-temperature fields that supply hot water for the Reykjavik DHS are located in the Hengill area and are referred to as "Hengill fields" in this paper. Temperatures over 200 °C are only found below 400-500 m depth in the Hengill fields (Gunnarsson et al., 2010). In both Rotorua and Hengill fields wells drilled within the upflow zones show increased temperatures with depth while wells within the outflow zone typically have inverted geothermal gradients (Gunnarsson et al., 2010; Ratouis et al., 2016).

Table 2 – Reykjavík and Rotorua geothermal fields: natural state and exploitation.

GEO-THERMAL FIELDS	REYKJAVÍK	ROTORUA
Exploited geothermal fields	• 3 low-T fields in Reykjavik and 2 high-T fields in the Hengill area	1 high-T field underneath Rotorua City
Reservoir temperature	• Low-T: 65 °C to 130 °C • High-T: 200 °C to 320 °C	120 °C to 200 °C
Surface area	• Low-T: 5-10 km² • High-T: Part of the ~110 km² Hengill low-resistivity anomaly	~15 km²
Exploitation area	• Low-T: 0.08 km² to 5.5 km² • High-T: ~12 km²	~10 km²

3.3.2 Impacts of exploitation on the field

The geothermal fields that supply hot water to the Reykjavík DHS are sustainably managed for long-term scenarios from a production perspective and not to protect the surface features (Axelsson et al., 2010). The surface features (mostly hot springs) of the Reykjavík low-temperature fields have disappeared after large-scale downhole pumping started in the 1960s (Table 3). Pumping was only reduced in the 1990s with the commissioning of the Nesjavellir combined heat and power plant (CHP plant) to meet the increasing demand for hot water from the DHS. Since then the reservoir partially recovered and a semi-equilibrium between production rate and reservoir water level has been achieved in the low-temperature fields (Gunnlaugsson et al., 2015). Surface features might reactivate with a further increase of the reservoir pressure (Tómasdóttir et al., 2020).

Table 3 – Impacts of exploitation on surface features and reservoir and recovery of the geothermal fields.

GEO-THERMAL FIELDS	REYKJAVÍK	ROTORUA
Surface features natural state	• Low-T fields: Hot flowing springs • High-T fields: Details unclear. Hot springs, fumaroles	• >1600 high-temperature surface features (geysers, hot springs, mud pots and pools, etc)
Historical impacts on the geothermal field	• Low-T fields: Surface features disappeared, water levels drop up to ~150 m, groundwater inflow, change of the water chemistry • High-T fields: Details unclear	• Geothermal aquifer water level drop • Increased hydrothermal eruptions and other disturbances • Changes in water chemistry and natural heat flow
Current state of the surface features	• Low-T fields: Surface features not recovered. Expected to reactivate with increased reservoir pressure • High-T fields: Details unclear. Surface features still present and monitored.	• Most surface features recovered to north, matching pre-1980s activity levels and geochemistry • Mixed recovery to the northeast and south (activity levels and geochemistry)
Current state of the reservoir	• Low-T fields: Reservoir in "semi-equilibrium"; water levels up to 120 m below natural levels • High-T fields: Large annual pressure drawdown (35-40 m), rapid cooling. Reservoir being engineered to reduce pressure drop and cooling	• Geothermal aquifer water level recovered by 1.5-2 m (~20 kPa) with reinjection • Stability of the deeper reservoir (geothermometry)
Other current impacts from use	High-T fields: • Impacts of surface discharges to lakes and streams • Large surface scars around CHP plant infrastructure • Vegetation (moss) removal • Gas emissions (H_2S and CO_2) • Visual impact of the power plant and infrastructure	• Change in geothermal ecosystems • Impacts of surface discharges to lake, streams and land • Physical modification of surface features

Production from the CHP plants has also adversely affected the geothermal reservoir. The Hellisheiði field has a pressure drawdown equivalent to about 35-40 m annually and is cooling rapidly (Gunnarsson et al., 2020), even though it utilises best practices on sustainable reservoir management (Steingrímsson, et al., 2006). The more recent Hellisheiði CHP plant has also incorporated better environmental practices compared to the Nesjavellir CHP plant (Zarandi and Ivarsson, 2010).

The effects of over-exploitation of the Rotorua field between the late 1950s and mid 1980s have been subject of many papers (e.g. Allis and Lumb, 1992). In brief, early use was inefficient and the lack of pressure support through little reinjection severely impacted surface features. The 'Bore closure program' and government directives requiring reinjection and limiting some uses implemented in the mid-1980s resulted in an increase in the geothermal water level and surface activity. Since then, surface features have shown good but not complete recovery (Scott et al., 2005; Pearson-Grant et al., 2015).

The geothermal field is currently managed to maintain its state and surface expression. Modelling carried out in 2004 / 2005 (Burnell, 2005) indicated that even a small increase on the mass production or reinjection within 1 km of Pohutu Geyser would adversely affect the Whakarewarewa area to some degree but a mass production increase of 500 tonne/day between 1 km and 1.5 km of the Pohutu Geyser radius would only have a small effect on the surface outflow. According to the model, an increased production from the CBD and along Fenton Street would adversely impact the outflow at Kuirau Park. The model also indicated that adding another 15-20 heat exchangers within the 1.5 km Pohutu Geyser exclusion zone (1280 kW heat take) would likely have negligible effect on surface features.[3]

The policies for the Rotorua field support the use of low-effect non-extractive methods and high efficiency technologies (e.g. downhole heat exchangers; (e.g. Alpin Motel) over less efficient extractive methods. The use of low-effect non-extractive methods is particularly important in areas where surface features that rely on the aquifer temperature and pressure are present. Rotorua's boiling alkaline-chloride water springs and geysers operate at very low pressures (typically ~3 kPa and 10 kPa) therefore are at greater risk due to field exploitation (Ratouis et al., 2017). Saptadji et al. (2016) presented a numerical model for the Pohutu Geyser that could qualitatively reproduce the geyser behaviour. However, the numerical model is still not quantitatively accurate and could not be fully integrated to the Rotorua field numerical model.

3.4 Hot water - direct use

Around 99.9% of the dwellings are serviced by the Reykjavík DHS (Gunnlaugsson, 2015). Around 50% of the DHS hot water is geothermal fluid and 50% heated fresh water. In the Rotorua, <5% of the dwellings utilise geothermal energy for space heating (Table 4; Scott, 2019). The current development model for the Rotorua field is based on heating schemes for single users or small group of users (5-25 dwellings). The main extractive direct use of hot water for residential, commercial and municipal amenities is for space heating and mineral baths.

In Rotorua less than 10% of the dwellings have central heating. Around ~90% of the dwellings would need to be retrofitted to be serviced by a DHS and a large proportion of the dwellings requires thermal performance improvements for efficiency.

Table 4 – Overview of the Reykjavík and Rotorua demographics and the use of geothermal energy.

DEMOGRAPHICS; HOT WATER USE	REYKJAVÍK	ROTORUA
Urban area	~45 km^2	~48 km^2
Number of dwellings	~32 000	~17 200
Population (urban)	~120 000	~60 000
Population growth projection	3-4% per year	~2.2% in 5 years (2018-2023[4])
Dwellings heated by geothermal	• ~32 000 • 99.9%	• ~420 • <5%
Geothermal water and energy use	• 85% space heating • 15% bathing and washing	• Residential: 16% • Commercial and municipal: 84%

3.5 Heat production and potential of the fields

Around 13 500 TJ/yr is produced from the Reykjavík and Hengill CHP plants per year, which is ~11x the total heat produced from the Rotorua field. The calculated net heat take from the wells in Rotorua is ~520 TJ/yr (BOPRC data), which is ~1.2 times higher than the calculated heat required for heating and supplying hot water for 17200 dwellings (Table 5). Downhole heat exchangers currently represent a fraction (20 TJ, ~1.6%) of the total heat take from the field (Bendall and Lind, 2012).

3.6 Reykjavík DHS and Rotorua infrastructure

Around 50% of the hot water for the Reykjavík DHS comes from the Reykjavík low temperature fields and ~50% from two CHP plants in the Hengill area (Nesjavellir and Hellisheiði). The Reykjavík municipality developed an extensive infrastructure to transport fluids from the production plants and distribute to the users (Table 6).

Geothermal fluids produced from the Reykjavík low-temperature fields and heated fresh water from the Hengill high-temperature fields are stored in tanks, transported through mains and distributed to consumers through distribution pumping stations, mains and branches (Gunnlaugsson, 2015). The two types of fluids are never mixed in the distribution system and they supply hot water for different parts of Reykjavík (Tómasdóttir et al., 2020). In Rotorua the transport and distribution systems are of much smaller scale and limited to small group schemes.

Geothermal water from the Reykjavík low-temperature fields is used directly in the district heating system with no treatment (Gunnlaugsson, 2015). Geothermal water from the Hengill high-temperature fields cannot be used directly in the district system due to the relatively high content of dissolved minerals and gases. Geothermally heated fresh water is produced and circulated instead. Geothermal fluids in Rotorua have also a high content of dissolved minerals

[3] The BoPRC is currently updating the reservoir model for Rotorua as part of the plan review process.

[4] Stats NZ. Population growth projection review post-Covid19 has not been published by the submission date.

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and gases, which causes calcite scaling and corrosion of the pipes and fittings in the direct take schemes (Bendall and Lind, 2012).

Table 5 – Geothermal heat and hot water production and potential of the Reykjavík and Rotorua fields.

HEAT AND HOT WATER PRODUCTION	REYKJAVÍK AND HENGILL FIELDS	ROTORUA FIELD
Hot water production	• ~70 gigalitres[5]	~2.8 gigalitres/yr[6]
Heat production	13 545 TJ/yr[7]	1224 TJ/yr[8]
Heat reinjection	N/A	699 TJ/yr[9]
Net heat take	N/A	~520 TJ/yr[10]
Energy demand (space heating + hot water)	Production meets the city demand	• 440 TJ/yr[11]
Geothermal fields potential	• Exploited fields fully utilised • Large potential on Hengill area	• ~7875 TJ/yr (~250 MW_t)[12] • ~147-153 MW_e (power plant)[13]

3.6.1 Production system

Production from the Reykjavík low-temperature fields are from ~52 production wells, ~1 000 m – 2 000 m deep. None of the fields are reinjected. In the Hengill high-temperature fields each of the two CHP plants has over 40 production wells, ~700 m – 2 000 m deep. The Nesjavellir CHP plant has deep and shallow reinjection wells and the Hellisheiði plant reinjects discharge water through ~10 reinjection wells. In Rotorua hot water production is mostly from production-injection systems and secondarily from wells with downhole heat exchangers (DHX). Rotorua wells are considerably smaller and produce from shallow depths.

Table 6 – Reykjavík DHS and Rotorua infrastructure.

DHS SUBPARTS	REYKJAVÍK	ROTORUA
Production wells	• Low-T: ~52 large wells • High-T: Over 80 large wells	• ~76 small wells • ~38 wells with DHX
Production wells depth	700-2200 m	<200 m
Reinjection	• Low-T: NO • High-T: YES (CHP plant discharge water)	• YES (~90%) • 10% to sewer, land soakage or surface water
Distance fluid transported	• Low-T fields: 0 km to ~18 km; • High-T fields: ~20 km and 27 km	N/A
Distribution system length	• >3000 km • Double and single systems	Largest group scheme (Golden Glow): ~1.4 km

3.6.2 Transport system

The transport system for the Reykjavík DHS is ~47 km long in total. Transport distances from the geothermal fields to the Reykjavík City ranges from 0 to 27 km. For comparison, those distances are of similar scale of transferring hot water from as far as the Lake Rotoiti field (~20-25 km).

The pipelines and mains are designed to perform under challenging geotechnical and seismic conditions and to minimise heat loss throughout the transport system. The heat loss is only 0.5-1 °C despite the low outdoor temperatures and enough snow to bury the pipes in the colder months (Figure 1; Verkis website, K. Luketina pers. comm.).

In Rotorua geothermal fluid for space heating is distributed directly from well to user, given that much of the city sits directly above the geothermal field. The well is typically located within the user property so transport distances are negligible in most cases. For group schemes fluids may be transferred over short distances (see Golden Glow example – section 3.6.3). Group schemes normally have centralised heat exchanger(s) and distribute geothermally heated town water to the units.

Four potential group schemes were proposed in areas with heat demand density >3 MW/m^2 in Rotorua (section 3.1; Boyles et al., 2013). Fluid transport distances through mains for those group schemes ranged from 300 m to 1860 m (or 3720 m for the supply and return to reinjection wells).

3.6.3 Distribution system

The Reykjavík DHS distribution system has over 3000 km of pipelines. There are single and double distribution systems. In the single system, the backflow drains directly into the sewer system while in the double system, the return flow from the consumer runs back to the pumping stations, is mixed with hotter geothermal water and then is re-circulated (Gunnlaugsson, 2015).

Small scale distribution systems are deployed in group schemes in Rotorua. The Golden Glow scheme is the largest of them, supplying heated town water for around 14 homes,

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[5] Gunnlaugsson et al. (2015)

[6] Assumptions: (i) BoPRC measured and allocated data. (ii) Fluid density (ρ_f) = 952 kg/m^3.
Calculation record: Average take = 7300 T/day → 2 664 500 000 kg/yr / 952 kg/m^3 = 2.8x10^9 litres/yr

[7] 430 MW_t according to Gunnlaugsson et al. (2015).
Calculation record: 1 MW_t = 31.5 TJ/yr → 430 MW_t = 13 545 TJ/yr

[8] Assumptions: (i) BoPRC measured and allocated data. (ii) Fluid temperature (T_f) = 108.6 °C; (iii) Fluid enthalpy (h) = 459.46 kJ/kg = 459 460 J/kg.
Calculation record: Average total take (mass/day) = 7300 T/day = → Heat take = fluid mass x h = 2 664 500 000 kg/yr x 459.46 kJ/kg = 1224 TJ/yr.

[9] Assumptions: (i) BoPRC measured and allocated data. (ii) T_f = 70.3 °C; (iii) h = 294.57 kJ/kg = 294 570 J/kg.
Calculation record: Average reinjection = 6497.27 T/day → Heat reinjection = fluid mass x h = 699 TJ/yr

[10] Assumptions: (i) BoPRC measured and allocated data. Calculation record: Net heat take = total heat take - heat reinjected = 1224 TJ/yr – 699 TJ/yr = 525 TJ/yr

[11] For ~17 200 dwellings; ~240 TJ/yr for space heating and 200 TJ/yr for hot water (Bendall and Lind, 2012).

[12] Boyles et al. (2013) apud Lawless and Lovelock (2001). Production constraints not considered.

[13] Ciriaco et al. (2018). Production constraints not considered.

4 motels and one health spa. The total pipeline length of the double distribution system is around 1.4 km.

Fig. 1: Hot water pipeline (transport system) seen from the ground surface. Note the size of the pipe, the roadside ditch the pipe is housed in and a small bridge for snowmobiles (beige, by the sign). The whole area is snow-clad for most of the year (©Katherine Luketina).

3.7 Legal and regulatory framework

Both Iceland and New Zealand have a long history of use of geothermal resources and developed a strong legal framework on the protection, development and regulation of the geothermal resources[14], notably:

- In Iceland the ownership of the resource is attached to the private or public land. In New Zealand there is no ownership of the geothermal resource. The Resource Management Act (RMA) vests the management of the geothermal resources to the regional authorities.

- Section 6 of the RMA makes specific provision for matters of national importance. This creates strong imperatives for the protection of surface features in Rotorua as a priority over extractive uses. Geothermal fields exploited for the Reykjavík DHS do not have such protective status.

- In New Zealand resource consents from local and regional authorities are required for invasive exploratory activities and for the take and discharge of geothermal fluid. In Iceland an utilisation license from the National Energy Authority (NEA) is required for any development with heat take over 3.5 MW_{th}.

- In New Zealand consent conditions can be reviewed by the regional authorities when the effects of the development on the resource or the environment are deemed more severe than specified or anticipated. In Iceland the NEA is responsible for monitoring of the geothermal field. Violations on the requirements of the utilisation licenses can result in the license being revoked (Act on Official Monitoring 27/1999).

- In Iceland deep drilling in high-temperature or low-temperature fields with surface features are subjected to environmental impact assessments - EIA (Environmental Assessment Act 106/2000). In New Zealand an EIA is required for both government and private projects. The level of detail corresponds with the scale and significance of the effects that the activity may have on the environment (RMA Section 88)

- Exploitation of the Reykjavík low-temperature fields occurred between the 1930s (Laugarnes) and the 1960s (Elliðaár), when EIAs were not required. The Nesjavellir CHP plant was commissioned in the 1990s, also prior to the EIA 106/2000. The Hellisheiði CHP plant started operating after the EIA Act (2010), incorporating better practices as result to the licensing operating conditions (Gunnlaugsson and Ívarsson, 2010).

3.8 Ownership of the DHS, funding and costs

3.8.1 Ownership of the DHS

The Reykjavík DHS is owned and run by Veitur, a subsidiary of Reykjavík Energy (Table 7). Veitur also manages the wastewater system, which takes the hot water discharges after domestic use. The CHP plants are owned and run by ON, another Reykjavík Energy subsidiary company. Reykjavík Energy and its subsidiaries are all municipally owned.

In New Zealand it is generally considered outside the legally mandated scope of the functions, powers and duties of regional authorities to provide such amenity services. Utility services normally sit with territorial authorities and the Rotorua Lakes Council is currently not offering this service.

3.8.2 Funding and running costs

The Reykjavík municipality met the capital cost for the initial development of the DHS. The central government supported the DHS through funding from the Energy Fund and partnership with ÍSOR (state-owned geological survey agency). The Energy Fund (NEA) offered loans and grants to companies for geothermal exploration and drilling, for the construction of transmission pipelines and for converting household heating systems from electricity or oil to geothermal heat. Geological risks were reduced by the loan being defaulted to the Estate if drilling was unsuccessful.

Currently the DHS heat sales cover the costs of production, distribution and maintenance of the system (Gunnlaugsson, 2015). The combination of public investment and the successful operation of the DHS allowed for cheap hot water for the population (~US$ 72 per month for heating a 200 m^2 house; Gunnlaugsson, 2015).

In Rotorua the user pays for construction of the geothermal infrastructure (wells, pipelines and heat exchangers), well maintenance, resource consenting fees and annual compliance costs. Even though there is no charge for the geothermal water and heat per se, the use of geothermal water or heat can be fairly expensive.

Currently there are no publicly-funded schemes for the uptake of geothermal energy in Rotorua. The BoP Regional Council runs schemes to support the switch to cleaner heating alternatives, however only electric heating, infrared heater and low and ultra-low emission wood burners are

[14] Compiled from van Campen and Petursdottir (2016); Jóhannesson et al. (2016); Burnell et al. (2016) and Orkustofnun website.

currently offered. The Hot Swap scheme only granted over $5m in interest-free or low-interest loans.

Table 7 – DHS administration, costs and funding.

ADMIN., COSTS AND FUNDING	REYKJAVÍK	ROTORUA
Ownership of the system	• Reykjavík Energy subsidiaries: • Veitur Utilities (production from the low-temperature fields, transport and distribution systems) • ON (production from the CHP plants)	Private
Capital cost	• Reykjavík Energy (municipally owned) • Government funding and grants	• Private. User pays for resource consenting and well construction
Funding for running the system	• Veitur Utilities - DHS heat sales	• User pays for well construction and compliance
Charges for hot water	~1.147 US$/$m^3$ hot water (as at 2015)[15]	None
Estimated cost to run and establish a multi-user system	• Example: ~60 MW_{th} DHS: US$ 43 million[16]	• Direct system[17]: ~NZ$25 100 • Indirect system[19]: NZ$28 800

4. DISCUSSION

Comparisons between Reykjavík and Rotorua are often made, where the Icelandic DHS is advocated as a model for Rotorua, and a more efficient and effective use of the resource. Some critical differences emerged, notably:

- Heat generation is not the primary use of the Rotorua field. Geothermal fields in and around Reykjavik are primarily used for this purpose.

- Exploitation of the geothermal fields in and around Reykjavik caused severe impacts on the surface features and reservoir. The fields are now sustainably managed but not to support the recovery of surface features. The Rotorua field was overexploited and is still not fully recovered. Maintaining conditions for sustained recovery is one of the field management priorities.

- Knowledge gaps around the deep Rotorua field impose 'geological risks' for a DHS project. Filling those gaps requires investment. The ÍSOR (Iceland) carried out extensive research on geothermal science and technology, which greatly minimised the risks to the project.

- Reykjavik has a high heat demand, year-round and a high heat demand density. Rotorua has a relatively low heat demand, short heating season and low heat demand density for most areas outside the Fenton Street corridor and the CBD.

- Less than 10% of the dwellings in Rotorua have central heating systems and low thermal performance (e.g. home insulation) is a major issue. In Reykjavík high thermal performance and central heating is a norm.

- Veitur Utilities developed five geothermal fields in over 70 years to meet the increasing demand of hot water for the DHS. It is unclear whether the Rotorua field could currently supply enough heat for a DHS in harmony with other extractive and non-extractive uses.

- Rotorua is experiencing medium population growth but there are no other geothermal fields with development status in a short distance. This is significant when considering the 'future-proofing' of a DHS. There is large potential for further developments on the Hengill area to cover the Reykjavík DHS expansion needs.

5. CONCLUSIONS

Despite both being relatively small island nations endowed with extensive geothermal resources, Reykjavík and Rotorua have incommensurable climate, economic, historic, social, environmental and legal backgrounds. Environmental protection of the Rotorua field and the need to harmonise extractive and non-extractive uses would pose significant constraints on a large-scale DHS.

District heating systems are designed for climates and city configurations different than the ones found in Rotorua. Solutions to adapt the Reykjavik DHS model to Rotorua would be costly and probably economically infeasible.

The geothermal resource in Rotorua could be more efficiently and equitably utilised for residential space heating. However it is expected that better results would be achieved by fine-tuning the operative Rotorua Geothermal Regional Plan according to the local settings than replicating the Reykjavík DHS in Rotorua.

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[15] Gunnlaugsson, 2015
[16] Installed capacity; Ragnarsson and Hrólfsson (1998)
[17] Prices per dwelling. Bendall and Lind (2012) prices adjusted for 10.8% CPI inflation from 2012 to 2020.

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