Hot Dry Rocks Pty Ltd
Geothermal Energy Consultants

PO Box 251
South Yarra, Vic 3141
Australia
T +61 4 0733 7069
E info@hotdryrocks.com
W www.hotdryrocks.com

ABN: 12 114 617 622

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DIRECT USE OF GEOTHERMAL ENERGY: GLOBAL MARKET SCAN

Prepared for Latrobe Valley Authority

April 2021 <Draft >

Graeme Beardsmore

Executive summary

Extensive sandstone aquifers beneath Gippsland host world-class potential for cheap, clean and sustainable geothermal energy. Simple calculations suggest that individual projects to utilise the geothermal energy could generate 10% per annum financial returns and offset or avoid thousands of tonnes of CO_2-equivalent greenhouse gas emissions per year. If responsibly managed, the hot aquifers could help position Gippsland as a clean energy hub for generations to come. Global experience suggests that such a transition would require a coordinated effort by government, industry, academia and the community to define and execute a shared transition plan. The Latrobe Valley Authority is ideally placed to coordinate that process.

This document details the circumstances and experiences of 12 regions around the world that have embraced the use of geothermal energy from aquifers in a comparable temperature range to those beneath Gippsland. Key findings are presented within the framework of Smart Specialisation Strategy design principles and can be summarised as follows.

- Specific sectors dominate the consumption of geothermal energy in many, if not most, ‘geothermal economies’—greenhouses in the Netherlands and Tunisia; aquatic centres in Perth; district heating systems in Paris, Boise (Idaho) and the Polish Lowlands.
- Regional specification could be a natural outcome of ‘user driven’ geothermal development where large heat consumers make long term capital investments to drill their own wells and develop their own surface infrastructure. Successful projects reduce risk and encourage replication by the original developer, colleagues or competitors.
- Resulting ‘geothermal monocultures’ provide regions with geothermal energy identities and economic benefits via cheap energy and expanding networks of local specialists.
- A small number of regions, exemplified by the town of Veresegyház in Hungary, employ a different development model whereby geothermal energy is produced and distributed by a utility company. The utility model enables equal access to geothermal energy for small, medium and large consumers across a broad range of sectors, maximising the user base and arguably creating a more resilient geothermal economy.
- In all cases, the role of central government is to provide a coherent, enabling and persistent policy and legislative framework to promote and facilitate secure access to, and sustainable use of, the geothermal resource.

- The Netherlands is the clear global leader for utilising geothermal energy in greenhouses; Paris leads the world for implementing geothermal district heating systems; Hungary delivers world-leading education programs in geothermal energy; Perth hosts world leading expertise in geothermal aquatic centres; Beijing is home to one of the world's most successful cascaded geothermal energy system. Gippsland can and should access knowledge and expertise from each of these regions.
- Regions in which government, industry, academia and the community collaborate to define and achieve a common goal are those that most successfully develop sustainable geothermal economies. In the Netherlands, for example, Geothermie Nederland provides a forum for a broad range of geothermal stakeholders to efficiently identify and address barriers to development.
- Successful transformation to a geothermal economy is often driven by a local, visionary, committed and enduring leader or leadership group with a strong personal connection to the region. Municipal governments appear to play a particularly important role in successful transformations, having the power to influence and implement long-term regional transition plans.
- A geothermal economy is economically sustainable for hundreds of years if nurtured through its early growth phase and supported by a coherent, enabling and persistent legal and policy framework.
- Geothermal reservoirs can be sustainably managed through reinjection and with ongoing monitoring of the reservoir (temperature, pressure and chemistry) via the production and injection bores.
- Surface plant (pipes, pumps, heat exchangers etc) can be sustainably managed through regular monitoring and maintenance programs.
- Geothermal energy business models can adapt to changing commercial conditions. For example, a geological risk management program by the French Government dramatically changed the business model for geothermal district heating systems in Paris. As another example, the geothermal energy distribution network in Veresegyház, Hungary, has continuously adapted to changing national legislation and demand.
- Regions with sustainable geothermal economies also encourage and embrace active research and development into the geothermal resource, surface plant, business systems,

environmental and social impacts, and more. Examples include state government funding for the Western Australian Geothermal Centre of Excellence in Perth; successful trials of cutting edge horizontal drilling techniques in the Paris Basin; and investigations into regional economic impacts of geothermal developments on the Polish Lowlands.

- Common characteristics of active learning and discovery programs include a clear collective vision for the development of the geothermal opportunity; broad deployment of sensing and monitoring systems; close cooperation between project developers, regulators, and local research institutes; and integration of monitoring data into management and planning structures.

Specific recommendations for the Latrobe Valley Authority to foster an efficient, effective and sustainable transition to a geothermal economy in Gippsland include:

- Expand the Geothermal Innovation Group to broaden the range of stakeholders. New members could be invited from the financial (including risk management) sector, industrial heat consumers, the Victorian Department of Earth Resources, indigenous leaders, high school teachers, environmental groups, media companies, and others.
- Identify and empower one or more permanent ‘champions’ within local government(s) to influence and implement a long-term transition to a geothermal economy.
- Facilitate personal, institutional and/or inter-governmental linkages with experts in regions around the world that have made the transition to a geothermal economy in order to gain access to world-leading knowledge and state-of-the-art equipment. Specific targets could include the town council of Veresegyház (Hungary), Geothermie Nederland (Netherlands), European Geothermal Energy Council (Belgium), Nangong village council (China).
- Perform an opportunity and gap analysis to assess the potential for Gippsland to become a centre of geothermal training for a global market.
- Highlight the sustainable management of the geothermal reservoir(s) and surface systems as the core of any policy and legislative framework for geothermal energy. This could include a points-based risk assessment framework; reinjection where deemed appropriate; ongoing monitoring of reservoir characteristics (temperature, pressure and chemistry) using production and injection bores; and systematic monitoring and maintenance programs for surface plant.

- Consider appropriate incentive schemes (e.g. geological risk mitigation) to nurture the growth of a geothermal economy through its early growth phase.
- Explicitly investigate the feasibility of an energy utility model for delivering geothermal energy to small, medium and large consumers in Gippsland.
- Encourage coordinated research into environmental, social and economic issues associated with a transition to a geothermal economy in Gippsland.

Acknowledgements
Many individuals assisted the author by providing information about geothermal developments in specific parts of the world. In alphabetical order, the author would especially like to acknowledge contributions by Miklos Antics, Branislav Fričovský, Robert Gavriliuc, Valiya Hamza, Beata Kępińska, Nevton Kodhelaj, John Lund, George Melikadze, Harmen Mijnlieff, Yurii Morozov, Sanja Popovska-Vasilevska, Martin Pujol, Alexander Richter, Gábor Szita, and Aniko Toth.

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1. Introduction

1.1. Purpose of the environmental scan

The Gippsland region of Victoria is underlain by the sedimentary formations of the Gippsland Basin. These formations include the world-class brown coal deposits that lie close to the surface beneath the Latrobe Valley, and which have provided Victoria with a competitive advantage by way of relatively cheap fuel for electrical power generation for decades. But with the era of coal-fired power generation seemingly drawing to a close, attention is turning to another abundant source of energy within extensive sandstone aquifers in the region—natural hot water. If responsibly managed, these hot and productive aquifers can provide reliable and sustainable geothermal energy in the form of heat for a wide range of applications far into the future.

Low-emissions sources of industrial heat are uncommon. Solar and wind sources can power electrical heaters, but bio-fuels, waste-to-energy, solar-thermal and geothermal energy are the main low-emission sources that can directly challenge natural gas as fuel for heat. The potential value of low-emission sources, including geothermal, must be compared against the local cost of heating with natural gas, which has been volatile over the past year or two. The Australian Energy Market Operator ('AEMO') has recorded fluctuations in the wholesale price of natural gas in Victoria since the start of 2019 from as high as $9 per gigajoule ('GJ') to as low as $4 per GJ, driven largely by volatility in the global liquified natural gas ('LNG') market in which Australia has been a major participant since 2016. With an eye to the future, a modest 'carbon price' of $25 per tonne of CO_2-equivalent (CO_2-e) emissions could permanently add approximately $1.25 per GJ to the wholesale price of heat from natural gas, which has an emissions intensity of 51.5 kg.CO_2-e per GJ[1].

Other regions around the world have embraced the use of geothermal energy from aquifers in the same temperature range as those beneath Gippsland. While the economics of heat supply are inherently local, Gippsland stakeholders can learn from those other regions' experiences. This document presents a high level global scan, identifying regions exploiting geothermal aquifers in a comparable temperature range, examining their local drivers and pathways for energy transition, the dominant uses to which the geothermal energy is applied, socio-economic impacts of the energy transition, the role of governments, and key organisations and individuals. Equipped with this global understanding, stakeholders in Gippsland will be well positioned to realise the opportunities, and avoid potential pitfalls, of developing Gippsland's geothermal energy resource.

1.2. Gippsland geothermal aquifers

The presence of hot water beneath Gippsland and its potential as a source of geothermal energy have been known for decades. As far back as 1962, government geologist J.J. Jenkin tabulated many "occurrences of high temperature waters in East Gippsland"[2], including 70°C water at 525 m depth at Maryvale. Ironically, the thick and shallow brown coal deposits are primarily responsible for the elevated aquifer temperatures and resulting geothermal energy resource. As well as being a source of energy itself, the coal also provides a thick layer of thermal insulation (Figure 1). Over geological time, this 'thermal blanket' has caused the temperature of the underlying rocks to increase to levels greater than would otherwise be expected (Rawling *et al.*, 2013[3]). Some of these underlying rocks are naturally porous and permeable Tertiary-aged sandstones with a demonstrated ability to deliver water from wells at rates on the order of 100 litres per second.

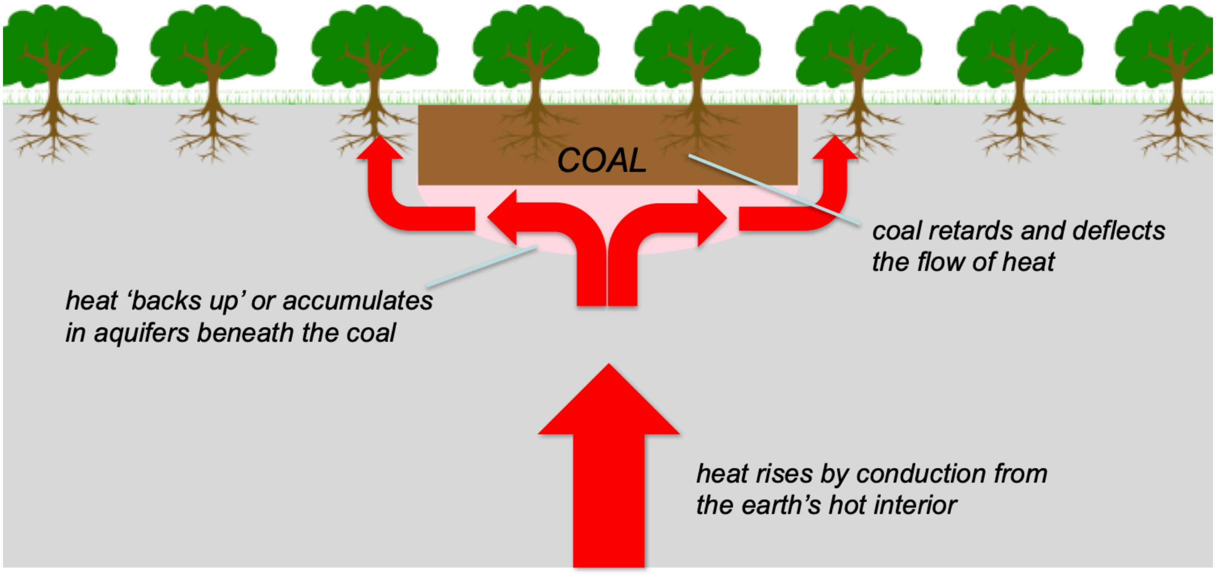


Figure 1. *Thick layers of brown coal retard and deflect the natural flow of heat from the Earth's interior, causing the heat to accumulate and warm the aquifers lying beneath the coal.*

There are several sandstone aquifers stacked vertically within the Tertiary sequence of the Gippsland Basin. Some of these lie within the coal seams, and others beneath. Southern Rural Water ('SRW') refers to the deepest aquifer as the 'Lower Aquifer' and notes that the Lower Aquifer typically produces water in the range 30–70°C[4]. The Lower Aquifer underlies about 6,000 km^2 of Gippsland, from approximately Morwell in the west to Lakes Entrance in the east, and from Maffra in the north to Yarram and the coast in the south (Figure 2). The Lower Aquifer represents the primary target for geothermal energy, although shallower aquifers holding warm water are also potential targets.

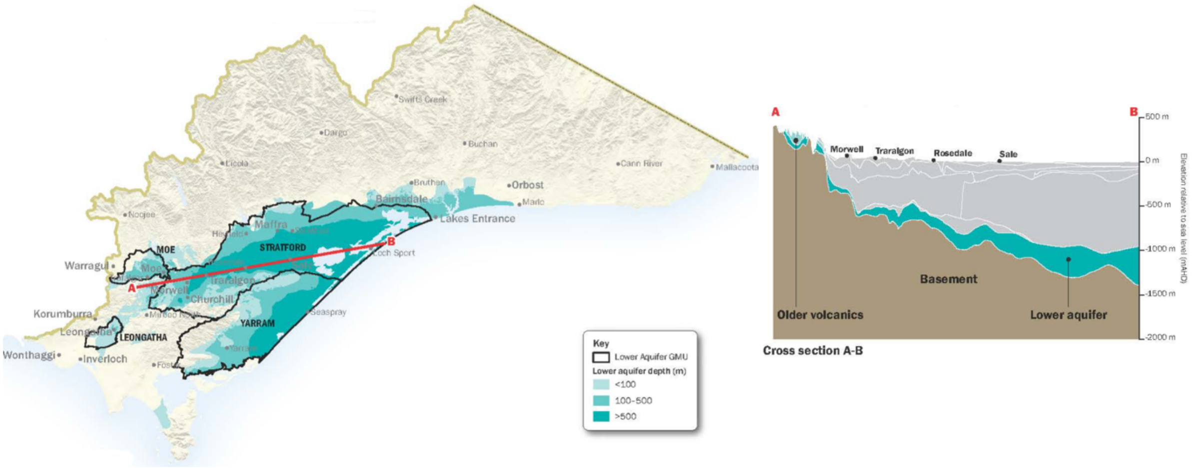


***Figure 2**. Left: Extent and depth to the top of the Lower Aquifer within the Gippsland Basin Tertiary sequence. Right: West-to-east cross section showing the Lower Aquifer generally deepening from about 500 m beneath Morwell and Traralgon, to about 1,000 m beneath Loch Sport. Source: Southern Rural Water (2012)[4].*

1.3. Potential value of the Lower Aquifer geothermal energy

Geothermal energy should only be considered as a possible catalyst for an energy and social transition in Gippsland if there is *prima facie* evidence that geothermal aquifers represent economically competitive sources of energy into the future. The potential economic value of geothermal energy to any specific extraction and utilisation project depends on factors unique to that project. These include the site-specific depth, temperature and productivity of the target aquifer; the cost of drilling and well completion; the heat demand of the specific project; operation and maintenance costs; the value of the end product; the cost of alternative energy sources; and so on. The following thought experiment, however, allows an estimate of the notional value of the geothermal energy stored within the entire Lower Aquifer (onshore section only) relative to the cost of heat from natural gas over recent years.

Consider a program to drill 3,000 wells into the Lower Aquifer at an average spacing of one well every two square kilometres, with half of the wells (1,500) designed to produce hot water and the other half to inject cooled water back into the aquifer. Each well is designed for a 50-year lifetime and costs an average of one million dollars (including all ancillary surface equipment). The cost of the capital program is, therefore, $3 billion with no net consumption of groundwater.

SRW[4] estimates that the onshore part of the Lower Aquifer holds 70,000 GL of groundwater. This volume could be fully cycled through the network of 1,500 production–injection well ‘doublets’ over 50 years at a rate of 0.93 GL per year (average 30 L/s) per doublet. Each gigalitre of groundwater would yield 42,000 GJ of heat if cooled by 10°C before reinjection, for a total of 2.94 billion GJ from the full 70,000 GL. If the cost of heat from natural gas is $5 per GJ, then 2.94 billion GJ equals $14.7 billion worth of energy, yielding a 10% per annum year-on-year internal rate of return (IRR) over the full 50-year lifetime of the $3 billion drilling investment. Furthermore, the geothermal heat produced by each doublet would avoid over 2,000 tonnes of CO_2-e greenhouse gas emissions from natural gas combustion annually.

While the scenario presented above is hypothetical and relies on a very simplistic economic model, it nonetheless presents a compelling *prima facie* argument that the availability of geothermal energy could attract significant economic investment into Gippsland. The first projects to be developed will undoubtedly be located at optimal locations and will extract energy at a greater rate over a shorter time period than the example above, so could generate financial returns greatly exceeding 10% IRR. Furthermore, the adoption of geothermal energy as a heat source in Gippsland could also bring environmental and social benefits relative to natural gas consumption by reducing greenhouse gas emissions, preserving groundwater levels, providing a new sector for local skilled workers and suppliers, providing a basis for strong employment growth in new industries, and so forth.

2. Global Environmental Scan

Armed with confidence that the geothermal opportunity is worth pursuing for Gippsland, it is sensible to look at the experiences of other regions that have developed analogous geothermal resources around the world. Identifying such regions and gathering information about their experiences requires a high-level scan of the entire world. As the umbrella organisation representing dozens of regional geothermal energy associations across the globe, the International Geothermal Association (IGA) provides a gateway to explore the geothermal world.

The IGA periodically collates and reports on global geothermal energy usage, both for electricity generation and 'direct use' of heat. To achieve this, the IGA solicits 'country update' reports from a large number of countries. Information about geothermal power generation and direct use of heat is extracted from these reports and collated into global summaries. The most recent of these summaries was presented during an online forum of the World Geothermal Congress (WGC) from Iceland in April 2021, after being postponed from its original planned date of April 2020 due to the COVID-19 pandemic. The summary papers, along with all the individual country updates, have been published. Prof John Lund (USA) and Dr Aniko Toth (Hungary) co-authored the paper[5] summarising the 'direct use' of geothermal energy around the world as of late 2019.

I contacted Prof Lund and Dr Toth for their suggestions of regions on which this global scan should focus, and received some valuable advice in return. Prof Lund, in particular, was especially helpful in providing the direct contact details for all Eastern European correspondents who had provided Country Update reports to the IGA. I followed up directly with each of those individuals and received enthusiastic responses from many. While many of the respondents regretted that their countries contained no geothermal resources analogous to Gippsland, the respondents from Hungary, Poland and Slovakia were particularly helpful in providing the information that underpins the case studies from their regions presented in the following pages.

Seven regions were chosen for detailed review of how they developed industrial energy supply or other applications using geothermal energy from aquifers in the 30–70°C temperature range. The seven regions cover a range of geological and political settings. The seven examples were chosen from a larger list because of relatively easy access to published information or because comprehensive responses were received following inquiry emails. In all cases, additional details were sought and found through other online means such as literature searches or regular search engine inquiries. Sources for specific pieces of information are generally cited in the relevant sections below. Where a citation is not provided, the information can generally be attributed to personal communication with the individuals listed as Key Contact(s) for each region.

As well as the seven reviewed regions, evidence was also found for the development of geothermal aquifers in the same temperature range in locations including Idaho, Tunisia, Ukraine, Georgia (country), Brazil and others (Figure 3). While detailed information for these regions was difficult to obtain within the timeframe and scope of this report, further work to learn from those regions' experiences might be justified.

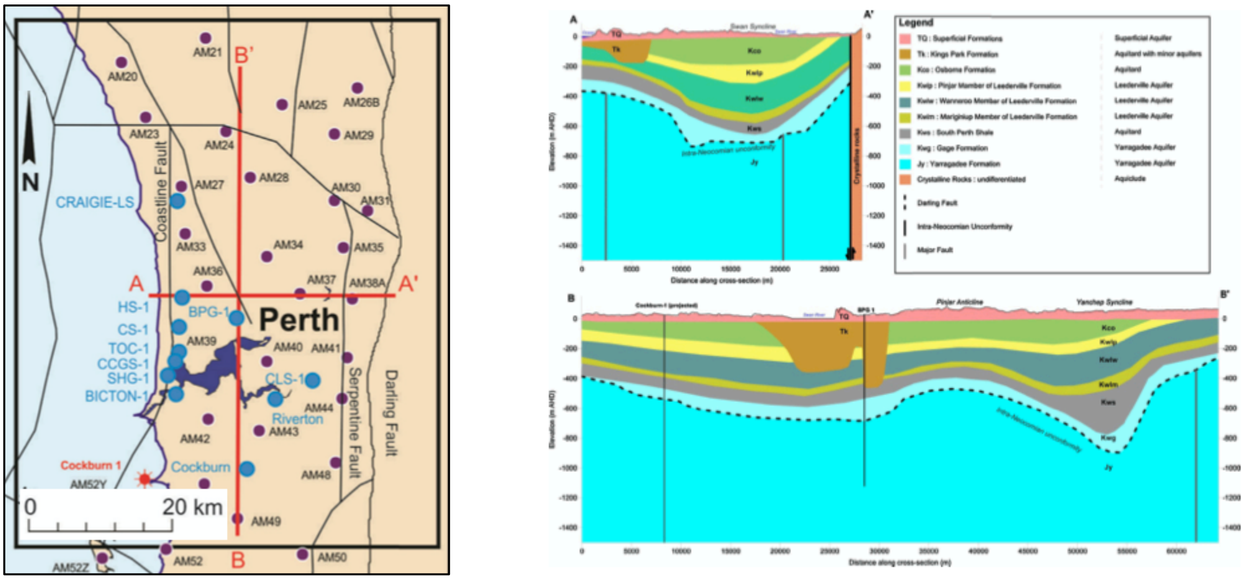
Figure 3. Developments of geothermal aquifers in regions labelled in pink are described in detail in the following sections. Regions labelled in blue were identified as also deriving geothermal energy from aquifers at a similar temperature to Gippsland, but the timeframe and scope of this report did not allow a detailed examination.

2.1. Perth Basin—Western Australia

The Perth Metropolitan Region covers almost six and a half thousand square kilometres in Western Australia, most of it sprawled across the flat plains of the Perth Basin between the Indian Ocean and the Darling Scarp. The Water Corporation of Western Australia reported that 40% of the water consumed by the Perth Metropolitan Region in 2019 came from groundwater[6] in the Perth Basin. The three main aquifer systems are the Mirrabooka Aquifer, the Leederville Aquifer, and the Yarragadee Aquifer. The deepest of these, the Yarragadee Aquifer, provides a useful analogue for the geothermal aquifers beneath Gippsland. There are historical examples of geothermal energy from the Yarragadee Aquifer being exploited as a by-product of domestic and commercial water supply since the earliest exploitation of the aquifer. In recent decades, however, the geothermal energy itself has become a principal reason for drilling.

2.1.1. The Yarragadee Aquifer

Highly permeable coarse sandstones, with minor finer-grained sandstones, host the mid-Jurassic (Bathonian) aged Yarragadee Aquifer, interbedded with impermeable carbonaceous shales (Pujol *et al.*, 2015)[7]. The aquifer underlies most of the Perth Metropolitan Region, but the depth to its top surface varies irregularly between about 400 m to 900 m in both east–west and north–south directions (Figure 4). Only one well, Coburn 1 near the southern end of the B–B' line on Figure 4a), has intersected the full thickness of the aquifer, where it was about 1,200 m thick.



(a)

(b)

Figure 4*. (a) Approximate extent of the Perth Metropolitan Region (Western Australia); (b) Geological cross sections along A–A' and B–B' indicating the approximate depth to the top of the Yarragadee Aquifer (black dashed line). After Pujol et al. (2015)*[7].

Geothermal bores into the Yarragadee Aquifer typically target temperatures between 40°C and 52°C and production rates of 10–40 L/s from depths between 750 m and 1,150 m. The aquifer could support higher flow rates, but these have not been required for the scale of current projects. Collectively, these geothermal plants provide an estimated 247 TJ of thermal energy per year. Regulations require 100% reinjection of the cooled fluid. As seen with many clastic geothermal sources globally, the main operational issue has been to manage bore injectivity. Gradual design improvements and adoption of best practices from the deep groundwater replenishment and oil and gas industries have resulted in successful, economic reinjection (Pujol *et al.*, 2018)[8].

2.1.2. End users

The earliest utilisation of geothermal energy from the Yarragadee Aquifer dates back to the early 20th century, when heat was recognised as a useful by-product of groundwater produced primarily for consumption. Pujol *et al*. (2015)[7] mentioned users including the South Perth Zoological Gardens (for heating the reptile enclosure), a laundry in Claremont (for direct hot water), a wool processing plant in Jandakot (for drying wool), and an open air bathing pool at Crawley (the result of uncontrolled artesian flow from an uncapped bore). None of these early uses continue in the present day.

A new wave of geothermal energy developments has targeted the Yarragadee Aquifer since the late 1990s, all associated with leisure and aquatic centres. Beardsmore *et al.* (2020)[9] listed fourteen such geothermal energy systems built to heat buildings and pools between 1997 and 2018 (Table 1). The first of these was the Bicton Pool operated by the Melville Water Polo Club on the bank of the Swan River (Figure 5), which was originally heated via a heat exchanger drawing waste water from a sugar-mill across the river. When the sugar-mill closed in 1997, the heat source was replaced by a geothermal bore producing 40°C water at a maximum of 8 L/s from 750 m depth, with no reinjection. The small complex has only two pools, today including a popular ‘geothermal hydrotherapy pool’ maintained at 37°C year round.

The technical and financial success of the Bicton Pool project stimulated other developments across Perth. Most of the geothermal systems reinject 100% of the cooled water back into the aquifer, with only the Bicton Pool and HBF Stadium using 100% and 25%, respectively of their produced geothermal water for irrigation. Reinjection is typically into a shallower part of the Yarragadee Aquifer to maintain pressure while protecting the deeper temperatures.[7]

***Table 1**. Geothermal heating systems installed between 1997 and 2018 and drawing on the Yarragadee Aquifer. Source: Rockwater Pty Ltd*

Year	User	Max temperature (°C)	Max flow (L/s)	Reinjection
1997	Melville Water Polo Club (Bicton)	40.0	8	0%
2001	Christ Church Grammar School	42.3	12	100%
2004	HBF Stadium	43.0	40	75%
2004	Claremont Pool	43.7	18	100%
2006	Craigie Leisure Centre	38.3	18.5	100%
2011	Saint Hilda's School for Girls	49.8	20.5	100%
2012	Canning Leisure Centre	48.0	18	100%
2013	Beatty Park Leisure Centre	49.2	35	100%
2014	Hale School	47.2	37	100%
2015	Riverton Leisure Centre	48.0	19	100%
2017	Mandurah Aquatic Centre	43.0	30	100%
2017	Cockburn Central West	49.9	40	100%
2017	Scarborough Pool	50.6	35	100%
2018	Armadale Leisure Centre	43.7	48	100%

***Figure 5**. Bicton Pool on the banks of the Swan River.*
Photo source: www.facebook.com/pg/bictonpool/photos/?ref=page_internal

Although outside the temperature range of primary interest for this report, a geothermal cooling system attached to the Pawsey Supercomputing Centre is worth noting. Two production and two injection wells cycle 20.8°C water from the Mullaloo Aquifer between 45 m and 130 m depth through a heat exchanger at 30 L/s (Sheldon *et al.*, 2015)[10]. CSIRO estimates the system saves more than 7 ML of water per year compared to conventional cooling towers[11].

2.1.3. Research and training

In response to the growing adoption of geothermal energy as a heat source for aquatic centres in Perth in the early 2000s, research into geothermal energy in Western Australia received generous support over a three year period from 2009 to 2012 through a $2.3M grant from the WA Department of Commerce to establish the 'Western Australian Geothermal Centre of Excellence' (WAGCoE). WAGCoE was a joint venture between CSIRO, the University of Western Australia, and Curtin University of Technology, and was established to provide "a foundation for a sustainable geothermal industry by conducting advanced scientific and engineering research into Western Australia's geothermal resources, principally hot sedimentary aquifer resources in the Perth Basin, and to develop and transfer to industry innovative new technologies for direct heat use."[12]

At the end of its three-year life, WAGCoE was celebrated for being instrumental in securing a $20M grant from the Australian Government for the 'CSIRO Geothermal Project' to cool the Pawsey Supercomputing Centre described above (Wright, 2013)[13]. WAGCoE was also a key factor in the recognition of Perth as a "world leader in geothermal municipal development" for its goal of becoming "the very first geothermally cooled city with commercial geothermal-powered heating and air-conditioning units" (Geothermal Energy Association, 2009)[14], and encouraged subsequent research on the thermal characterization of the Yarragadee aquifer (Niederau *et al*., 2017)[15] and mechanical engineering for pool heating (Lovell *et al*., 2019)[16].

2.1.4. Regulatory framework

Geothermal energy resources in Western Australia are owned by the Crown and legislated through the Petroleum and Geothermal Energy Resources Act 1967 and the Petroleum and Geothermal Resources Regulations 1987. The Act defines geothermal energy as "thermal energy that results from natural geological processes and is contained in subsurface rock or other subterranean substances." However, the Act "does not apply to operations…that involve small scale recovery of geothermal energy not for a commercial purpose, or that are of a kind prescribed by the regulations." The Regulations current at the time of writing (version 03-j0-00, 1 July 2020) are silent on the matter of exclusions but, in practice, projects which draw water from shallower that 1,000 m to heat swimming pools and aquatic centres are typically excluded from the Act (pers. comm. Martin Pujol, Rockwater Pty Ltd, 26 November 2020).

The Western Australian Department of Water and Environmental Regulation ('DWER') regulates all 'small-scale' geothermal heating projects that are excluded from the Act. As evident from Table 1, all such projects since 2004 have included 100% reinjection of the cooled geothermal fluid because of tightly held allocations for consumptive use of water from the Yarragadee Aquifer. The licensing process for such projects includes:

a. Application for a 26D licence to construct a well based on a conceptual design meeting the minimum construction requirements for water bores in Australia[17]. The department may request a hydrogeological study to support the application, especially if the hydrogeology of the area or aquifer is poorly known;
b. Application for a 5C licence to take a net-zero volume of water from the aquifer (i.e. 100% reinjection). Licence is typically granted subject to a hydrogeological assessment of the risks to other aquifer users, including groundwater dependent ecosystems (GDEs).

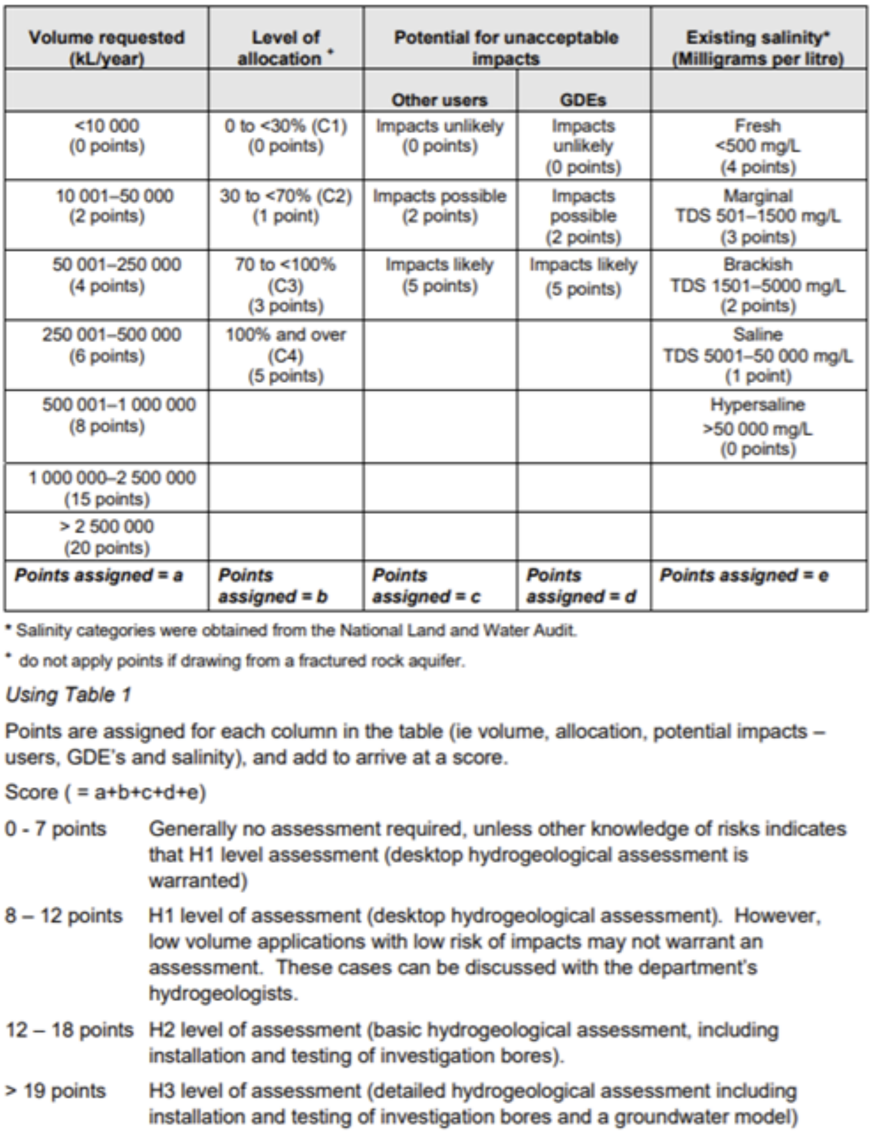
A points-based system dictates the level of hydrogeological assessment that an applicant must complete and document prior to requesting a 5C licence. Points are assigned based on five variables related to the *a priori* risk posed by the proposed development on the groundwater resource. The five variables are (a) the requested annual (net) extraction volume, (b) the level of allocation of the aquifer (100% for Yarragadee Aquifer over most of Metropolitan Perth[18]), (c) the potential for unacceptable impacts on other aquifer users including (d) groundwater dependent ecosystems, and (e) aquifer salinity. Higher risk results in more points and a higher level of compulsory prerequisite assessment.

Table 2 lists the points allocated for each variable, and summarises the level of hydrogeological assessment required for each stated points range. For example, an application for a 5C licence to extract zero net volume of water (i.e. 100% reinjection) from the fresh Yarragadee Aquifer (100% allocated), at a location where an impact on another user (but not a groundwater dependent ecosystem) is possible (as ultimately decided by the Department of Water), would have a point value of 0 + 5 + 2 + 0 + 4 = 11. These circumstances would warrant an H1 level of assessment (desktop hydrogeological assessment.) If the DWER decided, however, that the project would have a likely impact on another user, the point value would be 14 and an H2 level of assessment (basic hydrogeological assessment including more investigation/monitoring bores) would be required.

In practice, licences are granted through a cooperative process whereby applicants always complete an initial desktop (H1) hydrogeological assessment to gauge the *prima facie* risk.

DWER reviews the veracity and outcomes of the H1 assessment to decide whether a more detailed (H2 or H3) assessment is warranted[19].

Table 2. *Points-based determination of level of hydrogeological assessment required prior to application for 5C licence. Source: Rockwater Pty Ltd*



Volume requested (kL/year)	Level of allocation *	Potential for unacceptable impacts		Existing salinity* (Milligrams per litre)
		Other users	GDEs	
<10 000 (0 points)	0 to <30% (C1) (0 points)	Impacts unlikely (0 points)	Impacts unlikely (0 points)	Fresh <500 mg/L (4 points)
10 001–50 000 (2 points)	30 to <70% (C2) (1 point)	Impacts possible (2 points)	Impacts possible (2 points)	Marginal TDS 501–1500 mg/L (3 points)
50 001–250 000 (4 points)	70 to <100% (C3) (3 points)	Impacts likely (5 points)	Impacts likely (5 points)	Brackish TDS 1501–5000 mg/L (2 points)
250 001–500 000 (6 points)	100% and over (C4) (5 points)			Saline TDS 5001–50 000 mg/L (1 point)
500 001–1 000 000 (8 points)				Hypersaline >50 000 mg/L (0 points)
1 000 000–2 500 000 (15 points)				
> 2 500 000 (20 points)				
Points assigned = a	***Points assigned = b***	***Points assigned = c***	***Points assigned = d***	***Points assigned = e***

* Salinity categories were obtained from the National Land and Water Audit.

* do not apply points if drawing from a fractured rock aquifer.

Using Table 1

Points are assigned for each column in the table (ie volume, allocation, potential impacts – users, GDE's and salinity), and add to arrive at a score.

Score (= a+b+c+d+e)

0 - 7 points	Generally no assessment required, unless other knowledge of risks indicates that H1 level assessment (desktop hydrogeological assessment is warranted)
8 – 12 points	H1 level of assessment (desktop hydrogeological assessment). However, low volume applications with low risk of impacts may not warrant an assessment. These cases can be discussed with the department's hydrogeologists.
12 – 18 points	H2 level of assessment (basic hydrogeological assessment, including installation and testing of investigation bores).
> 19 points	H3 level of assessment (detailed hydrogeological assessment including installation and testing of investigation bores and a groundwater model)

At the time of writing (January 2021), DWER has never imposed a requirement for a separate monitoring bore for any geothermal project utilising the Yarragadee Aquifer, although monitoring bores are sometimes a condition for licencing projects drawing on very shallow aquifers[19]. Instead, the impact of each geothermal system on the aquifer, relative to the predictions of groundwater models, is monitored using data collected from the production and injection wells. The geothermal heating system installed at the Hale School in 2014 provides a good example. The geothermal system provides sufficient heat to maintain 50 m and 25 m outdoor pools at 26.5°C and 28.0°C, respectively, year round, from a 974 m bore producing 47.5°C water, with a 477 m reinjection bore about 20 m away. DWER monitors and regulates the operator's compliance with its licence conditions by reviewing groundwater pumping rates, water levels in the production and injection bores, production and injection temperatures, and groundwater chemistry, each of which are measured and recorded as often as every 15 minutes. The monitoring program at Hale School, reportedly[20] the most comprehensive in the Perth area, reveals the impact of the geothermal system on the aquifer and provides a robust dataset for statutory reporting and regulation.

2.1.5. Socio-enviro-economic factors

All geothermal heating developments in Perth since 2000 have been driven by financial considerations. Geothermal energy provides a cheaper option compared to natural gas at normal market prices for heating swimming pools and aquatic centres.

2.1.6. Key contact

Grant Bolton, Rockwater Pty Ltd—GBolton@rockwater.com.au

2.2. Paris Basin—France

Paris, the capital of France, provides one of the world's best examples of the sustainable widespread utilisation of geothermal energy for residential space heating. The first doublet heating system (utilizing both production and injection wells) came online at Melun l'Almont in 1971 as a private joint venture with no public subsidies[21], and 2021 marks 50 years of continuous operation[22]. The success of that first system spawned imitation systems across the greater Paris metropolitan region, development of which continue to this day in spite of many earlier systems being decommissioned during the 50-year period.

2.2.1. The Dogger aquifer

The main geothermal aquifer beneath Paris is hosted within the Dogger Formation, a series of limestones and dolomites of Mid-Jurassic age at depths between 1600–1800 m and at temperatures between 56°C and 85°C[22]. The Dogger Formation is within the Paris Basin, a large, nearly circular, sedimentary basin underlying more than 150,000 km^2 of northern France plus part of the English Channel (Figure 6). The Dogger aquifer recharges where it outcrops in the east, from where the water slowly migrates through the aquifer to the northwest before discharging into the sea floor beneath the English Channel[23].

The full Dogger aquifer sequence is typically 100–150 m thick and hosts between three and twenty individual productive layers depending on location. The productive layers typically total about 20 m in cumulative thickness[23]. At basin scale, the salinity of the aquifer generally increases from very fresh (around 0.5 g/L) in the southeast recharge zone, to seawater concentration (c.35 g/L) in the deeper sections. The salinities of individual productive layers, however, can vary at the same location, and salinity is not directly correlated with depth[23].

Lopez *et al*. (2010) mapped the temperature and 'relative transmissivity' of the Dogger aquifer in the region around Paris (Figure 7). They defined 'relative transmissivity' as the ratio of aquifer transmissivity (permeability-thickness) in darcy-metres to dynamic fluid viscosity in centipoise.

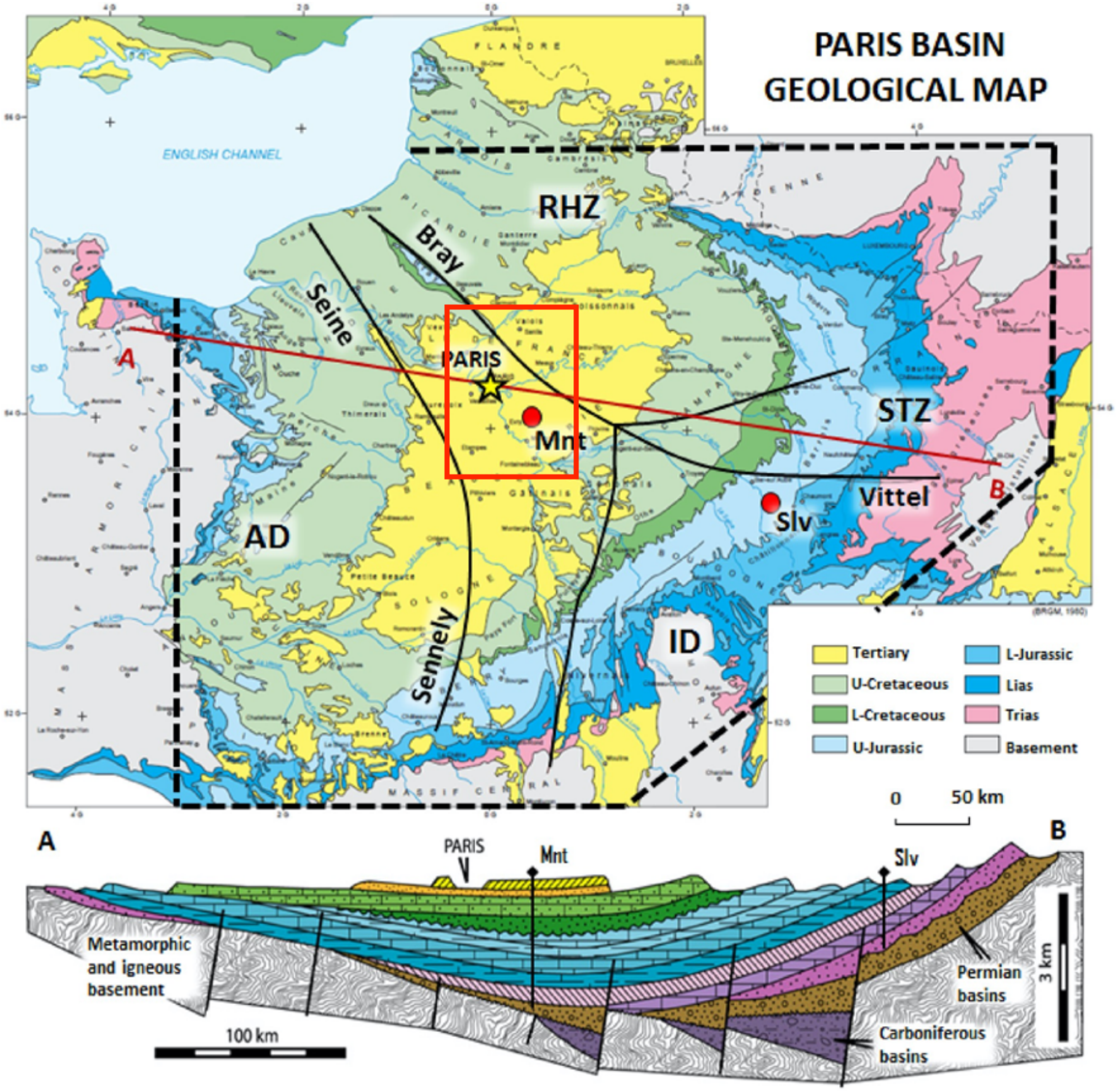


***Figure 6**. Top: The coloured sections show the extent of the Paris Basin and the geological age of outcropping formations. The Dogger Formation is represented by the intermediate blue shaded 'L(ower)-Jurassic' layer. The red rectangle shows the approximate extent of the maps on Figure 7. Bottom: Geological cross-section running west to east along line A–B. Modified from Torelli et al. (2020)[24].*

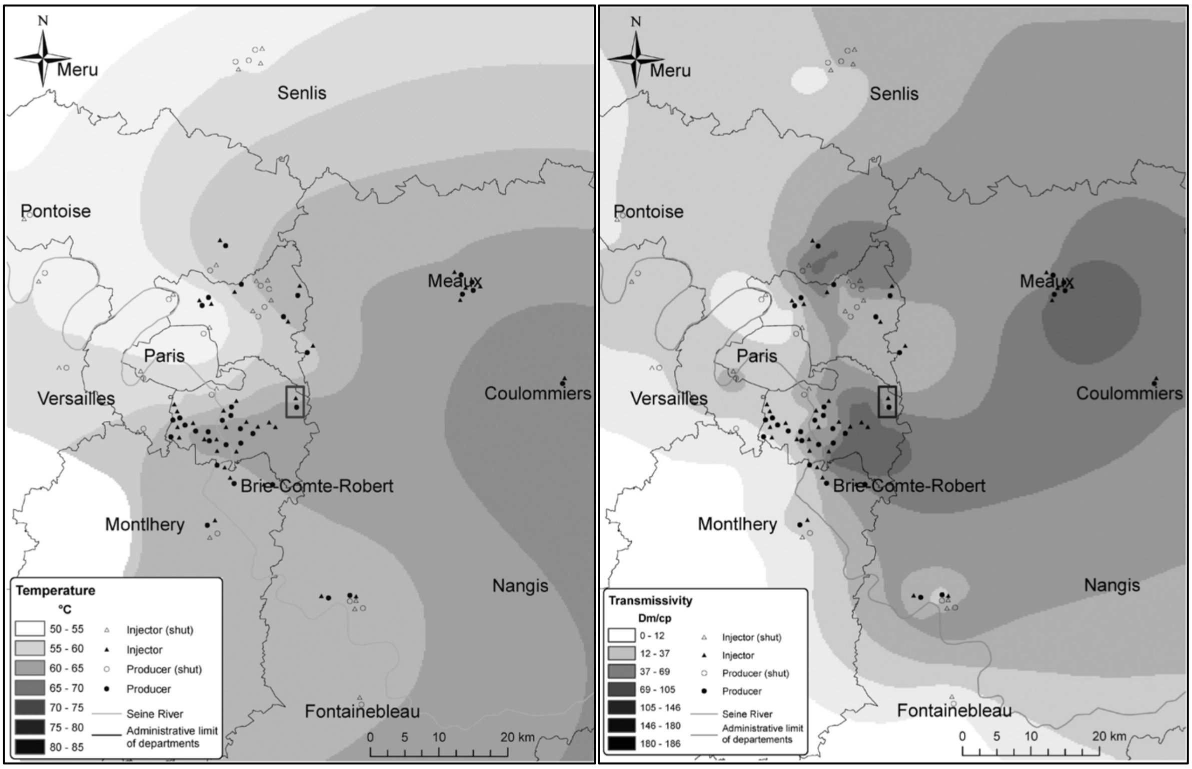


***Figure** 7. Left: Temperature in °C at the top of the productive zone of the Dogger aquifer. Right: Relative transmissivity of the Dogger aquifer expressed in darcy-metres per centipoise. Both maps also show the active (solid shapes) and decommissioned (open shapes) production (circles) and injection (triangles) bores existing in 2010. See Figure 6 for map location. From Lopez et al. (2010)*[23].

2.2.2. End users

Geothermal energy is drawn from the Dogger aquifer beneath Paris exclusively for collective, mostly residential, heating systems. The most recent published figures (for 2019)[22] confirm that the Dogger aquifer supplies the largest number of direct use geothermal systems in the world. Forty-six (46) individual systems currently provide geothermal heat to 6–7 % of the total Paris population of 11 million. A typical geothermal system in the Paris region delivers energy to 4,000–6,000 dwellings for space heating and domestic hot water.

The feasibility of using geothermal energy from the Dogger aquifer was first tested in 1962 with a single bore in the suburb of Carrières-sur-Seine. The water was found to be hot enough, but a plan to discharge the cooled water into the Seine River was abandoned when the salinity of the water was discovered to be much higher than expected[23]. The high salinity, in fact, permanently influenced the design and maintenance of geothermal systems in the Paris Basin.

The immediate impact of the high salinity was that geothermal energy could only be exploited if 100% of the cooled water was injected back into the aquifer. That required each geothermal system to have at least two bores and for the saline water to remain isolated from exposure at the surface—a ‘doublet’ of one production bore and one injection bore connected at the surface by a sealed conduit passing through a heat exchanger. The first such doublet heating system came online at Melun l’Almont in 1971 as a purely private joint venture with no public subsidies[21].

The technical success of that first doublet system facilitated its rapid replication as the oil shocks of the 1970s led the government to introduce policies that strongly favoured alternative energy sources and energy efficiency. The result was that 110 geothermal wells were drilled into the Dogger aquifer to create 55 doublet systems between 1970 and 1985. Each system was independently owned and operated by local communities, public housing departments, hospitals, mutual societies, and other public or semi-public organisations.

In general, the geothermal bores are cased and cemented to just above the aquifer interval to avoid any possible oil contamination from shallower reservoirs. The bores are generally completed ‘open hole’ at 8-inch (20 cm) diameter within the Dogger aquifer.[23]

However, the geothermal heating sector suffered substantial setbacks that endured for a quarter of a century after 1985 due to a global drop in oil price, the onset of corrosion and scaling problems brought on by the high salinity water, and a reduction in interest rates penalising older loans. Drilling was limited to replacing damaged wells on existing facilities, and many doublets were decommissioned in favour of natural gas heating systems. Of the 55 original geothermal doublets, only 34 were still operating in 2010, providing energy to 29 heating systems (some systems combined energy from more than one doublet)[23].

The period since 2010, however, has seen a renaissance in geothermal heating from the Dogger aquifer as government policies have focussed on addressing climate change through low emissions technologies. As mentioned above, as of early 2021 the Dogger aquifer provides energy to 46 individual heating systems. Two entirely new systems were drilled, installed and commissioned over the three years from 2016 to 2019. Engie Solutions posted a video to YouTube (https://youtu.be/ZvA_l-Ig0uc) showcasing one of these, at Dammarie-les-Lysone, on 17 February 2021. That doublet produces up to 12 MW_t of geothermal power from the 71°C Dogger aquifer, meeting 90% (30 GWh) of the annual heat demand of 3,800 dwellings via 36 distributed sub-stations.

In parallel with new doublet systems being drilled and commissioned in recent years, the lifetimes of several older systems have also been greatly extended during the same period. In one case, a new doublet was drilled using modern horizontal drilling methods to fully replace two previous 34 year-old doublets. The new doublet—employing long (c.1000 m), sub-horizontal, open-hole sections that follow the most permeable sections of the aquifer at 1500 m depth—is more productive than the sum of the previous two doublets; 125–140 L/s versus 100 L/s. In five other cases, existing doublets were converted into triplets by drilling a new large diameter production well and relining and repurposing the pre-existing doublets into pairs of injection bores. In those cases, productivity typically improved from 55–70 L/s to 85–100 L/s.[22]

As an aside, it is worth noting that Paris is also beginning to investigate geothermal cooling. For example, Le Parisien newspaper reported in late 2020[25] that "geothermal energy will cool the Olympic village" being planned as part of the 2024 Paris Olympic Games. The story described how 14°C water from 60 m depth will be exploited via eleven boreholes (three producers and eight injectors), heat exchangers and heat pumps to provide a cooling network to which the accommodation for 15,000 competitors and Olympic staff will be connected. After the Olympic Games, the affected buildings will be converted into 120,000 m^2 of office space, 2,200 family dwellings, and 980 student apartments.

2.2.3. Research and training

R&D efforts apply to all sectors of the geothermal industry in France; direct use of hot aquifers, power generation, and shallow heat pump systems. This section describes only those R&D and training activities relevant to the exploitation of the Dogger aquifer beneath Paris.

Lopez *et al*. (2010)[23] of the French Geological Survey ('BRGM') described the research priorities of that organisation with respect to managing the sustainable exploitation of the Dogger aquifer at that time. Those priorities included updating and reinterpreting data about the porosity, permeability, temperature and salinity of the aquifer; forecasting wellhead pressure and the times of chemical and thermal breakthrough for doublet systems through improved numerical modelling; understanding and controlling corrosion and scaling with chemical inhibitors; the use of natural chemical species (especially iron sulphide) as tracers; reducing uncertainty in aquifer stratigraphy and thermal properties (conductivity, diffusivity, heat capacity); and developing a long-term sustainable exploitation plan.

Boissavy *et al*. (2020)[22] reported fields of more recent research and development yielding positive outcomes. In one example, sophisticated sensing-while-drilling technologies allowed the real-time drilling trajectory of the horizontal wells mentioned in Section 2.2.2 to remain within high permeability layers. In another example, casings made from composite materials (steel lined with fibreglass) used to reline production wells facilitated higher production rates and significantly reduced corrosion and scaling. In a third example, the addition of heat pumps to several geothermal systems increased the amount of heat extracted from the same volume of water (i.e. lower injection temperature.)

The French Agency for Ecological Transition ('ADEME') is the major national funding body for geothermal research and development[22]. Theme 4 of ADEME is focussed exclusively on improving the economics of geothermal energy (including geothermal district heating) by reducing system costs, maximising production potential, and improving social awareness and acceptance of geothermal energy. The National Agency for Research ('ANR') and the Fund for Industrial Clusters ('FUI') also provide funding for upstream research and technical innovation, respectively.

Through its 'Investments in the Future' program, ADEME supported the formation of Géodénergies—an 'Institute of Excellence' to research the use of the underground in the energy transition—in July 2015. In early 2021, the Géodénergies consortium included ten companies and seven public research institutions. Its most relevant project for this report ('PERTHEM') aimed to develop a tool and methodology to detect and monitor the advance of 'cold fronts' between injection and production wells in the Dogger aquifer using controlled-source electromagnetic ('CSEM') methods.[26]

The Association of French Geothermal Professionals ('AFPG') coordinated and launched the GEODEEP research cluster in June 2014. GEODEEP's 17 partners include large multinational companies, geothermal engineering service companies, power engineering firms, equipment manufacturers, drilling companies, providers of project finance, project developers, and geothermal professional societies[22]. Together, the partners cover the entire value chain for geothermal projects including exploration and drilling, power plant and district heating design and construction, training, operations and maintenance, and technological monitoring.

To facilitate training of a new generation of researchers and skilled workers, Géodénergies facilitates technology and knowledge transfer between 'traditional' (i.e. fossil fuel) earth resource sectors to 'new energy' sectors (i.e. geothermal, but also CO_2 sequestration.) Géodénergies' research sector partners also interact with other universities and schools to influence education programs and training.

While there is no evidence for dedicated degree courses in geothermal energy in France, the CY Cergy Paris University hosted a five-day 'Geothermal Spring School 2020' on its Neuville campus over the period 16–20 January 2020 under the auspices of the MEET consortium funded by the European Union's Horizon 2020 research and innovation program. A follow-up four-day online ‘Geothermal Winter School 2021’ ran over the period 16–19 February 2021 and included in its program a one-hour lecture by Christian Boissavy—'Deep geothermal energy for district heating network: case histories in Paris Basin and lessons learned since 50 years.’

In late 2020, the Université Paris-Saclay advertised a PhD position to work on an ANR-funded project—Geothermal energy in siliciclastic reservoirs: Contribution of field analogues and hydrodynamic simulation[27]. In January 2021, the Climate and Environment Sciences Laboratory and the French Geological Survey (BRGM) jointly advertised for a postdoctoral fellow position to assess the role of carbonate and sandstone reservoir heterogeneities on the performance of geothermal doublets in Paris[28].

2.2.4. Regulatory framework

The following information is drawn dominantly from Boissavy *et al.* (2020)[22].

All exploration and production of geothermal energy in France is regulated under the Mining Code (new). The European Geothermal Energy Council (EGEC) described the regulatory framework in a report c.2004[29]. The following summarises that document.

Decree 77-620 (16 June 1977) added a new title, ‘Low temperature geothermal deposits,’ to the Mining Code, creating an obligation to obtain exploration and exploitation licences before drilling for or producing water from deeper than 100 m between 20–150°C when measured at the surface (different rules govern higher temperature resources.) Decree 74-498 (24 March 1978) subsequently defined the framework for requesting and granting the two licence types. The state’s objectives are (a) to optimise the exploitation of the resource; (b) to minimise the environmental risks of the activities, and (c) to guarantee the health and safety of workers.

An application for an exploration licence must be supported by technical, economic, administrative, financial and environmental documents. The application is considered by the local Prefect (i.e. local government) following a public enquiry and consultation with affected state and local government services, during which competing or opposing claims can be lodged. For example, the legislation stipulates that no well deeper than 100 m can be drilled within 50 m radius of dwellings and their adjoining enclosures without the explicit consent of the owners of those dwellings.

If granted, an exploration licence gives the holder exclusive rights to drill at specific sites or within a fixed perimeter for three years, and to request an exploitation licence within that deadline. The Prefect also has authority to grant an exploitation licence for a maximum of 30 years with a possible extension up to 15 years. An exploitation licence defines the volume of production allowed from an aquifer volume lying within a defined surface perimeter and between two defined depths. A request for an exploitation licence must include information on the drilling sites, the expected fluid and heat production rates, the reinjection plan, the proposed use(s) for the heat, and an environmental impact study.

A production licence typically includes requirements for ongoing monitoring of the system. Monitoring ensures the system is operating within expected parameters and provides early warning of any adverse effects on the reservoir or geothermal system. The following is a list of common monitoring requirements[30], all of which are performed within the doublet (or triplet) wells:

- Continuous monitoring of flowrate, temperatures and pressures in both production and injection bores
- Chemical sampling of brine from production and injection bores every two months
- Corrosion monitoring every three months using sacrificial metallic 'coupons'
- Report on the efficiency of corrosion inhibitor treatments every two months
- A report on well performance (flow rate as a function of pressure) every three months
- Well integrity investigation using multi-finger calliper every three years on the injection well and every five years on the production well

Even though it provides a solid legal framework for allocating rights to geothermal exploration and exploitation, in 2004 EGEC considered many aspects of the Mining Code legislation poorly defined or ambiguous from an operational perspective.

An interesting detail of the legislation is that reinjection of the cooled geothermal fluid does not require any additional licence so long as the fluid is neither polluted nor has it received any additives (e.g. to mitigate corrosive properties.) In all other cases, additional authorisation is required for injection.

A ministerial ordinance of 24 July 2019[31] aimed to streamline applications for geothermal licences in order to stimulate development of more geothermal systems. The ordinance recognised different levels of complexity for applications depending on the state of knowledge of the geothermal reservoir, the phase of exploration, the purpose and maturity of the project, the degree of project complexity and innovation, and the duration of the works. A simplified application process was introduced for projects in known geological settings requiring only limited additional exploration and reservoir characterisation.

Along with the licencing framework, risk mitigation and incentive funds have arguably had the greatest impact on the development of geothermal district heating systems in Paris. The local production characteristics of a geothermal aquifer (temperature, flow rate, chemistry) can only be confirmed after a borehole is drilled. There is a real risk that the first well will encounter lower temperature, less permeable and/or more corrosive conditions than predicted. This upfront risk is a substantial barrier for commercial lenders to support a public or community institution to develop a local geothermal heating network. Furthermore, once constructed and operating there remains a significant risk that heat production rates from the system will degrade over time relative to initial predictions, again a risk that represents a barrier to commercial lenders.

Recognising that geological risks pose a significant barrier to project financing, the French government set up two complementary geothermal risk mitigation funds that, combined, operated successfully from 1980 to 2015. The funds were, effectively, insurance policies whereby project developers paid a premium to the fund in return for a guaranteed rebate if the project failed due to geological uncertainties.

Boissavy (2017) provided a useful description of the two funds[32]. The ‘Short Term Fund’ (1982–1996) was a hybrid drilling subsidy-risk mitigation-R&D grant scheme, providing a guaranteed 20% subsidy plus a rebate of up to 90% of the initial drilling cost if the results of the drilling were insufficient for the project to continue on a firm economic footing. The premium was set at 1.5% of the maximum rebate. The fund compensated 15 claims over its lifetime. Between 1986 to 1992, the ‘Short Term Fund’ also provided €3.4 million to high-priority research of benefit to the entire geothermal sector.

The ‘Long Term Fund’ (1981–2015) guaranteed the repayment of long-term loans against geological uncertainties affecting the operation of heating systems over 15–30 years. 42 projects took out cover under the fund during its lifetime. Since 2015, the geothermal heating sector in Paris is viewed by commercial investors as technically mature and finance is readily available for well-managed projects. Even so, new developers still seek insurance products to cover the geological risk. It is worth noting that, in the mid-2000s, the government of The Netherlands set up a risk mitigation fund very similar to the French funds, which helped stimulate geothermal drilling in The Netherlands.

Since the conclusion of geothermal risk mitigation program, the Renewable Heat Fund (‘Fonds Chaleur Renouvelable’) has provided financial subsidies for public buildings, social housing, tertiary institutions, industry and the agricultural sector to install renewable energy heating systems, including geothermal. Between its inception in 2009 and the latest figures for 2018[22], the fund (managed by ADEME) provided a total of €141 million to 495 geothermal heating installations (including shallow ‘ground source heat pump’ installations) now producing 6.3 million GJ of heat per year across all French territories. Sixty five of those facilities were in the Paris region.[22]

As a final word, the European Geothermal Energy Council published a note on 26 January 2021[33] stating, “The good news is that as from June 2021 in France no new private building can be heated by gas or fossil fuels. Therefore renewable energy, among which geothermal is one of the best placed, is a priority for the energy supply in buildings.”

2.2.5. Socio-enviro-economic factors

Lopez *et al*. (2010)[23] attributed the initiation and growth of the Paris geothermal district heating industry to three factors:

- Presence of a productive geothermal reservoir at a reasonable depth and with characteristics suitable for district heating networks;
- Existence of a potential heat market in the form of high-density residential buildings and districts;
- Public policy incentives and insurance policies that favoured the development of new energy sources.

Boissavy *et al*. (2020)[22] reported a “total market for geothermal energy in France” of €388 million in 2015. This estimate included all geothermal sectors; power generation, direct use, and ground source heat pumps. Boissavy *et al*. (2020)[22] further reported an estimate of direct employment in the geothermal energy sector in the whole of France at 2,340 EFT in 2017. The ‘direct’ jobs related to preliminary studies, drilling, equipment manufacturing and installation, operation & maintenance of equipment, and sales. While the source did not provide a breakdown of the estimated value and employment into the different geothermal sectors, the district heating sector perhaps accounted for 40–50% of the totals.

In spite of the relatively widespread use of geothermal energy in the Paris region for 50 years, there is evidence of community resistance to further development of the resource. The online news service, 94.citoyens.com[34] reported on 16 February 2021 the outcome of a public inquiry into the proposed expansion of a geothermal system at Champigny-sur-Marne. The public-owned company L’Etablissement Public Campinois de Geothermie (Campinois Public Geothermal Establishment) plans to drill a new doublet to provide geothermal water for a 9 km extension to an existing distribution network. The extension will increase the number of connected dwellings from 7,000 to 14,000 and offset 9,000 tonnes of CO_2-e greenhouse gas emissions per year. The public inquiry was triggered by community concerns about drilling noise, a lack of consultation, damage to public amenity, atmospheric pollution, traffic control, property depreciation, potential seismicity, and two petitions demanding the outright abandonment of the project. The commissioner responsible for the inquiry ruled in favour of the project but stipulated maximum sound-proofing.

The YouTube video from Engie referred to in Section 2.2.2 (https://youtu.be/ZvA_l-Ig0uc) estimates that the project to convert the Dammarie-les-Lys district heating system from natural gas to geothermal resulted in a reduction in greenhouse gas emissions of 7,000 tonnes CO_2-e per annum. The video also estimates 30 GWh of annual heat supply from the system, equivalent to AU$0.54 million per year in natural gas at AU$5 per GJ wholesale price, or AU$2.7 million per year at AU$25 per GJ retail price.

The website actu.fr[35] reported economic projections for another planned geothermal doublet system on 8 February 2021. A joint venture between Engie Solutions and the local municipality will develop the 1,500 m deep doublet in the commune of Rueil-Malmaison beginning in mid-2021. The €65 million project will circulate 62°C geothermal water through a 25 km distribution network to provide geothermal energy to social housing, private apartment blocks and private residences amounting to 60% of homes in the region, with potential for future network extension. The project is expected to offset 21,000 tonnes of CO_2-e greenhouse gas emissions per year and deliver savings between 10% and 20% on user's energy bills over 10 years.

In 2019, a joint venture between the community of Paris-Vallée-de-la-Marne and Engie Solutions successfully crowdsourced €1 million through the Lumo online platform to support the €40 million development of a geothermal district heating system at Champs-sur-Marne[36]. While providing only a small proportion of the total capital cost, the crowdsourcing "allowed the inhabitants of Paris-Vallée-de-la-Marne and more broadly the Parisians to invest their savings in this facility"[37] to "reinforce the territorial anchoring of the project by involving local residents in its success."[37] By early 2021, the project was well advanced with its drilling program.[36]

2.2.6. Key contact

Miklos Antics, Managing Director—GPC-IP / GEOFLUID and President of European Geothermal Energy Council—M.antics@geoproduction.fr

2.3. West Nederlands Basin—Netherlands

A steady growth in the exploitation of geothermal energy for greenhouse heating in the Netherlands, and recent expansion to heating the 'built environment', is a direct outcome of government policy and targeted support mechanisms. While geothermal energy is also being used in northern parts of the Netherlands, this report focusses on geothermal energy resources in the West Nederlands Basin in the South Holland region, a thermal analogue for the Lower Tertiary Aquifer of the Gippsland Basin.

2.3.1. Geothermal aquifer

Upper Jurassic to Lower Cretaceous sandstone formations within the West Nederlands Basin host the main geothermal aquifers in the south of the Netherlands. The aquifers underly 4000–5000 km^2 of the province of South Holland. Willems *et al*. (2020)[38] described the aquifer geology in detail. In short (Figure 8), the Delft Sandstone Member of the continental Nieuwerkerk Formation represents the principal geothermal reservoir target, with the deeper Alblasserdam Member increasingly considered an additional target (a geothermal system was developed in 2017 that draws from both aquifers.) The target depth interval is typically 1800–2200 m to achieve reasonable productivity in the temperature range 65°C–80°C (Figure 9). While 5–10°C warmer and three times deeper than the Lower Tertiary Aquifer beneath the Latrobe Valley, the aquifer characteristics are similar enough to the Lower Tertiary Aquifer to draw valuable conclusions with respect geothermal energy potential in Gippsland.

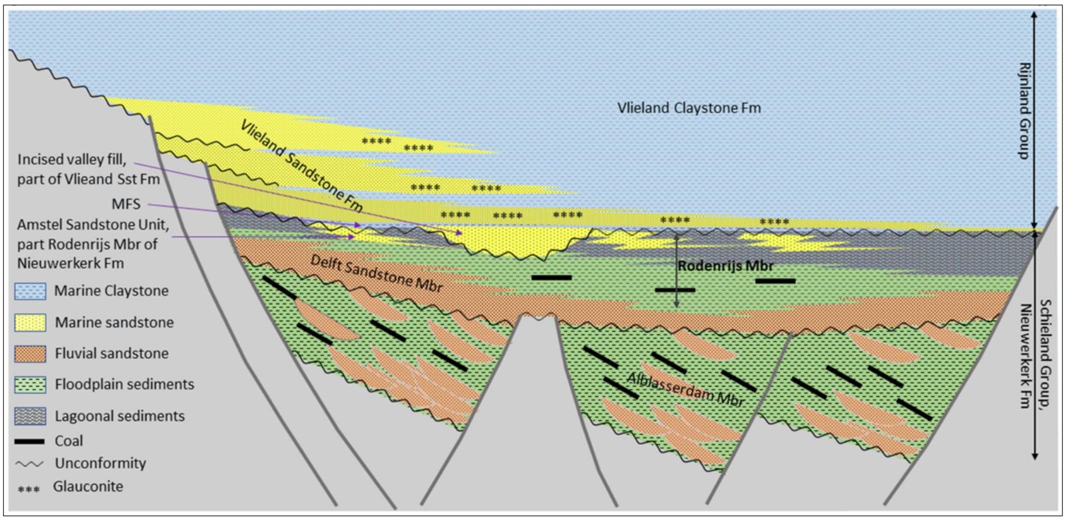


Figure 8. Representative cross section (south to north) through the West Nederland Basin, showing the relationship between the Delft Sandstone Member and the Alblasserdam Member. The Delft Sandstone Member is generally 1800–2200 m deep, and the Alblasserdam Member deeper. From Mijnlieff (2020)[39].

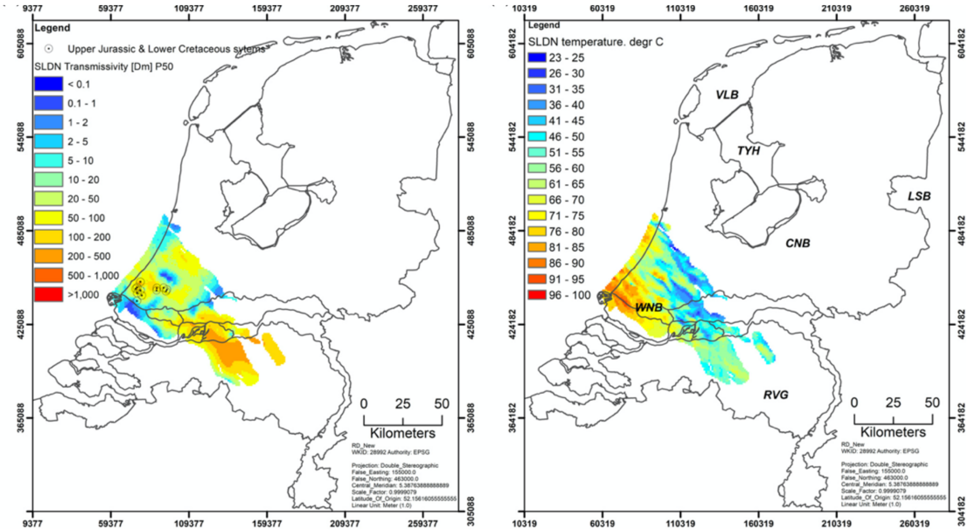


Figure 9. *Left: Transmissivity of the Nieuwerkerk Formation reservoirs. Right: Average temperature of the Nieuwerkerk Formation reservoirs (Delft Sandstone Member and Alblasserdam Member.) From Mijnlieff (2020)*[39].

2.3.2. End users

Industrial scale greenhouse operations are the dominant end users for geothermal energy from the Nieuwerkerk Formation, although efforts are underway to extend usage to the supply of heat to the 'built environment.' There are currently (April 2021) 18 geothermal systems in operation or under development in the West Nederlands Basin region (Figure 10)[40]. They are all based on 'doublets'—one production and one injection well. For example, Wayland Energy operates a geothermal doublet with a thermal capacity of 9.9 MW_t at Bergschenhoek, producing 97.2 TJ of heat per year[41]. As a second example, VoF Geothermie operates a 16 MWt system at De Lier, producing 480 TJ of heat per year[41].

Figure 10. *Left: Locations of geothermal systems in operation or under development in the West Nederlands Basin region in April 2021. Red flags show systems exclusively supplying industrial scale greenhouses, green flags show systems providing heat also to the 'built environment.' Modified from Geothermie Nederland website*[40].

Bakema *et al*. (2020)[41] reported that 3–5 new projects are being initiated across the whole of the Netherlands each year. Many of these are in South Holland. For example, the Polanen Heat Cooperative is currently developing a geothermal heat distribution system to supply heat to 39 greenhouse horticulture company partners at Monster, SW of Den Haag, with a possible network extension to provide heat to 'built environment' areas (Figure 11)[42].

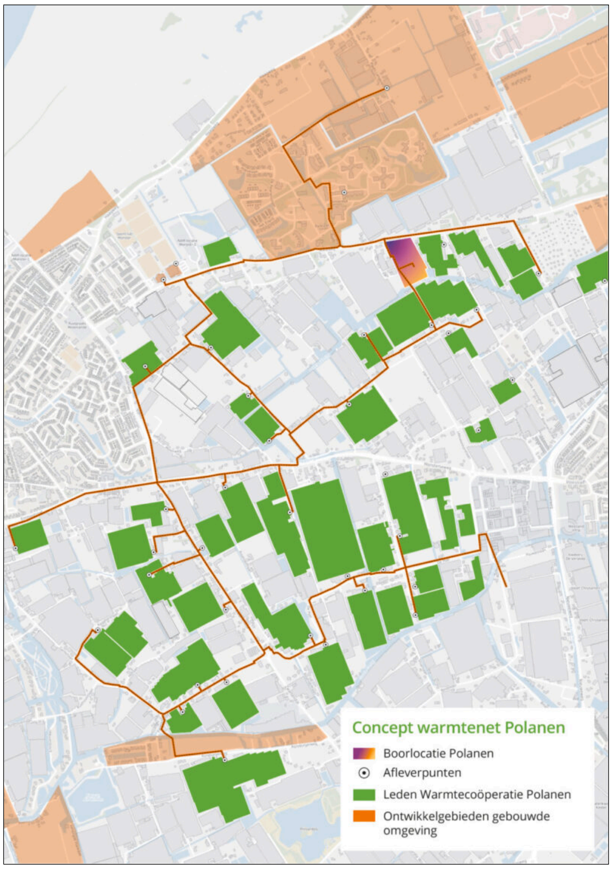


Figure 11*. Conceptual plan for a geothermal heat distribution system for the Polanen Heat Cooperative at Monster, SW of Den Haag. 'Boorlocatie' = drilling location; 'Afleverpunten' = heat delivery points; 'Leden Warmtecooperatie Polanen' = cooperative partners; 'Ontwikkelgebieden gebouwde omgeving' = built environment development areas. From Energie Transitie Partners*[42].

2.3.3. Research and training

Geothermal Science and Engineering is a theme within the Department of Geoscience and Engineering at Technische Universiteit Delft (Delft Technical University), where an interdisciplinary team conducts research across a broad range of topics relevant to sustainably utilising geothermal heat. The university even has its own geothermal research well

Utrecht
Ex-Shell drilling research facility

https://www.nlog.nl/en/geothermal-energy-0
https://www.tudelft.nl/citg/over-faculteit/afdelingen/geoscience-engineering/research/geothermal/geothermal-science-and-engineering
https://www.geocap.nl/about-geocap/
https://www.tno.nl/en/focus-areas/energy-transition/roadmaps/sustainable-subsurface/towards-an-energy-producing-environment/accelerating-sustainability-of-local-heating-supply/innovation-lab-geothermal-energy-entrepreneurs/

2.3.4. Regulatory framework

Bakema *et al.* (2020)[41] summarised the main policy instruments affecting the exploration and production of geothermal heat in the Netherlands. They attributed the strong growth in the geothermal direct heat sector to four factors:

a. Decisions in March 2018 and September 2019 to end production of natural gas from the Groningen gas field in NE Netherlands, triggered by growing concerns about related subsidence and seismicity[43];
b. An ambitious Agreement on Energy for Sustainable Growth (2013) that set a target of 14% share of renewable energy in the Netherlands' total energy consumption by 2020, and 16% by 2023;
c. The Dutch voluntary 'nationally determined contribution' commitment to the Paris Climate Agreement (2015) of a 49% reduction in greenhouse gas emissions by 2030, relative to 1990 levels;
d. A Climate Agreement (2019) developed collaboratively by more than 100 stakeholders from across Dutch society to combat global warming, including: commitments to remove legislative and regulatory bottlenecks to renewable energy developments; delivery of a knowledge and innovation program to manage risk in the exploitation phase; pledges to professionalise the geothermal heat sector; the development and adoption of industry standards; building additional knowledge of the subsurface through seismic acquisition; and a target cost reduction for geothermal heat of 50%.

"The central government also maintains the RNES guarantee scheme and the SDE + scheme for this technology. An ongoing point of discussion is that renewable heat is still a relatively unexplored domain, wherein both DGE and SGE can play an important role, but also need the infrastructure to transport the heat to a future user."

A permit is required to explore for and produce geothermal heat from depths greater than 500 metres. The State Supervisor of Mines (SodM) regulates the permit system. Reinjection of spent geothermal brine is mandatory.

The Dutch government instigated the Geothermal Heat Action Plan, which lays out a cohesive package of government assistance and programs to stimulate the switch from natural gas to geothermal energy. The package includes:

- Provision of a government-backed drilling risk insurance scheme to help businesses manage the financial risks of drilling for geothermal heat (c.f. Section 2.2.4);
- Development and maintenance of ThermoGIS, an online mapping and analysis tool that empowers companies and government authorities to explore for geothermal heat;
- The 'energy-producing greenhouse' programme: a collaborative venture in which government and industry work together to reduce CO_2 emissions from greenhouse horticulture, notably by providing businesses with information;
- Renewable Energy Grant Scheme (SDE+);
- Grants for fixed geothermal heat pumps are available via the Sustainable Energy Investment Scheme.

https://www.government.nl/topics/renewable-energy/government-stimulates-geothermal-heat#:~:text=Using%20geothermal%20heat%20for%20homes%20and%20greenhouses&text=There%20are%20currently%2012%20geothermal,supplies%20geothermal%20heat%20to%20homes.

https://www.nlog.nl/en/geothermal-energy-0

2.3.5. Socio-enviro-economic factors

https://www.westlanders.nu/gemeentenieuws/opnieuw-meer-aardgas-bespaard-met-geothermie-38337/

A relatively recent development (January 2021) was the merging of DAGO, the previous geothermal industry representative body, and Platform Geothermie (what was this?) into Geothermie Nederland, a new association uniting all companies and organizations with a business interest in the geothermal sector.

The Wayland Energy operation at Bergschenhoek produces the equivalent of almost AU$500k of heat per year, based on a price of AU$5/GJ for natural gas, while the VoF Geothermie project at De Lier produces almost AU$2.5M of heat per year at the same comparison rate. Averaged across the Netherlands, geothermal projects offset c.10,000 tons of CO_2 emissions from avoided natural gas combustion per doublet per year[41].

2.3.6. Key contacts

Harmen Mijnlieff, TNO—Harmen.Mijnlieff@tno.nl

Radboud Vorage, chairman of Geothermie Nederland— info@geothermie.nl

Martin van der Hout, geothermal greenhouse consulting engineer—
martinvanderhout@hotmail.com

2.4. Veresegyház—Hungary

There is a long history of utilisation of geothermal springs in Hungary. The Roman Empire developed hot springs for balneological use in Budapest thousands of years ago, and the medieval Ottoman Empire continued the development of therapeutic spas near natural hot springs[44]. Hungary lies entirely within the Pannonian Basin, an extensive geographic and geological feature that extends across several eastern European countries. Oil prospecting in the basin from the 1920s onwards led to the discovery of large reservoirs of hot water (60–90°C) in 100–300 metre thick sandstone beds at 700–1,800 metres depth. These have since been extensively exploited across Hungary, dominantly for balneology—therapeutic bathing and medical treatments[44]—and spas are today an integral element of Hungarian identity. Indeed, the Hungarian Tourism Agency refers to Hungary as "The Land of Thermal Waters."[45]

Even after two millennia of exploitation of geothermal waters, Hungary continues to find new sources and applications for geothermal energy, often at the municipality level. The town of Veresegyház provides a fine example of how a local community relatively recently realised its geothermal energy potential. Veresegyház lies 30 km northeast of Budapest in north central Hungary (Figure 12) and boasts a population of about 20,000[46]. The community only began utilizing geothermal energy in 1993, but today is home to Hungary's largest urban geothermal heating system[47].

Figure 12. *Location of Veresegyház (red flag) in north central Hungary.*

2.4.1. Triassic limestone aquifer

Veresegyház lies near the northern limit of the Pannonian Basin, where the sandstone aquifers that host geothermal water in other parts of the country are shallow, thin and cool. This probably explains why the geothermal energy potential beneath Veresegyház lay undiscovered until the 1990s. It is now recognised, however, that a Triassic-aged karstic limestone formation in the basement beneath the Pannonian Basin sediments hosts a geothermal aquifer at depths of 1,450–1,700 m beneath Veresegyház. Three wells sunk into the basement currently produce >60 L/s total flow (Toth *et al*., 2020[48]) of 64–72°C water (at the wellheads), which is delivered to energy consumers through a network of 18 km of pipe. After the heat is utilized, more than 90% of the water is reinjected into a single well. The gas and salt content (TDS: 1,250–1,450 mg/l) of the karstic water are both at levels that allow the water to be used safely and profitably[48].

2.4.2. End users

Szita (2016)[47] related the progressive growth in Veresegyház's geothermal energy system over a 20 year period from 1993. A summary of that history is presented here.

In the 1980s, a local geologist successfully encouraged the village[49] leaders to drill the basement rocks beneath the town to explore for hot water. The nearest geothermal bore at the time was in Budapest, so the venture carried significant risk. Nevertheless, the community raised the money and successfully discovered and produced a stream of 64°C water at 8 L/s in 1987. The result justified building a new outdoor municipal swimming pool that opened in 1992, and both the well and the swimming pool still operate today (Figure 13).

***Figure 13**. A Google street view image from January 2012 of Veresegyház's public geothermal swimming pool.*

The geothermal bore (‘B-15’) produced far more thermal energy than needed for the swimming pool, so a forward-thinking local engineering firm put a proposal to the village leaders to replace a fuel-oil heating system in a local primary school (700 m from the bore) with a heat exchanger drawing heat from the geothermal water. The proposal was accepted, a pipeline was laid, and the new heating system was installed in the school in 1993. The investment paid for itself in three years, so in 1997 a new pipeline was laid and fuel-oil heating systems were replaced with geothermal energy systems in five other public buildings (a primary school, two kindergartens, a music school and a cultural centre.)

At this point, the geothermal heating systems still utilized only half of the thermal energy produced by the bore, and the town leaders were keen to extend the geothermal heating network to all public buildings in the town centre. A new law introduced in 2004, however, made reinjection of cooled geothermal water compulsory throughout all of Hungary. For Veresegyház to increase production from B-15, it first had to add an injection well to the network. A site was chosen, and in 2007 an injection well (‘K-23’) was successfully completed 1.6 km from B-15. This allowed the immediate extension of the geothermal pipeline to a total of 6.5 km, and the conversion of the heating systems from fossil fuels to geothermal energy in another 12 public buildings (cinema, shopping centre, post office, town hall, nursing home, church, and others). Significantly, five additional consumers also privately financed their own connections to the geothermal network to replace fossil fuel heating systems during this period, including one private dwelling.

Demand for cheap and environmentally friendly geothermal heat continued to grow but the thermal capacity of B-15 had been fully utilized. So in 2011 the municipality drilled a second production well (‘K-25’) and laid 5.9 km of new pipe, largely to supply heat to existing large industrial consumers including pharmaceutical and textile plants, and a General Electric Aviation facility. Heat production from the new well was sufficient to also supply eight additional public and private consumers. The existing injection well could accommodate all of the additional flow. Figure 14 illustrates the progressive development of the geothermal heating network from its humble beginnings until 2014.

Interest in the geothermal energy did not stop there. Around 2014, a prospective investor appeared in Veresegyház looking for cheap land and energy to build and operate a 3.2 Ha greenhouse facility. Veresegyház could provide both, but the two existing geothermal production wells had no excess capacity. To win the new greenhouse facility, the town committed to 100%

finance a third production well, to increase the capacity of the injection well, and to lay 2.4 km of additional large-diameter pipeline. When completed to 1,700 m in 2015, production well ‘K-26’ flowed 72°C water at the wellhead. As well as attracting the new greenhouse operation, the new geothermal heat supply also influenced General Electric Aviation’s decision to invest in a large new engine manufacturing plant in Veresegyház. A new block of 190 apartments became a third cornerstone customer for the geothermal energy from K-26. A new church, a supermarket, and a block of 78 apartments also connected to the geothermal network in early 2016. Table 3 lists the heat consumers connected to the geothermal network in late 2016, and Figure 15 shows their locations around the town.

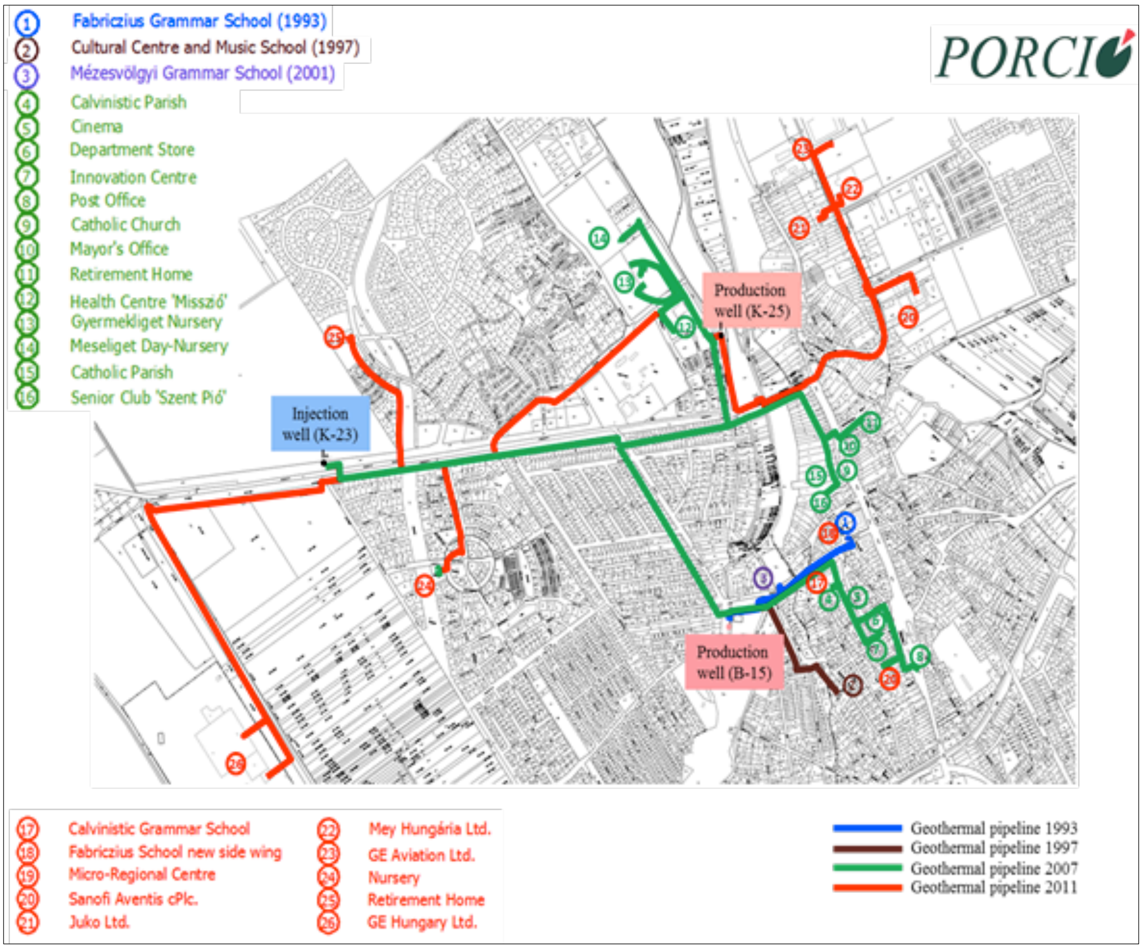


Figure 14. *Geothermal wells, pipelines and consumers in Veresegyház, colour coded according to the time period of development. Source: Toth (2014)*[50]

Table 3. *Geothermal heat consumers in Veresegyház in late 2016, categorised according to customer type (public entity, large corporation, or private company/individual). Source: Szita (2016)[47]*

Nr.	Name	Public	Corp.	Private	Nr.	Name	Public	Corp.	Private
1	Fabriczius Elementary School	X			21	Municipal Nursing Homes	X		
2	House of Culture	X			22	Old Catholic Church	X		
3	Mézesvölgyi Elementary School	X			23	Catholic Parish	X		
4	Thermal Spa Dressing Room	X			24	Szent Pió Elderly Home	X		
5	Calvinistic Parsonage	X			25	Private House			X
6	Cinema	X			26	New Catholic Church	X		
7	Main Square Shopping Centre		X		27	Sanofi Pharmaceutical Co.		X	
8	Innovation Centre	X			28	Juko Ltd.		X	
9	Post Office		X		29	Mey Textil Co.		X	
10	Calvinistic School	X			30	General Electric Aviation Co.		X	
11	Town Hall	X			31	Lévai kindergarten	X		
12	Calvinistic Church	X			32	Horváth Gipsz Ltd.		X	
13	Sports Locker Room	X			33	GE Aviation Co. New prod. hall		X	
14	Lehár Gated Community			X	34	Mission Hospital	X		
15	Csonkás Kindergarten	X			35	Gyermekliget Kindergarten	X		
16	Diakonia Elderly Home	X			36	Meseliget Nursery	X		
17	Csonkás block of flats			X	37	Blocks of flats (190 flat)			X
18	Őszi Liget Elderly Home	X			38	General Electric Energy Co.		X	
19	CBA Supermarket		X		39	Horticulture (3.2 ha glasshouse)		X	
20	Old Town Hall	X							

Figure 15. *Geothermal wells, pipelines and heat consumers in Veresegyház in late 2016. Refer to numbers in Table 3 for identification of heat consumers. Source: Szita (2016)[47]*

The latest information available for this report[47] noted that (as of late 2016) “many others [were] waiting for their run” at the geothermal resource, including another primary school, a grammar school, two sport halls, three hectares of greenhouses, a block of 46 apartments, and a block of 110 apartments.

2.4.3. Research and training

Nádor *et al*. (2019)[51] reported that several Hungarian research institutions have recently coordinated or participated in large European research projects covering subjects including geothermal district heating, reinjection of brines into sandstone reservoirs, extraction of minerals from thermal water, mitigation of technical risks in geothermal energy exploration and production activity, geothermal risk insurance, and assessment of geothermal reservoirs. Furthermore, the University of Miskolc and University of Szeged were partners in a major European project (CHPM-2030, completed in 2019) which aimed to develop technology to simultaneously extract heat, power and strategic metals from deep, hot, metallic mineral formations. And the Eötvös Loránd University in Budapest was granted three years of funding to investigate interrelationships between subsurface water, heat and minerals, and how those interrelationships impact water management, geothermal energy utilisation, and the exploration and extraction of raw minerals.

Private industry has also carried out independent geothermal R&D. Most notable is Portió Ltd, the engineering firm which first proposed geothermal heating for Veresegyház. In 2018, the European Geothermal Energy Council (EGEC) recognised Portió’s novel production and reinjection system into a sandstone reservoir at the Gyopáros Thermal Spa as a top-five contender for EGEC’s Innovation Prize. An entrepreneur also designed a special heating substation that allowed private citizens in Veresegyház to tap into the municipal geothermal network at an affordable price.

Nádor *et al*. (2019)[51] reported that the only university in Hungary with a dedicated geothermal training program is the University of Miskolc, which has offered a four-semester postgraduate (BSc or MSc) Geothermal Engineering program since 2008. In partnership with the University of Colorado, the University of Miskolc also delivers undergraduate geothermal e-learning lectures by international professors and geothermal experts. Relevant topics include elements of renewable energy, advanced geology, advanced geophysics, fluid dynamics, hydrogeology, drilling well design, geothermal reservoirs, geothermal water production, geoinformatics, geothermal chemistry, geothermal heat-transfer systems, geothermal power production, geothermal direct uses, geothermal heat pumps, and geothermal environmental impacts.

2.4.4. Regulatory framework

In spite of (or perhaps because of) Hungary's very long history of exploiting geothermal resources, there remains no clear legal framework for ownership of geothermal heat. Municipal geothermal networks such as that in Veresegyház are regulated by water licenses. Elsewhere, public utility companies produce and sell geothermal heat on a contract basis through comprehensive district heating systems regulated by the Hungarian Energy and Public Utility Regulatory Authority. In each case, the well is owned by the developer who drilled it. The produced geothermal energy is the property of the mining contractor[52]. Reinjection of cooled geothermal water has been compulsory in Hungary since 2004.

Toth (2015)[52] reported, "The 1345/2018 (VII 26) Governmental Decision on the Action Plan of the Utilization and Management of Energetic Mineral Resources addresses geothermal risk mitigation: it calls on the Minister for Innovation and Technology and the Minister for Finances to make a joint proposal on introducing financial tools for the mitigation of high upfront risks for geothermal projects (i.e. a risk insurance scheme) by June 2019." No evidence was found for this report that such a drilling risk insurance scheme has yet been introduced in Hungary.

2.4.5. Socio-enviro-economic factors

Part of the success of the Veresegyház geothermal network can be attributed to the fact that the heat from the three production wells is shared by dozens of end users. The cost for any single user to build and operate its own production and injection wells would make geothermal energy uneconomic in almost every case. But the municipal distribution network has allowed the costs to be shared equitably throughout the community.

The dominant use of the geothermal resource in Veresegyház is for space heating, largely replacing old fossil fuel heating systems. A recent publication[44] estimated the installed thermal capacity of the geothermal network at 14 MW_{th}, and the total annual heat delivered at 141,530 GJ. This is equivalent to an annual offset of AU$700k in natural gas at AU$5/GJ, and over 7,000 tonnes per annum of avoided CO_2-e emissions.

The availability of geothermal heat was instrumental in attracting significant new investments to Veresegyház. While General Electric Aviation already had a presence in Veresegyház prior to development of the geothermal heating network, conversion to geothermal heating provided the company with substantial energy cost savings. It is reasonable to infer that this was a key consideration in GE Aviation's decision to enlarge its Veresegyház facility with a new engine manufacturing plant in 2015. Today, Dun and Bradstreet (accessed 23 July 2020) estimates that GE Aviation's Veresegyház facility employs 595 people and generates US$216.80 million in annual sales.

Veresi Paradicsom Ltd deliberately chose Veresegyház for its new high-tech three hectare greenhouse in 2015 due to the availability of geothermal heat. In 2017, the US$1.5 billion greenhouse employed 40 staff, turned over US$650 million, and made US$107 million profit, up from US$13.5 million profit in 2015 and US$80 million in 2016[53].

Szita (2016)[47] related that the hardest step in developing a geothermal system in Veresegyház was overcoming the initial scepticism of the municipal leaders. Only when the proposing engineering consultancy (Porció Ltd) offered to self-finance the geothermal retrofit of the primary school heating system in 1993, in return for a 10-year energy sales contract, did the mayor of the village decide that the village itself would make the investment. Szita (2016)[47] furthermore attributed the successful development of a geothermal network in Veresegyház to "bravery in initiatives, honesty in business, low price of energy, operable municipality, healthy local community with openness to the world—and a good leader." On the final point, it is perhaps relevant that the mayor of Veresegyház has held the position for over fifty continuous years! Continuity of leadership has ensured an ongoing belief in and commitment to the geothermal system.

Perhaps of greatest significance is that Veresegyház now views itself as a geothermal town, a source of great pride for Hungarians. In the words of Gábor Szita[47], "People in Veresegyház have known geothermal. For heating everybody think of using thermal water as the first alternative. It is simply wonderful!"

2.4.6. Key contacts

Prof Aniko Toth, Dept of Petroleum Engineering, University of Miskolc—aniko@tothgeo.com

Mr Gábor Szita, President of Hungarian Geothermal Association—szitag@mgte.hu

2.5. Beijing Plains—China

Beijing is one of the world's leading urban centres for utilising geothermal energy from aquifers in the same temperature range as those underlying Gippsland. Beijing Municipality sprawls across more than 16,800 km^2 of the Beijing Plains[54]. Fifth century writings record the existence of Foyukou Hot Spring, 70 km northwest of modern-day central Beijing (Zheng, 2005)[55], while 15th century records from the Ming Dynasty document royal visits to the Xiaotangshan Hot Spring, 35 km north of central Beijing (Zhou *et al*., 2008)[56]. During the Qing Dynasty in 1666, two marble-lined pools and a royal 'bathing tank' were constructed (and remain to this day) over the source of the Xiaotangshan Hot Spring. Since then, the municipality has continuously drawn on geothermal water for therapeutic bathing.

The municipality recognised the potential for using the geothermal water as a source of energy in the 1970s. Intensive geoscientific investigations, including drilling, rapidly expanded the geographic extent of the known reservoirs. Exploration for new geothermal resources continues to this day across the municipality, as do developments of innovative new applications and business models.

2.5.1. Wumishan Group aquifer

The Beijing Plains are the surface expression of the Beijing Depression, a series of Mesozoic aged extensional basins overlain by unconsolidated Tertiary and Quaternary sediments[60]. Hou *et al*. (2018)[57] characterised the geothermal aquifers beneath the Beijing Plains as 38–70°C and lying at depths of 400–2,500 m. The Wumishan Group of the Jixian System (Jxw on Figure 16) hosts the most important geothermal aquifer across the region. The reservoir is composed of dolomitic rocks including stromatolite dolomite, algal dolomite, grain dolomite, mud crystalline dolomite, and silicified stromatolite dolomite (Wang, Mao *et al*., 2020)[58]. It is recharged by rainfall in the mountains to the north[56].

Today, geothermal aquifers are known across more than 2,200 km^2 of the total 'Beijing Geothermal Field', which is divided into ten subfields (Figure 17). Wang and Xie (2003)[59] described the characteristics of some of the subfields. The Xiaotangshan subfield produces water in the temperature range 35–64°C from 350–1,200 m depth, the Dongnanchengqu subfield produces 39–70°C water from 650–2,600 m depth, and the Liangxiang subfield produces 36–42°C from an unspecified depth. Most development has been in the Xiaotangshan, Dongnanchengqu, Lisui and Liangxiang sub-fields, so these are the focus of this review.

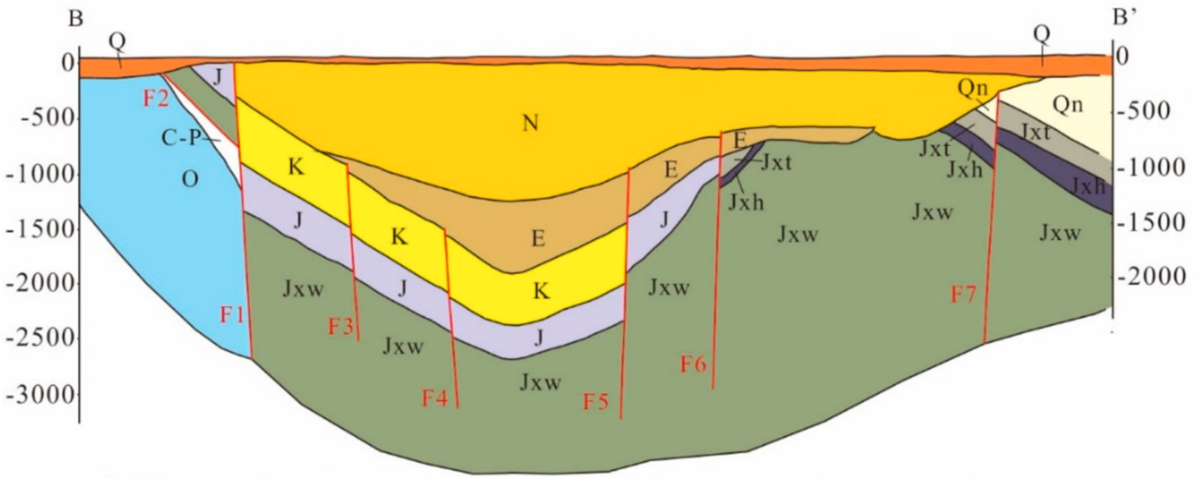


__Figure 16__. Cross section through the Beijing Depression along line B–B' on Figure 17. Horizontal extent is about 25 km and vertical scale is depth in metres. O = Ordovician; C–P = Carboniferous to Permian; Jxw/Jxh/Jxt = Wumishan/ Hongshuizhuang/Tieling Groups of the Jixian System; J = undifferentiated Jurassic; K = Cretaceous; Qn = Qingbaikou System; E = Palaeocene; N = Neocene; Q = Quaternary; F1–F7 = faults. Source Xu et al. (2019)[60].

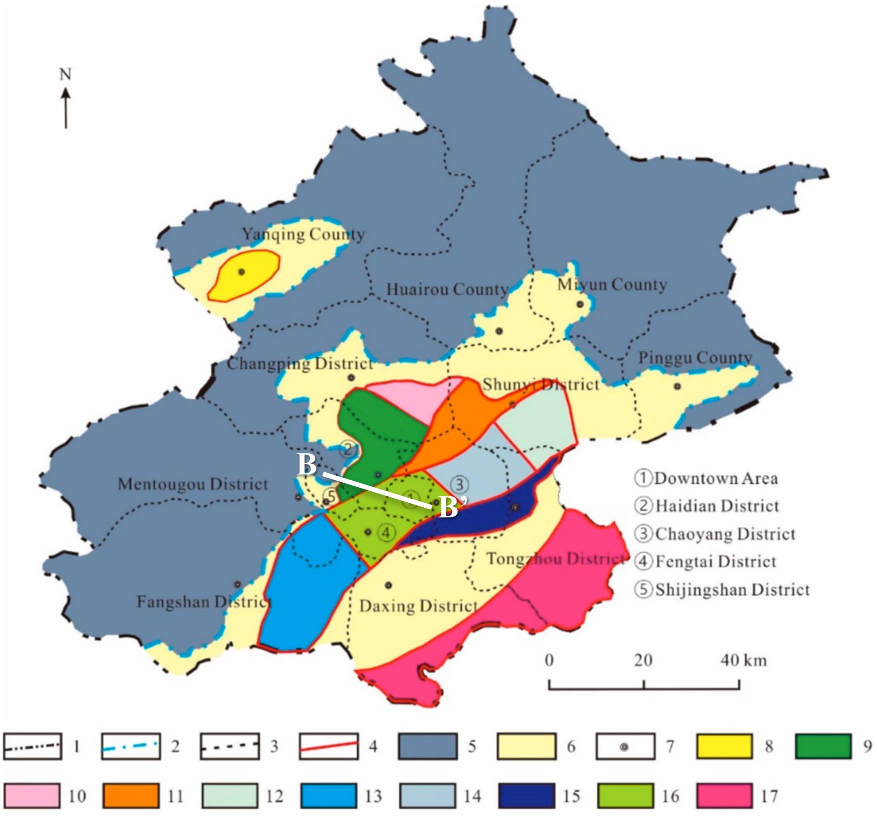


__Figure 17__. (1) Beijing municipal boundary, (2) Edge of plains, (3) County boundaries, (4) Sub-geothermal field boundaries, (5) Mountains, (6) Plains, (7) Country administrative centres, (8–17), subfields of the Beijing Geothermal Field [8–Yanqing, 9–Jingxibei, 10–Xiaotangshan, 11–Houshayu, 12–Lisui, 13–Liangxiang, 14–Tianzhu, 15–Shuangqiao, 16–Dongnanchengqu, 17–Fengheying]. Source: Xu et al. (2019)[60] Line B–B' shows location of cross section on Figure 16

2.5.2. End users

Pan *et al.* (2015)[61] summarized the first phase of geothermal development in Beijing, driven entirely by the government in the era before China entered the global market economy in the late 1980s. The first projects were mainly geothermal space heating and bathing facilities. Individual enterprises augmented or replaced fossil fuel boilers with their own geothermal heating systems circulating 50–60°C water 24 hours a day during winter. The systems were found to provide stable and comfortable space heating, and the cooled water was a suitable temperature for staff bathing facilities. Both the temperature and humidity of cotton spinning factories could be controlled with geothermal air-conditioning systems, which had the dual benefit of decreasing energy costs and increasing the quality of the cotton product. Subsequent developments included geothermal greenhouses growing high quality flowers and vegetables, and geothermal aquaculture delivering high yield and new edible varieties direct to the Beijing market.

After entering the global market economy in the late 1980s, privately owned enterprises began to develop geothermal projects. Geothermal hot spring bathing facilities were by far the most popular new businesses of that era, catering to daily bathing, medical care, tourism and relaxation markets. Early developers reaped high returns and attracted many subsequent investors, with some developers even offering residential villas with geothermal domestic hot water and each with a private "hot spring entering your home."[61]

Li *et al.* (2015)[62] listed a wide range of geothermal energy applications and end users in Beijing, including winter heating (hotels, guest houses, publishing houses, printing houses, textile mills, dyeing factories, nursing homes, and others), balneology, greenhouse cultivation, boiler feed water, industrial utilization (air-conditioning systems, textile printing and dyeing machinery, washing, cleaning), aquaculture, and more than fifty public geothermal bathing pools visited by as many as 50,000 people per day.

Wang, Liu *et al.* (2020)[63] reported that production of geothermal energy from hot aquifers across China has increased at a rate of 10% per annum since 2010, and that a total of 563 geothermal production bores had been drilled in Beijing since the mid-1970s, although Jiang *et al.* (2018)[64] suggested that only 184 wells were in active service in 2015, including 35 injection wells.

The village of Nangong, 25 km SW of central Beijing, is one of the world's prime examples of the cascaded use of a geothermal energy resource. In the 1990s, the Nangong village council decided to take advantage of its dual competitive advantages of geothermal resources (in the Liangxiang sub-field) and available land to pursue an ambitious program to both urbanise and adapt traditional agricultural practices to a ‘geothermal economy’55. A single geothermal well completed to 2,980 m depth65 in October 2000 flows 72°C water at 27.5 L/s and provides heat and water to a range of facilities.

The water is first used to heat and provide hot water to a total of 30,000 m^2 of buildings including residential houses, a guesthouse, a hotel, offices, and a geothermal exhibition centre. The water passes from the space heating system at 48°C and enters the ‘Hot Spring Water World’ and ‘Hot Spring Fishing Centre’ facilities. Here, more energy is extracted from the water in floor heating systems, and some of the water is used directly for recreation. Further cooled, the water passes into a ‘Hot Spring Special Aquafarm’ growing several species of edible fish. Finally, at a temperature less than 30°C, the remaining geothermal water is used in greenhouses for soil heating and irrigation, yielding up the last of its heat via heat pumps or by mixing with original water. The entire cascaded system makes full use of both the energy and water produced by the single well.

As well as benefitting directly from the heat and water, the geothermal industries are integrated with other facilities into a unified ‘World Geothermal Natural Science Park’ (Figure 18) which provides Nangong with a tourism drawcard. The park includes a 3,000 m^2 geothermal science exhibition centre that provides geothermal education to primary and secondary school students and the general public, sells local produce from its gift shop, and even offers medical treatments for tourists. A 5,000 m^2 hot spring aquaculture centre breeds “famous, special, excellent, new aquatic products, tropical ornamental fish and adult fish”[65] in four indoor and two outdoor facilities. A 12,000 m^2 hot spring fishing centre has several fishing pools, relaxation lounges, and a restaurant for fishers and tourists. Finally, 20,000 m^2 of intelligent greenhouses provide year-round vegetables, flowers, and fruit.

In spite of the apparent enthusiastic adoption of geothermal energy in Beijing, however, numerous sources state that existing projects are only drawing a fraction of the available heat from the aquifers. This conclusion comes from both formal estimates of the capacity of the energy resource, and observations that the temperature of the geothermal water has remained constant after more than four decades of production.

Figure 18. *Entrance to the Nangong World Geothermal Natural Science Park. Source: patpoh.com*[65]

2.5.3. Research and training

Liu *et al*. (2010)[66] reported that the Bureau of Land and Resources of Beijing (BLRB) funded several research projects each year, focussing on exploration, utilization techniques, resource assessment, information systems, and other topics as deemed important at the time. Many of these research projects in recent decades have focussed on reinjection of spent geothermal water.

However, Liu *et al*. (2019)[67] asserted that "China's research in geothermal technologies remains weak." Only one out of more than 2000 tertiary institutions in China offers a program in geothermal energy. A core of technical researchers were trained in geothermal programs in New Zealand, Iceland, Japan and Italy from the 1980s onwards, but training in recent years has mainly been through short-courses offered by national and international organisations that focus on specific topics. The overall level of geothermal research and training in China is arguably "incompatible with the rapid development of geothermal resources."[67]

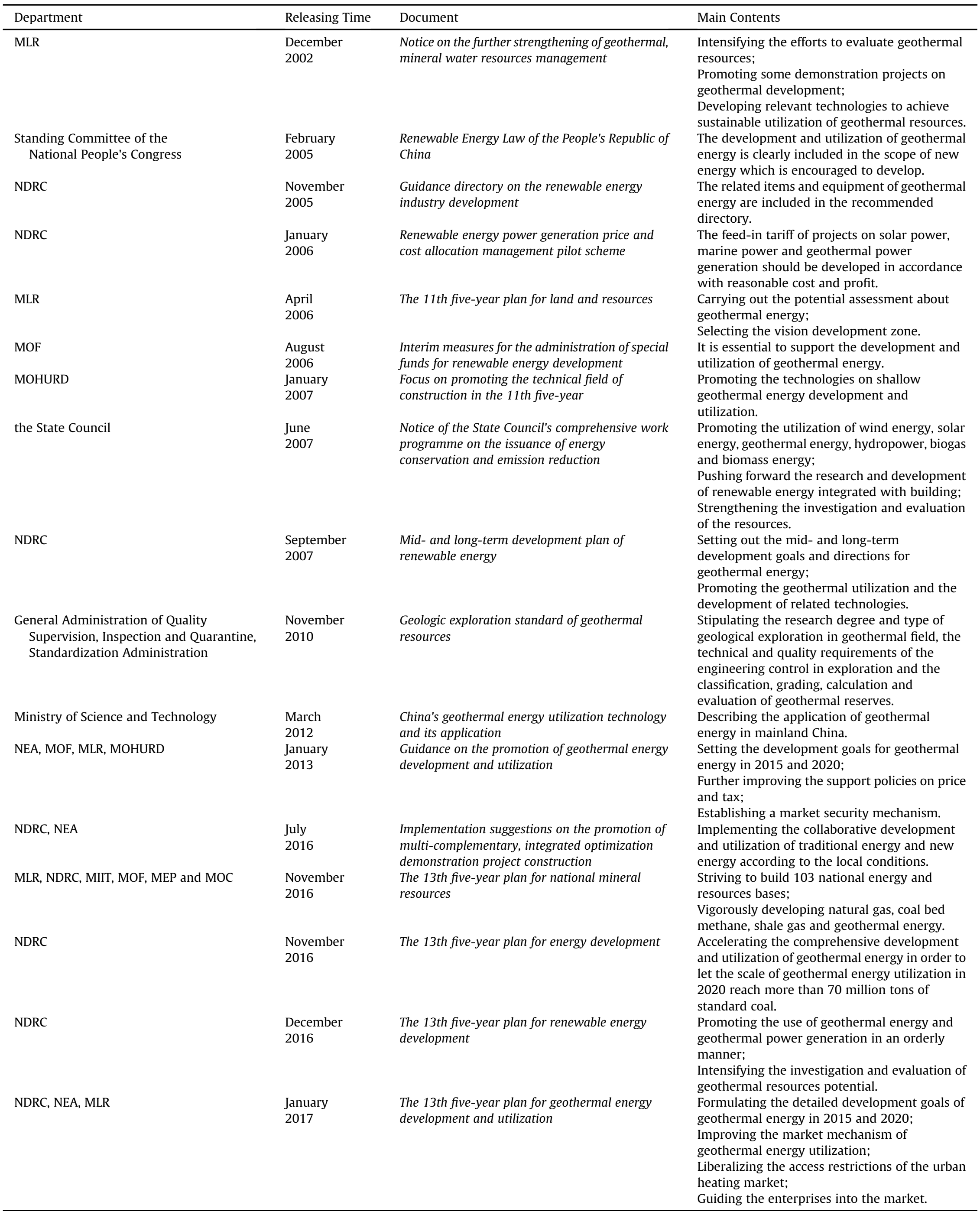
Hou *et al*. (2018)[57] also recommended that the Chinese government promote the training of technical and management personnel for planning, exploration, engineering design, construction, supervision, management, operation and investment in geothermal energy projects, ideally through cooperation with leading research organisations and universities around the world. They also suggested that more Chinese universities should establish relevant training programs.

2.5.4. Regulatory framework

Promoting the direct use of geothermal heat is a key element in the development strategies of both the Chinese central government and the Beijing municipal government. At least twelve central government agencies have issued policy documents and announcements explicitly related to geothermal energy development since 2000. Hou *et al.* (2018)[57] tabulated 17 such documents, reproduced in Figure 19.

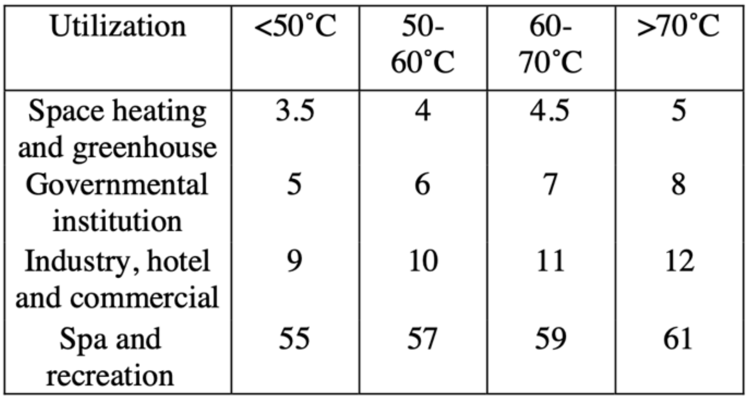
The '13th Five-Year Plan for Geothermal Energy Development and Utilization' (released in January 2017 but covering the period 2016–2020) recommended increasing the total floor area of geothermal space heating in Beijing from < 5 million square metres in 2015 to 30 million square metres by 2020[57]. The plan also recommended that to reach the target the government could consider market instruments such as franchise tender systems and public-private-partnerships for geothermal energy development, simplify access to the urban heating market, and actively encourage private enterprise into the market[57]. In spite of the recommendations, however, figures published by Tian *et al.* (2020)[68] suggest that the area of space heating from geothermal aquifers in Beijing is yet to significantly increase from 2015 levels.

The Beijing municipal government has also implemented policies aimed at increasing geothermal energy utilisation, driven by a need to address both energy shortages and air pollution in the city (Jiang *et al.*, 2019[69]). The Beijing Geothermal Management Regulation was put into operation in 2001, defining the roles and responsibilities of several divisions and institutes within the BLRB and the Beijing Bureau of Geology and Mineral Exploration and Development with respect to managing geothermal resources[66]. The BLRB was assigned responsibility for "(1) the procedure of tariff submission for geothermal exploration and utilization; (2) permit process for geothermal exploration and utilization; (3) the requirements for geothermal well drilling and related data and document acceptance; (4) the limitation of geothermal water extraction of each user and monthly reporting of temperature, water level and amount of geothermal water extraction; (5) measuring of production temperature and amount; (6) deduction of geothermal resources tariff for reinjection of return water from heating use; (7) the lower limit of return water temperature; (8) the punishment for activities breaking rules etc."[66] These regulations were critical for addressing reservoir depletion (described below) by setting tariffs on geothermal water (Figure 20), imposing production limits, and encouraging reinjection by only imposing tariffs on net production.



Department	Releasing Time	Document	Main Contents
MLR	December 2002	*Notice on the further strengthening of geothermal, mineral water resources management*	Intensifying the efforts to evaluate geothermal resources; Promoting some demonstration projects on geothermal development; Developing relevant technologies to achieve sustainable utilization of geothermal resources.
Standing Committee of the National People's Congress	February 2005	*Renewable Energy Law of the People's Republic of China*	The development and utilization of geothermal energy is clearly included in the scope of new energy which is encouraged to develop.
NDRC	November 2005	*Guidance directory on the renewable energy industry development*	The related items and equipment of geothermal energy are included in the recommended directory.
NDRC	January 2006	*Renewable energy power generation price and cost allocation management pilot scheme*	The feed-in tariff of projects on solar power, marine power and geothermal power generation should be developed in accordance with reasonable cost and profit.
MLR	April 2006	*The 11th five-year plan for land and resources*	Carrying out the potential assessment about geothermal energy; Selecting the vision development zone.
MOF	August 2006	*Interim measures for the administration of special funds for renewable energy development*	It is essential to support the development and utilization of geothermal energy.
MOHURD	January 2007	*Focus on promoting the technical field of construction in the 11th five-year*	Promoting the technologies on shallow geothermal energy development and utilization.
the State Council	June 2007	*Notice of the State Council's comprehensive work programme on the issuance of energy conservation and emission reduction*	Promoting the utilization of wind energy, solar energy, geothermal energy, hydropower, biogas and biomass energy; Pushing forward the research and development of renewable energy integrated with building; Strengthening the investigation and evaluation of the resources.
NDRC	September 2007	*Mid- and long-term development plan of renewable energy*	Setting out the mid- and long-term development goals and directions for geothermal energy; Promoting the geothermal utilization and the development of related technologies.
General Administration of Quality Supervision, Inspection and Quarantine, Standardization Administration	November 2010	*Geologic exploration standard of geothermal resources*	Stipulating the research degree and type of geological exploration in geothermal field, the technical and quality requirements of the engineering control in exploration and the classification, grading, calculation and evaluation of geothermal reserves.
Ministry of Science and Technology	March 2012	*China's geothermal energy utilization technology and its application*	Describing the application of geothermal energy in mainland China.
NEA, MOF, MLR, MOHURD	January 2013	*Guidance on the promotion of geothermal energy development and utilization*	Setting the development goals for geothermal energy in 2015 and 2020; Further improving the support policies on price and tax; Establishing a market security mechanism.
NDRC, NEA	July 2016	*Implementation suggestions on the promotion of multi-complementary, integrated optimization demonstration project construction*	Implementing the collaborative development and utilization of traditional energy and new energy according to the local conditions.
MLR, NDRC, MIIT, MOF, MEP and MOC	November 2016	*The 13th five-year plan for national mineral resources*	Striving to build 103 national energy and resources bases; Vigorously developing natural gas, coal bed methane, shale gas and geothermal energy.
NDRC	November 2016	*The 13th five-year plan for energy development*	Accelerating the comprehensive development and utilization of geothermal energy in order to let the scale of geothermal energy utilization in 2020 reach more than 70 million tons of standard coal.
NDRC	December 2016	*The 13th five-year plan for renewable energy development*	Promoting the use of geothermal energy and geothermal power generation in an orderly manner; Intensifying the investigation and evaluation of geothermal resources potential.
NDRC, NEA, MLR	January 2017	*The 13th five-year plan for geothermal energy development and utilization*	Formulating the detailed development goals of geothermal energy in 2015 and 2020; Improving the market mechanism of geothermal energy utilization; Liberalizing the access restrictions of the urban heating market; Guiding the enterprises into the market.

Figure 19*. Policy documents and announcements from Chinese central government agencies between 2000 and 2017 relating to geothermal energy utilisation. MEP = Ministry of Environmental Protection, MIIT = Ministry of Industry and Information Technology, MLR = Ministry of Land and Resources, MOC = Ministry of Commerce, MOF = Ministry of Finance, MOHURD = Ministry of Housing and Urban-Rural Development, NDRC = National Development and Reform Commission, NEA = National Energy Administration. Source: Hou et al. (2018)[57].*



Utilization	<50˚C	50-60˚C	60-70˚C	>70˚C
Space heating and greenhouse	3.5	4	4.5	5
Governmental institution	5	6	7	8
Industry, hotel and commercial	9	10	11	12
Spa and recreation	55	57	59	61

Figure 20*. Tariffs set on geothermal water production in 2004 by the Bureau of Land and Resources of Beijing. Note that the tariff (Chinese yuan per kilolitre) is a function of water temperature and end use. For comparison, 1.00 Yuan = 0.1991 AUD on 22 April 2021. Under this system, the Gippsland Regional Aquatic Centre would be charged A$11.75 per kL for geothermal water consumed. Source: Liu et al. (2010)[66].*

In spite of the relatively large number of policy documents pertaining to geothermal energy, Wang *et al*. (2020)[63] believe that a "lack of policy support has become a key factor in limiting the development and utilization of geothermal energy in China" because "the industrial development of geothermal energy in China is suffering from bottlenecks in terms of stagnant technological development, unclear policies and regulations, high power generation costs, and environmental concerns." They recommended that further development of consistent policies in the areas of geothermal resource regulation, technological advancement, investment financing, and environmental protection would "help realize the scaled development of geothermal energy, optimize the national energy structure, further promote the energy supply revolution, and better promote the strategic transformation and sustainable development of China's energy industry." Other sources express similar frustrations that the current level of usage of geothermal energy in Beijing is much lower than the resource could support.

2.5.5. Socio-enviro-economic factors

Transforming Nangong into a 'geothermal village' in the early 2000s had a profound impact on its 2,700[55] residents and the local rural economy. Every resident transitioned from supporting a traditional farming economy to contributing to one of the geothermal businesses. Annual economic output and average per capita income both rose significantly.

Many sources consistently identify water depletion from the reservoirs as a major environmental issue related to geothermal energy production in Beijing. Zhou *et al*. (2008)[56] documented the decline of groundwater levels in the Xiaotangshan subfield. They reported the natural discharge from the Xiotangshan spring as 4.4 L/s of 52°C water in the 1950s. Production of geothermal water from pumped wells in the Wumishan Group aquifer began at Xiaotangshan in 1975 and reached an average of 27 L/s by 1985. Drilling continued and total production accelerated to 49 L/s in 1992, 75 L/s in 1999, and 120 L/s in 2004. Natural discharge from the hot spring ceased by the mid 1980s as the water level of the aquifer fell. The water level stood at 3.4 m below ground level in 1985, 13.7 m below ground level in 1992, and 30.7m below ground level in 1999. By 2008, the water level was reportedly[56] around 40 m below ground level and descending at a rate of about 2 m per year, although there had been no measureable reduction in water temperature over time. Axelsson (2010)[70] provided a chart showing production rate and water level for the "Beijing Urban geothermal system" (probably equivalent to the Dongnanchengqu subfield) between 1979 and 2003 (Figure 21). The trend of declining water level is consistent with ongoing year-on-year decline.

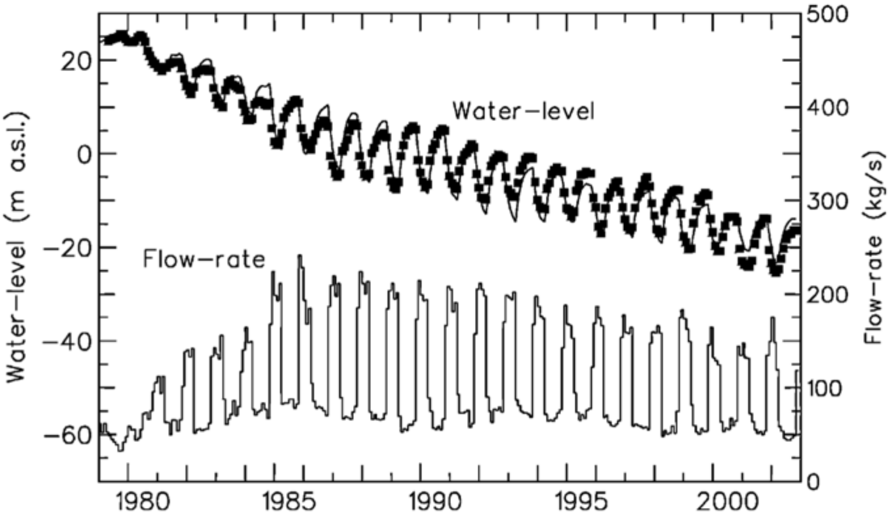


Figure 21. *Water level and production rate data for the "Beijing Urban geothermal system" from 1979 to 2003. Source: Axelsson (2010)[70].*

Liu *et al*. (2010)[66], however, reported data from a monitoring well in the Xiaotangshan subfield indicating a reversal of the reservoir decline from about 2004 as a result of reinjection. At that time there were six wells reinjecting 57% of the water produced from eight production wells in the Xiaotangshan subfield. By 2006, the water level was about 5 m higher than in 2004 (Figure 22) and was still rising in 2007. Jiang *et al*. (2018)[64] presented a chart (Figure 23) showing a continuing decline in net groundwater consumption as a result of increasing injection of spent geothermal water since the early 2000s. The effect of reinjection on maintaining water levels in the Dongnanchengqu subfield, however, was “not very obvious” yet in 2010[66].

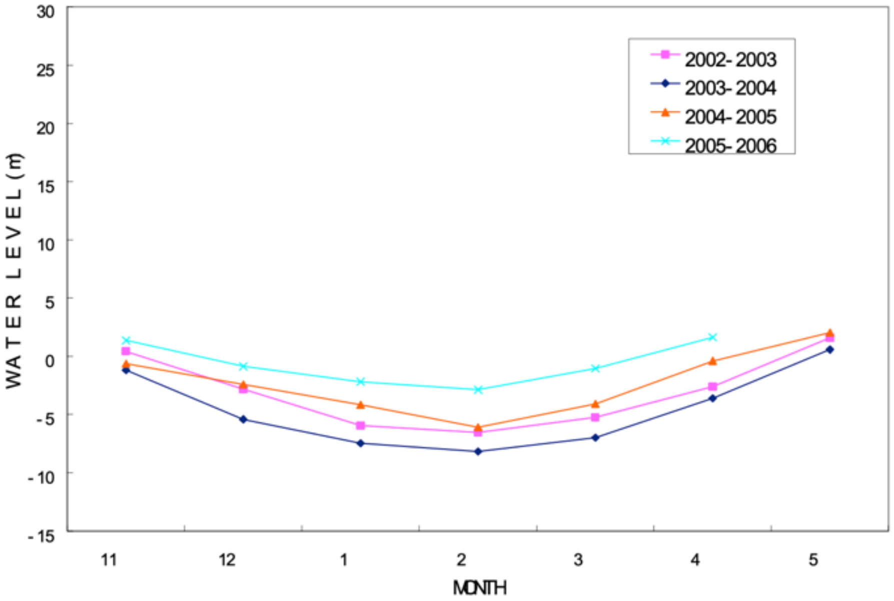


Figure 22. Water level in a monitoring well over four years in the Xiaotangshan subfield. Source: Liu et al. (2010)[66].

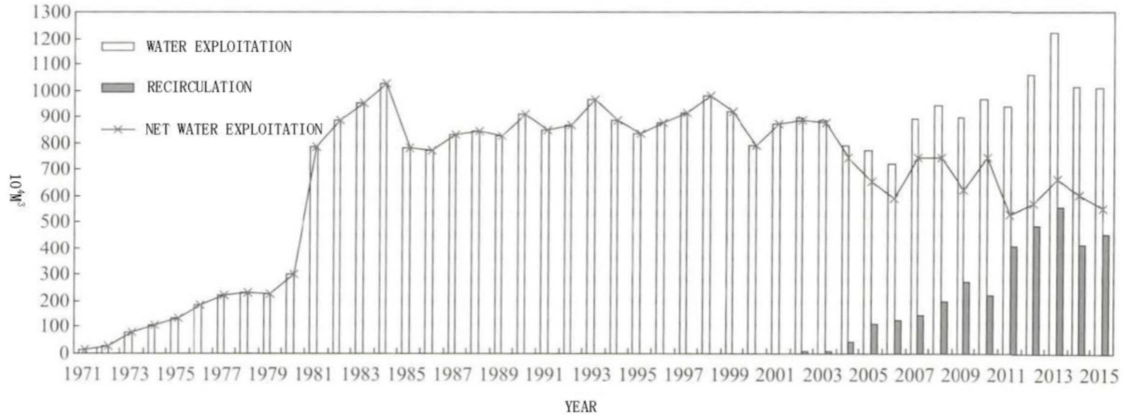


Figure 23. Annual geothermal water production, reinjection, and net consumption (x 10^4 m^3) across Beijing from 1971 to 2015. Source: Jiang et al. (2018)[64].

Jiang *et al*. (2019)[69] reported the results of a study of the economic impacts of the geothermal sector in Beijing. They investigated the local economic stimuli delivered by both the ‘pull’ effects that the geothermal sector has on other sectors providing goods and services to geothermal projects, and the ‘push’ effects of the geothermal sector providing products to other sectors. They concluded that the geothermal sector has “great demand-pulling and supply-promoting effects on the regional economy and…a strong association with other sectors." The sectors upon which geothermal projects delivered the greatest stimuli included electricity and heating sectors; equipment manufacturing; the geothermal sector itself (geothermal projects often consume their own products); and the real estate sector. Furthermore, they found that a strong geothermal sector could trigger structural changes to promote the utilization of renewable energy in other sectors.

2.5.6. Key Contact

Prof Zhonghe Pang, Director of Geothermal Research Centre, Institute of Geology and Geophysics, Chinese Academy of Sciences—z.pang@mail.iggcas.ac.cn

2.6. Hornonitrianska kotlina Basin—Slovakia

The Hornonitrianska kotlina Basin is in central Slovakia in Eastern Europe. It underlies the territory of Upper Nitra, which includes the districts of Partizánske and Prievidza covering 1,261 km^2 of the administrative region of Trenčín (Figure 24). As a traditional brown-coal mining and power generation territory, the Upper Nitra territory shares some striking similarities with the Latrobe Valley. It covers a similar area (Latrobe City = 1,426 km^2) within which four brown coal mines have provided fuel exclusively to the 266 MWe Nováky Power Plant since the plant was commissioned in 1953. The mines employ about 4,000 people directly and 11,000 indirectly[71].

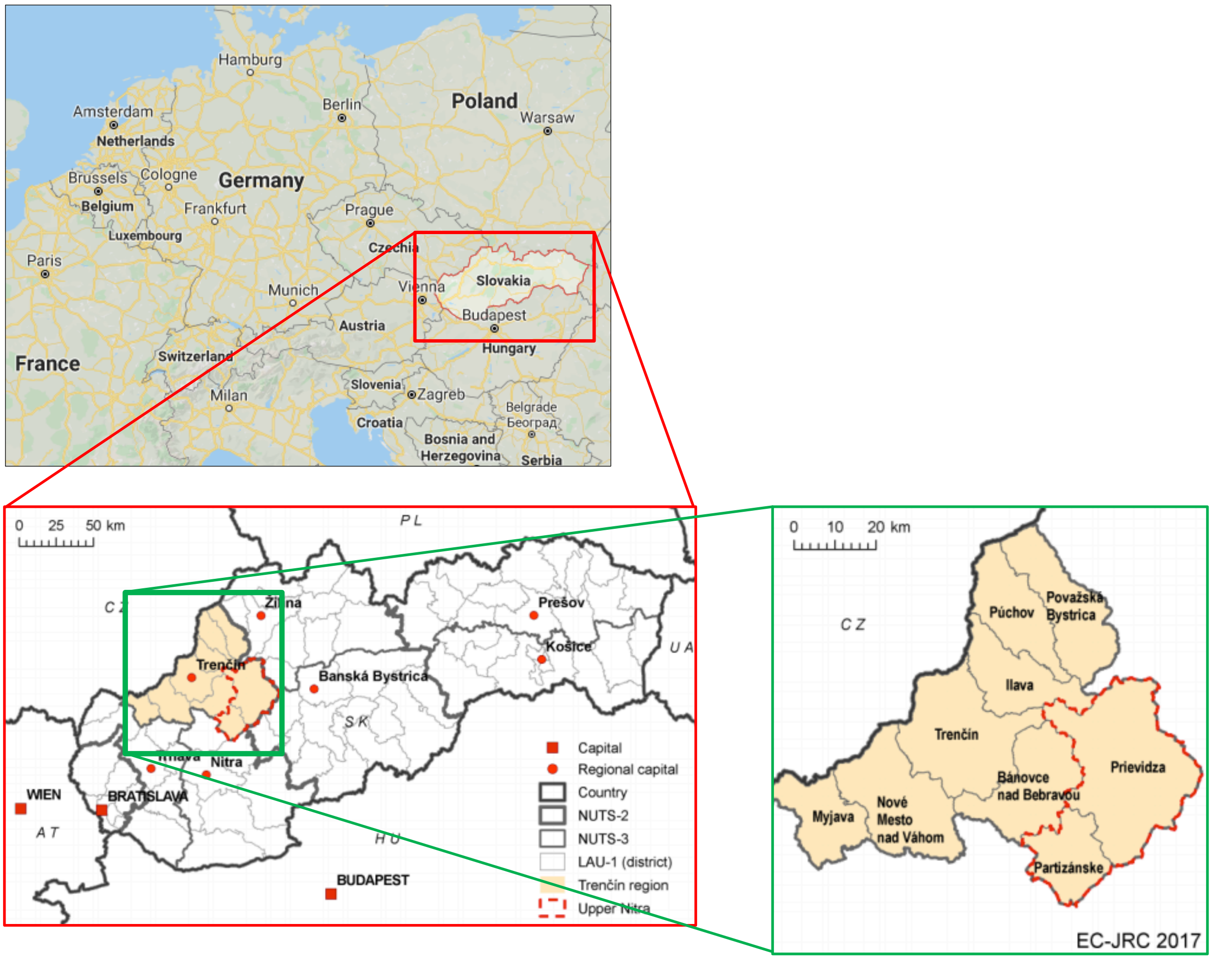


***Figure 24**. The Upper Nitra territory (red dashed outline) of the Trenčín administrative region of Slovakia in Eastern Europe. Modified after JRC (2018)[72].*

Coal-fired power production, however, became uneconomic in the region in the mid-1990s. The Slovakian government began subsidising brown coal mining at that time to delay dramatic increases in unemployment in the territory. The subsidies are scheduled to end by 2023. The first mine closed in 2017 and the remaining three are expected to close along with the coal-fired power plant by 2027.

Except where other sources are specifically cited, most of the information in the rest of Section 2.6 can be attributed to direct communication with Branislav Fričovský of the State Geological Institute of Dionýz Štúr (Bratislava) on 10 June 2020.

2.6.1. Geothermal aquifers

The geothermal aquifers of the Hornonitrianska kotlina Basin are hosted in Mid Triassic dolomite and Mid Triassic to Jurassic limestone beneath an overlying Tertiary sequence. The dolomite reaches a maximum thickness of about 800 m in the centre of the basin, but is typically 300–600 m thick elsewhere (Fendek *et al.*, 2004)[73]. The limestone is 200–300 m thick in the northwest (Franko *et al.*, 2009)[74], but its maximum thickness remains uncertain because production in the centre of the basin is only from the uppermost unit.

Reservoir temperature increases towards the central part of the basin along with the thickness of Tertiary overburden. Typical reservoir temperatures are 22.5–32.5°C at 500 m depth, increasing to 50–65°C at 1,500 m. Temperatures at aquifer depths greater than 3000 m are in the range 80–100°C (Remšík, 2012)[75].

2.6.2. End users

Figure 25 shows the locations of geothermal bores currently providing water and heat to four end users in the west of the basin, and disused geothermal wells in the east (Fričovský *et al.*, 2020). The end users include the Chalmová Resort, the Bojnice Spa, the Bojnice Resort, and a small cluster at the Nováky site.

The Chalmová Resort (Figure 26) lies amongst hills several kilometres southwest of the Nováky Power Plant. The resort operates 365 days a year for recreational bathing. It has basic on-site accommodation in the form of six two-bed hostel rooms and 18 four-bed cabins. Two indoor thermal pools are fed directly by natural hot springs and are regulated to 32–34°C and 38–40°C, respectively, by blending the natural spring water with geothermal water produced from three bores. The bores range from 150 m to 217 m deep and produce 31°C to 42°C water at an average 1.2 litres per second. As well as blending with the natural spring water, the bores also feed directly into three outdoor pools[76].

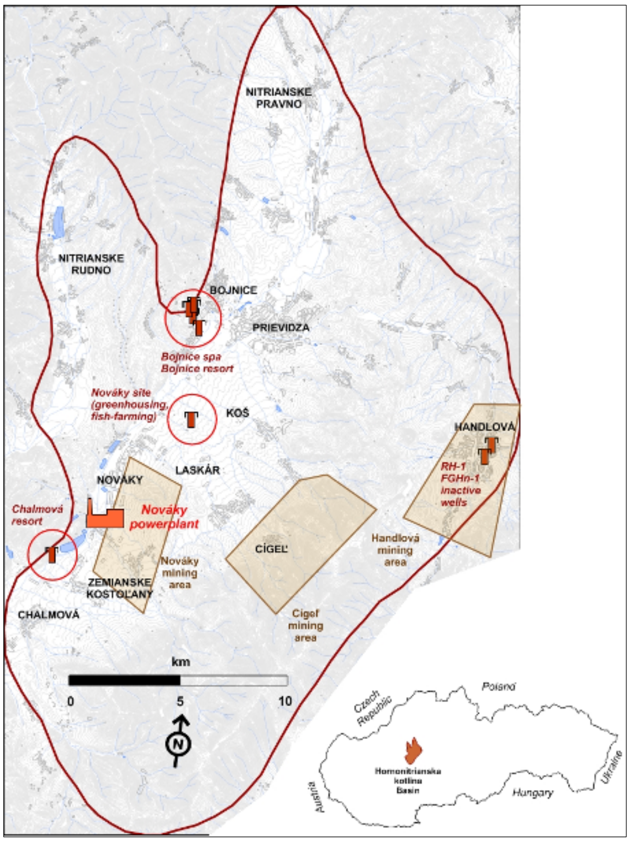


Figure 25. *Locations of the coal-fired Nováky Power Plant (orange polygon), three operating coal mining areas (brown polygons), geothermal end users (red circles), and geothermal wells (red vertical rectangles) within the extent of the Hornonitrianska kotlina Basin (red outline). Source: pers comm Branislav Fričovský (10 June 2020).*

Figure 26. *The main outdoor pool at the Chalmová thermal spa. Source: Palickap, 31 May 2008, CC BY-SA 3.0 licence.*

The Bojnice Spa in the northwest of the basin is amongst the oldest therapeutic spas in Slovakia, officially founded in the 16th Century. While initially serving only the nobility, it now provides 587 on-site beds to treat patients from all socio-economic backgrounds 365 days a year. Its thermal water is produced at a total 40 litres per second between 28° and 52ºC from nine bores between 1,200 – 1,500 meters deep, with a hydrogen-carbon-sulphate, calcic-magnesium hypotonic composition[77]. The spa specializes in treating musculoskeletal, gynaecological and occupational diseases, neurological disturbances, and urinary disorders with the thermal waters.

Adjacent to the Bojnice Spa, the Bojnice Resort comprises a set of open-air heated pools and water slides for public recreation. Two bores feed the pools with 39–40°C water at a mean total rate of about five litres per second.

Agro GTV, a subsidiary of the company that operates the region's three coal mines, also utilizes geothermal energy from a single bore to the north of the Nováky mining area. The bore produces 59°C water year round at a mean rate of about seven litres per second. The primary purpose of the bore was to warm the air in the lignite mines and the company offices, and pearl oyster mushrooms are grown in the controlled underground climate. Since 2010[78], however, geothermal production has expanded to utilization in greenhouses (primarily for tomatoes) and catfish farming in a cascaded manner. The spent water is rejected at 38°C. A mini-documentary about the greenhouse operation can be viewed (in Slovakian) on YouTube[79]. A food processing facility added in 2017 produces fish and mushroom pastes from the geothermally cultivated products[78].

2.6.3. Research and training

Fričovský *et al*. (2020)[80] reported that there are no dedicated courses on geothermal energy in Slovakia. However, lessons on the natural causes and distribution of geothermal energy sources are included within other courses by the Department of Hydrogeology in the Faculty of Natural Sciences, Commenius University in Bratislava. Furthermore, courses on technologies for utilizing geothermal energy are delivered at Technical University of Žilina and Slovak Technical University in Bratislava.

Fričovský *et al*. (2020)[80] further reported that state-run institutions, such as the Dionýz Štúr State Institute of Geology operated by the Ministry of Environment of the Slovak Republic, were solely responsible for locating and characterising geothermal energy resources until the end of the 20th century. Since then, however, a rapid transition in geothermal energy development and utilization in the country has seen private investors make major contributions to drilling and exploration, in both R&D and in practice. For example, Slovak company, GA Drilling, claims that its “PLASMABIT® drilling technology will enable efficient access to baseload and high temperature heat sources (300–400 °C) up to 10 km below the earth's surface.”[81]

There is currently no coordinating platform in Slovakia for academia and research institutions to collaborate with private sector industry.

2.6.4. Regulatory framework

Fričovský *et al*. (2020)[80] summarised the Slovakian legislative framework for geothermal energy. Exploration for geothermal resources is regulated by the Ministry of the Environment under the Geological Act No. 569/2007 Coll., as amended by Act No. 311/2013 Coll., which states that the allowable production from individual wells must be assessed based on long-term pumping tests, estimation of hydraulic, physical-chemical properties of water, and must include qualitative and quantitative monitoring (Fendek *et al*., 2016)[82]. Licences for geothermal water production (including withdrawal limits and fees) are regulated by the Water Act No. 364/2004 Coll. and later amendments (Fendek *et al*., 2015)[83]. The integration of renewable energy sources (including geothermal) into the national energy strategy is legislated through amendments to Act No. 309/2009 Coll. for Support of Renewable Energy Sources and Highly Efficient Combined Production (latest amendment No. 377/2018 Coll). This review found no evidence that injection of spent geothermal water is required under legislation.

2.6.5. Socio-enviro-economic factors

Some view geothermal energy as a possible driver for growth in new industries to offset the looming employment crisis associated with the closure of the brown coal mines and power plant, but there remains no official transition plan. In late 2017, for example, Energy Union boss Maroš Šefčovič (the Slovakian representative to the European Commission) talked up the potential for a transition to geothermal energy in the Upper Nitra region, even while the Slovakian Prime Minister was promising a future for the brown coal mines[84]. Commissioner Šefčovič’s advocacy paid dividends with the Upper Nitra region being chosen as one of three regions in Europe for an EC funded pilot study into the best methods to manage the socio-economic transformation of coal regions[72]. The study included a specific focus on geothermal power generation, and also concluded that a smart specialisation strategy was the best instrument to apply to the transition challenge.

The Bojnice Spa is central to the self-identity of that town. The spa is considered one of the most prestigious and popular in the country, benefiting from its close proximity to tourist attractions such as Bojnice Castle, the largest zoo in Slovakia, and scenic hiking trails. However, specific data on employment and visitations to the spa could not be obtained for this report. Neither could visitor numbers be obtained for the Chalmová or Bojnice Resorts.

The local community supports the cascaded geothermal energy system operated by the coal mining company at Nováky. The agriculture, aquaculture and food processing businesses directly employ tens of workers, and all produce is sold into the domestic market. Given the success of these small scale operations, the company is planning a dramatic expansion of its geothermal agriculture business over the coming few years to ease the impact on local employment after the mine is shut-down.

The reliance of several users on a single aquifer system, along with no apparent requirement to inject spent water, is already causing interference and tension between the different users. These conflicts could rapidly escalate if the geothermal industry expands within the current regulatory regime. For example, a progressive reduction in aquifer pressure has already been observed in the geothermal bores feeding the Bojnice Spa since geothermal water production increased at Nováky in 2010.

There is also concern about possible hydraulic communication between a coal-ash settling pit for the nearby power plant, and the geothermal aquifer feeding the Chalnova Resort. A barrier was installed between the pit and the resort in 2014 to limit the extent of groundwater contamination.

2.6.6. Key contact

Ing. Branislav Fričovský, Department of Hydrogeology and Geothermal Energy, Division of Geology, State Geological Institute of Dionýz Štúr, Bratislava—branislav.fricovsky@geology.sk

2.7. Polish Lowlands—Poland

Poland is about 37% larger in area than the state of Victoria, with the flat sedimentary plains of the Polish Lowlands covering almost 90% of the country.

2.7.1. Geothermal aquifers

Lower Cretaceous and Lower Jurassic sandstone formations within the Mogilno-Łódź and Warsaw Troughs underlying a portion of the Polish Lowlands are geological analogues for the geothermal aquifers beneath Gippsland in that they produce water in the 30–80°C temperature range (Figure 27), commonly at 50–100 L/s per bore. The Polish aquifers, however, are much deeper than the Gippsland analogues; generally greater than 2,000 m (Figure 28).

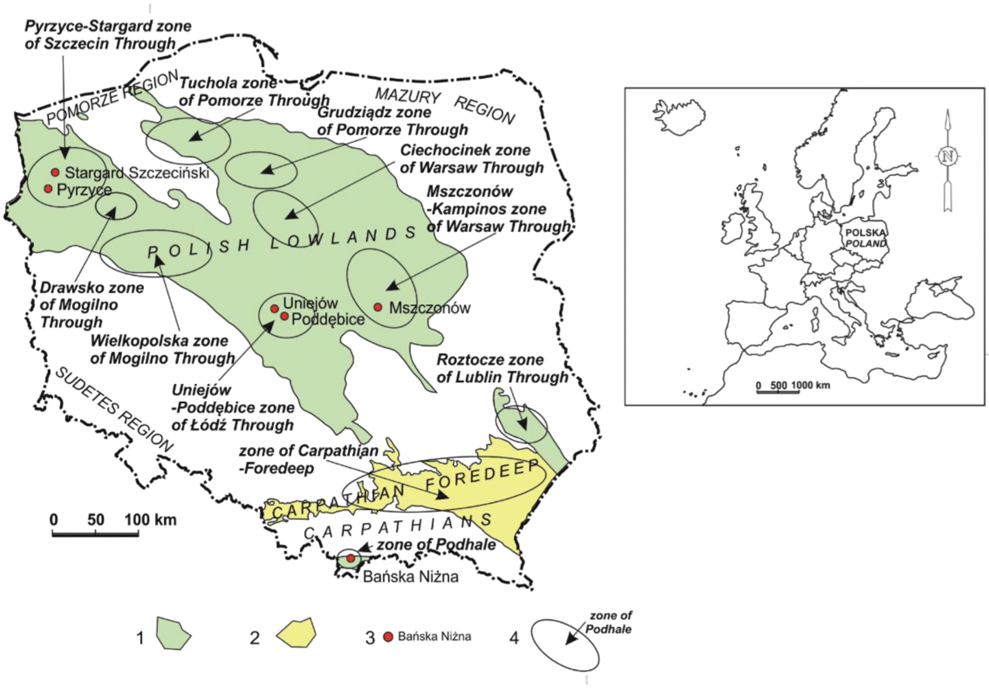


Figure 27*. Extent of Lower Cretaceous and Lower Jurassic geothermal reservoirs >30°C (green area), with particularly favourable zones circled (After Skrzypczak et al., 2020[85]).*

2.7.2. End users

The dominant use of the geothermal resources in the Poland Lowlands is for space heating through five centralised district heating systems (Skrzypczak *et al.*, 2020[85]; Kępińska, 2020[86]). Other individual users include six recreation centres (with four more in development as of 2018), six health resorts, an Atlantic salmon farm, and a heating system for a soccer pitch and walking paths[86]. Figure 29 shows the distribution of users across the Polish Lowlands (and the rest of Poland). There is not yet any user in the agriculture sector, although interest in agricultural applications was reportedly growing in 2020.

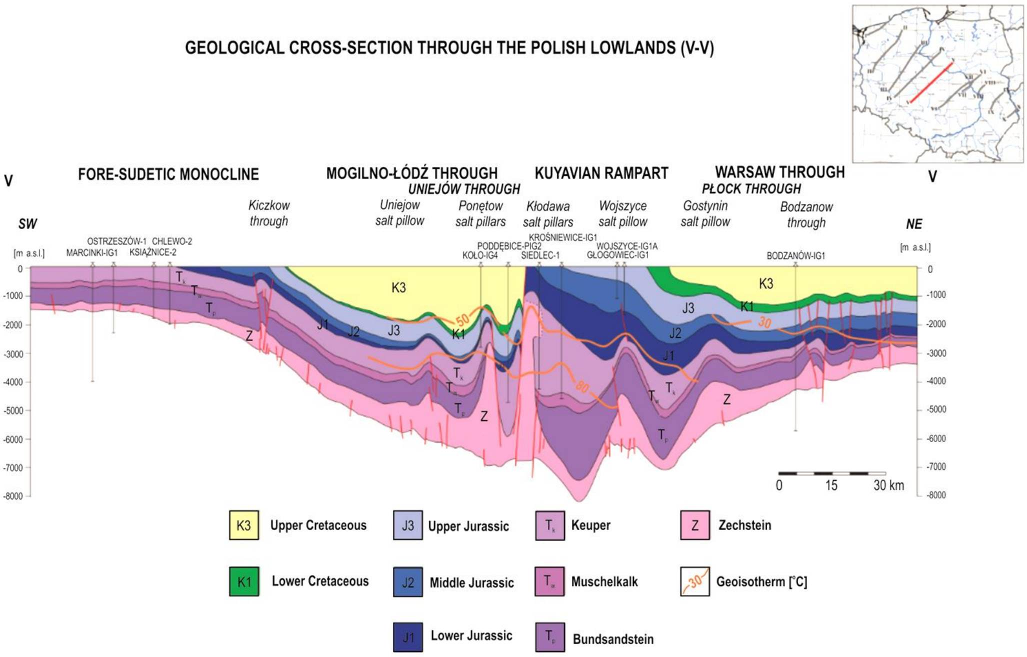


Figure 28. Cross-section through central part of Polish Lowlands showing the Lower Cretaceous (green, K1) and Lower Jurassic (indigo, J1) aquifer formations and inferred 30°C, 50°C and 80°C isotherms. After Skrzypczak et al., 2020[85].

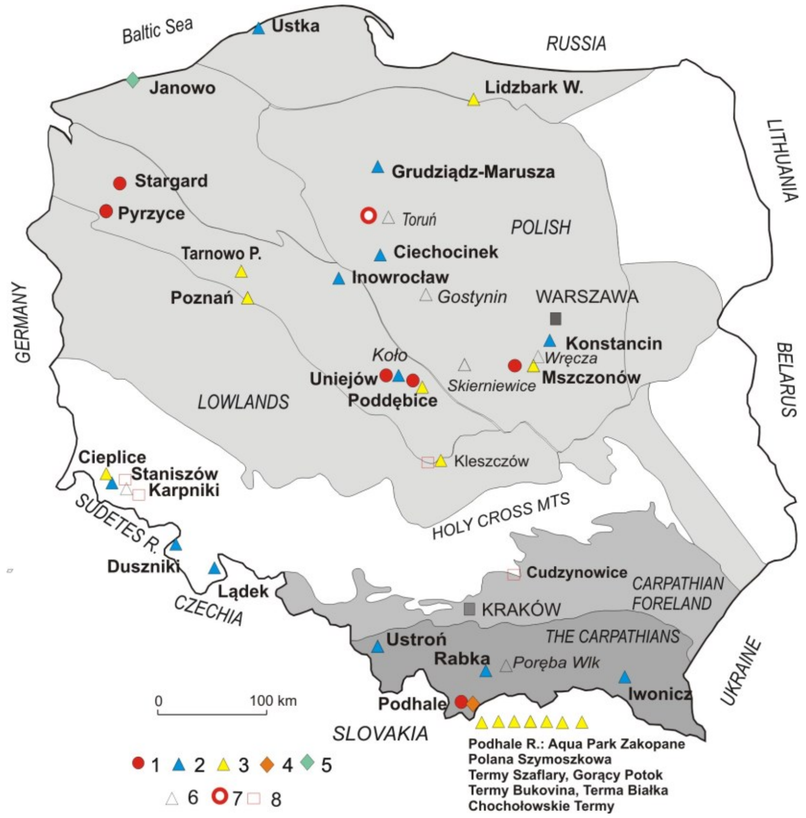


Figure 29. Geothermal energy projects in the Poland Lowlands (light grey area) and the rest of Poland in late 2018: 1. district heating plants, 2. health resorts, 3. recreation centres, 4. wood drying, 5. fish farming, 6. recreation centres in development, 7. district heating systems in development, 8. individual heating systems. After Kępińska (2020)[86]

Kępińska (2020) provided details of the five district heating systems, the oldest of which has been operating at Pyrzyce since 1996. The Pyrzyce plant supplies heat and domestic hot water to >90% of the town's population of 13,000 and meets about 60% of their total heat demand. The geothermal system was upgraded in 2017/2018 with a new well producing up to 55 L/s of 65°C water. All four older wells (two production and two injection) are now injection wells.

The Mszczonów district heating plant began operating in 2000, drawing a maximum 16.6 L/s of water at 42.5°C from a single well. The fresh (500 ppm mineralisation) water is used for drinking when cooled, while part of the warm water flow also supplies the Termy Mszczonów recreation centre. Research was ongoing into more efficient geothermal water and energy management, including a project looking at reinjection into shallow aquifers.

The Uniejów district heating plant began operating in 2001, drawing a maximum 33.4 L/s of 68°C water from a single well. In 2018, the plant supplied heat to about 80% of all the town's buildings. Portions of the used geothermal water are cascaded into a spa and recreation centre (up to 27.8 L/s at 42°C water), and a system to heat a soccer pitch and walking paths (8.3 L/s at 28°C).

The Stargard district heating plant began operating in 2012 after renovation of an older plant, drawing on a single geothermal well producing up to 50 L/s of 87°C water, and disposing of the spent water into a single injection well (note that this system produces hotter water than expected from the Gippsland Tertiary aquifers.) While the plant provided the entire heat demand for 75% of the town's population of 75,000 people, the geothermal system contributed only 27% of that heat, with the other 73% derived from thermal coal. In 2019, however, the operator of the geothermal plant began to drill four new wells to double the geothermal capacity and heat sales into the municipal district heating system.

The Poddębice district heating plant began operating in 2013, using fresh (400 ppm) water at an average rate of 32.2 L/s at 68°C from a single well. The plant supplies heat to public buildings, a school, a hospital, and multiple family homes. The well also supplies water and heat to swimming pools, and a large balneological health resort is in the planning stage.

Elsewhere, geothermal water in the 28–80°C range supplies heat for a school complex, hotel buildings, spa facilities, swimming pools and health spas in several localities. Also, several recreation centres have individual geothermal heating systems. Collectively, these applications are estimated to draw at least 11 MW_{th} of thermal power and consumed 100 TJ_{th} of geothermal heat in 2018, equivalent to AU$500k of natural gas at AU$5/GJ.

2.7.3. Research and training

Kępińska (2020)[86] reported approximately 30 full time professional research / teaching staff employed by Polish universities on the subject of geothermal energy in 2019. Some of these were focussed on fundamental domestic research topics such as geothermal water desalination; injection of spent geothermal water into shallower water horizons; geothermal uses in agriculture; aquifer/underground thermal energy storage; and energetic optimisation of geothermal systems. Others were participating in international research projects supported by the European Union.

2.7.4. Regulatory Framework

Geothermal development in Poland is largely regulated through provisions within the Geological and Mining Law (Kępińska, 2020)[86]. The Renewable Energy Sources Law (2018) focusses mostly on electricity generation rather than the heating and cooling sector. Work has begun, however, on a development strategy for the heating sector, which will take renewable energy sources including geothermal into account. Other state policy and strategy documents referring to geothermal energy (either directly or included as a valid renewable energy source) include the Strategy for Responsible Development (www.miir.gov.pl/strony/strategia-na-rzecz-odpowiedzialnego-rozwoju/) and the State Raw Materials' Policy (www.psp.mos.gov.pl). Geothermal heating might also be included in programs dedicated to retrofitting heating systems and improving air quality.

A Polish government program was introduced in 2015/16 to provide about 200 million PLN (Polish Zloty; ~AUD 69 million in April 2021) in grants (up to 100%) for geothermal research drilling, and 500 million PLN in loans (up to 40–50 % of eligible costs) for investment in geothermal infrastructure. The program stimulated rapid growth in the geothermal heating sector, resulting in 12 new exploration and research wells and three new production wells drilled in the Polish Lowlands up to and including 2019 (with another 10 in the planning stage). The program was extended with another 600 million PLN in 2019.

2.7.5. Socio-enviro-economic factors

Combined energy sales in 2018 from the five geothermal district heating plants totalled more than 360 TJ_{th}, comprising:

- 57 TJ_{th} at Pyrzyce,
- 15.5 TJ_{th} at Mszczonów,
- 9.6 TJ_{th} at Uniejów,

- 230 TJ_{th} at Stargard, and
- 50 TJ_{th} at Poddębice.

This would offset almost AU$1.8 million and avoid 18,500 tonnes of CO_2 emissions from natural gas combustion at AU$5 per GJ.

Pająk & Bujakowski (2018)[87] examined the tariff price of heat for space heating and hot tap water (which includes the cost of generation, transmission and distribution) as approved by the Polish Energy Regulatory Office up to September 2018. They found that the price of geothermal heat was similar to thermal ('hard') coal when the geothermal source was hot enough to use directly, and similar to natural gas and heating oil when a heat pump was required to boost the temperature of the geothermal fluid.

Kurek *et al*. (2020)[88] examined the link between geothermal-based tourism and regional development in Poland. They concluded that 'geothermal water parks' measurably accelerated the socio-economic development of each of the regions they examined. Remarks by Noviello and Smętkiewicz (2019)[89] regarding the "spectacular socio-economic development as a result of the use of geothermal waters for balneotherapeutic, recreational and energetic purposes" at Uniejów are also highly relevant. They observed that while "thermal infrastructure has become a driving force for development in the socio-economic and functional-spatial spheres, not just the existence of geothermal waters, but also the appropriate public awareness with regard to their use contributed to long-lasting transformation and sustainable development. A key factor is also the local policy conducted by the municipality: an innovative, strategic and long-term development plan. It was an original impulse that triggered a series of positive changes, through which the municipality changed its nature from a situation of stagnation, collapse and lack of prospects of development. The direction of development of the locality was taken by a group of people with a high degree of awareness of the potential that ought to be discovered and used. Such people had a visionary and prospective view of the future, based on sustainable development and effectively used the possibilities of financial and substantive support as well as the chances of cooperation based on the exchange of knowledge and experience."

2.7.6. Key contact

Beata Kępińska, Department of Renewable Energy and Environmental Research, Mineral and Energy Economy Research Institute of the Polish Academy of Sciences—bkepinska@interia.pl

2.8. Other examples

The seven examples of regional development based on 30–70°C geothermal aquifers described in detail above are not constitute an exhaustive list. Five more examples are listed below, albeit described in less detail due to limited public domain information and time constraints. There are almost certainly other examples around the world that this scan failed to identify.

2.8.1. Georgia

Georgia is a former Soviet republic at the eastern end of the Black Sea in the Caucuses. Its known geothermal aquifers have temperatures in the range 33°C – 101°C and lie at 1,500–3,000 m depth in two regions; Samegrelo in the west, and around the capital, Tbilisi, in the southeast (Figure 30). The following information is summarized entirely from Melikadze *et al*. (2021)[90].

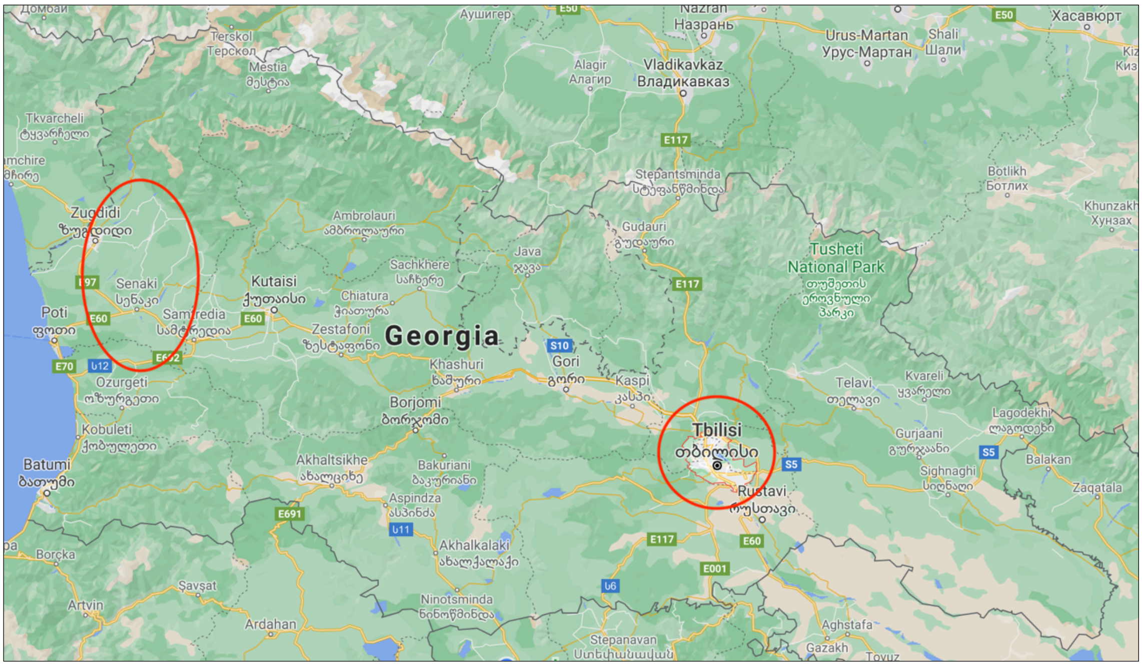


Figure 30. *Georgia, showing the approximate locations of the known geothermal aquifers (red ellipses).*

Development of Georgia's geothermal energy resources began in 1973 with the supply of hot water to residents of Tbilisi. All geothermal drilling, however, ceased in the early 1990s with the collapse of the Soviet Union. Maintenance also ceased in western Georgia, resulting in the failure and loss of every prior geothermal system in that region. Some private operators have developed new systems since then. In Tbilisi, supply of geothermal domestic heat was continuous, but at low efficiency.

Since 1991, the Government's contribution to rebuilding a geothermal sector has been limited to the creation of a legal and regulatory framework. Rights to geothermal water are regulated by

Resolution No 136 (‘Approval of the Regulations on the Rules and Conditions for Granting a Mineral License’, passed on 11 August 2005) mandates that exploration and production of geothermal water requires a license issued by the Ministry of Environment and Natural Resources Protection following an auction. Current (2020) production of geothermal water is estimated at about 22 GL per year from private bores. The geothermal energy is used for agriculture (mainly greenhouses) – 50%; residential heating – 30%; hot water supply for spa resorts, public baths and fish farms – 17%; and balneology – 3%. There is no obligation to reinject.

Regional assessment of Georgia’s geothermal potential has been left largely to academia and industry associations supported by donor agencies such as USAID and UNDP. One such study by the Georgian Geothermal Association determined that if production of geothermal water in Zugdidi area in western Georgia remains at the current level (0.1 ML/day), the amount of available heat will be reduced by 30%. The study recommended that world’s best practice for reinjection be adopted to halt and reverse the pressure drop.

Further recommendations by the Georgian Geothermal Association aimed at developing a pipeline of geothermal investments include: (i) development of a national Strategy/Action Plan/Road Map for the geothermal industry; (ii) a national geothermal resource assessment; (iii) identification of optimum technologies for residential heating and hot water supply (highest priority), greenhouses (high priority), and power generation (lower priority); (iv) feasibility studies based on the implementation of small-scale pilot projects utilising technologies identified under recommendation (iii); (v) setting of strategic development targets and corresponding policy instruments to achieve the targets; (vi) evaluation of the feasibility of projects based on the pilot projects, and introduction of short-term financial support mechanisms to ensure the financial, technical and environmental sustainability of the most promising project types.

Key contact: George Melikadze, President Georgian Geothermal Association—melikadze@gmail.com

2.8.2. Paraná Basin, Brazil

The Paraná Basin covers about 1.5 million square kilometres of Brazil, Argentina, Paraguay, and Uruguay; about 75% within Brazil. The basin hosts extensive aquifers within the temperature range of interest for this report. While geothermal systems are likely operating in Argentina, Paraguay and Uruguay, this section focusses on uses in Brazil (Figure 31) and draws heavily from material published by Vieira *et al*. (2015)[91] and Vieira *et al*. (2021)[92].

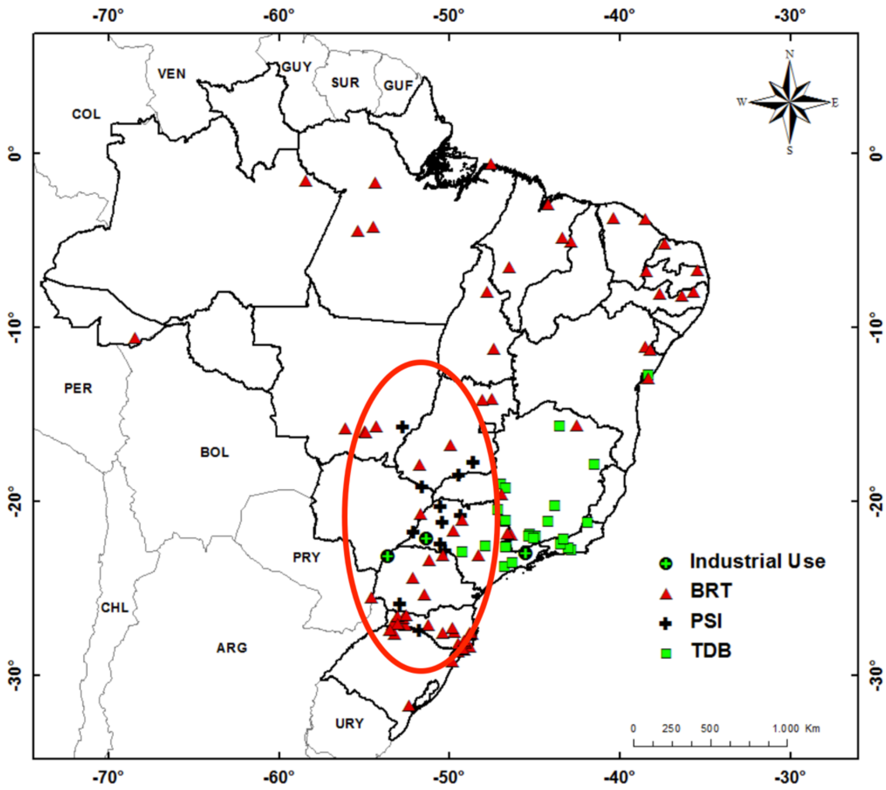


***Figure 31**. Locations of operating and potential geothermal systems in Brazil in 2015. The red ellipse shows the approximate outline of the Paraná Basin. Symbols denote different uses for the geothermal energy. BRT = bathing, recreation and tourism; PSI = potential for industrial use and space heating; TDB = therapeutic, drinking and bathing. After Vieira et al. (2015)*[91].

At least 77 individual geothermal systems drawing on water in the 30–60°C range are operating in the state of Paraná. The great majority of these are geothermal spas and resorts (e.g. Figure 32), which have become popular tourist destinations over the last few decades and attract an estimated 1.5 million visitors each year. The emphasis is on both entertainment and wellness in relaxing environments. As well as the direct financial benefits to the spa and resort owners, the operations also provide significant economic boosts to their local regions.

Cumulatively, the spa and resort operations are estimated to draw a total of 16 MW_{th} of geothermal power and consume about 189,000 GJ_{th} of heat annually. At AU$5/GJ, this is equivalent to offsetting AU$945,000 in natural gas consumption, and avoiding 9,700 tonnes of CO_2 emissions, per year.

There are very few direct uses of geothermal energy for industrial purposes. One of these few is in the municipality of Cornélio Procópio, where 48°C geothermal water has been used in the production of coffee powder since 1980. The water is pumped into a boiler as pre-heated feed water from a 950-metre deep well at an average rate of 8 L/s. The sources from which this information was drawn consider that there are significant opportunities to extend the use of geothermal resources in the Paraná Basin to more industrial and space heating applications.

Figure 32. *Águas Do Verê Termas geothermal spa resort in the Paraná Basin. Image from www.booking.com.*

2.8.3. Boise, Idaho

Boise is the capital and most populous city in the state of Idaho in the United States. It is home to one of the world's oldest and largest geothermal district heating networks. The system is included in this review for its longevity and continued development, although the geothermal reservoir itself is slightly hotter and geologically different to the reservoir beneath Gippsland (the geothermal reservoirs beneath Boise are in cretaceous aged fractured granitic and rhyolitic rocks associated with a major fault). The information below is sourced from Mink and Gunnerson (2021)[93] unless otherwise cited.

Boise's geothermal heating systems began with the drilling of two wells in east Boise in 1890. That system continues to service approximately 350 households and businesses today and is referred to as the Boise Warm Springs Water District. After a long hiatus, three additional, independent geothermal heating networks were constructed in the 1980s by the City of Boise, the State of Idaho, and the Veterans Administration, respectively. There are currently plans to further extend the geothermal network to provide heat to Boise State University (Figure 33).

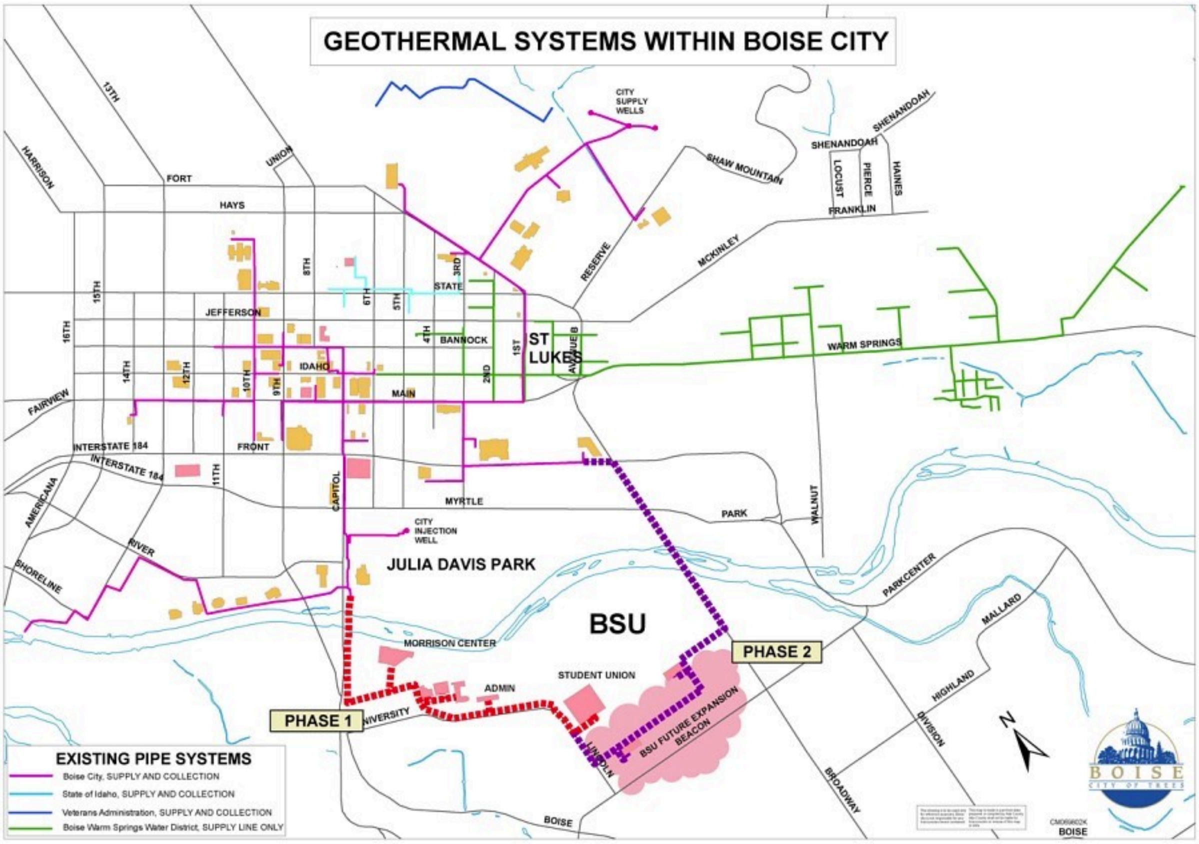


Figure 33*. Network map of Boise's four existing geothermal systems (pink = Boise City, light blue = State of Idaho, dark blue = Veterans Administration, green = Boise Warm Springs) and proposed Boise State University expansions (dashed lines). Area displayed is about 3.5 x 4.5 km. Source: Governor's Office of Energy and Mineral Resources (https://images.app.goo.gl/hhRnYU6x2oFw1yB56)*

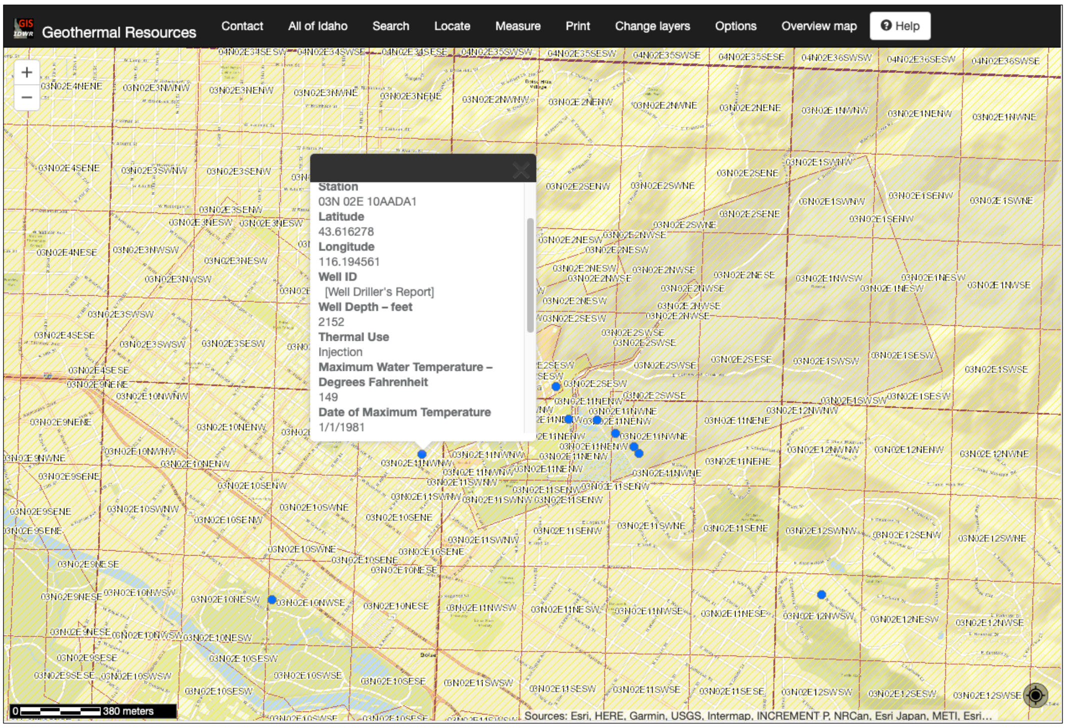
The City of Boise system draws 80°C water to heat more than 90 commercial, government, and institutional buildings. The State of Idaho system supplies heat to eleven buildings including the state capital building, the only US state capital heated by geothermal energy. The Veterans Administration system services a further 19 buildings. Combined, the four systems heat almost 700,000 m^2 of building floor area.

While dominantly used for space heating, a small number of domestic hot water systems, footpath snow-melting systems, recreational pools, laundry facilities and other users also draw geothermal energy from the networks. Of particular note, a commercial greenhouse connected to the Boise Warm Springs geothermal system in 1930 continues to provide fruits and vegetables into the local Boise market today.

To promote the continued development of geothermal heating systems throughout the state of Idaho, the Idaho Department of Water Resources within the Office of the Governor hosts and maintains a public online web portal providing information about geothermal springs and bores.

Users can find and access information about the location and characteristics of geothermal bores, including their depth, age and temperature (Figure 34).

Key contact: Leland Mink, President of MinkGeoHYdro—www.linkedin.com/in/roy-mink-26461429/



Station
03N 02E 10AADA1
Latitude
43.616278
Longitude
116.194561
Well ID
[Well Driller's Report]
Well Depth – feet
2152
Thermal Use
Injection
Maximum Water Temperature – Degrees Fahrenheit
149
Date of Maximum Temperature
1/1/1981

***Figure 34**. Closeup of Boise from the interactive map of geothermal bores and springs maintained by the Idaho Department of Water Resources (https://maps.idwr.idaho.gov/map/geothermal). The marked bore recorded a maximum 65°C at 656 m, equivalent to the bore supplying geothermal energy to the Gippsland Regional Aquatic Centre in Traralgon.*

2.8.4. Ukraine

Kondrat and Burachok (2019)[94] noted a 60°C geothermal reservoir in western Ukraine at a depth of 1,200 m, and other resources of unstated depths and temperatures beneath the Crimean Peninsula. Morozov and Barylo (2019)[95] reported that the first geothermal heating system in the Soviet Union was constructed on the Crimean Peninsula in 1986, with six similar plants also built through to 2002 to heat schools, hospitals, kindergartens, and office buildings. The combined thermal power of the plants was 11 MW_{th}. Two more geothermal plants were built in western Ukraine.

Morozov *et al*. (2020)[96] conversely dated the construction of the original nine plants as 1978 to 1998, and stated their uses as district heating (six plants providing a total 7.4 MW_{th} heat), bathing, swimming, balneotherapy and recreation (three plants providing a total 3.5 MW_{th} heat.)

They indicated that all of those plants were “experimental” to evaluate the commercial potential of geothermal energy, and that all were operational in 2005. By 2020, however, all six district heating facilities had closed because of “out-dated equipment and problems connected to corrosive properties of geothermal water which lead to high repair cost at geothermal stations.” More optimistically, they reported an increasing number of new geothermal projects for bathing, swimming, and balneology, with some also including space heating.

Key contact: Yurii Morozov, Head of Geothermal Energy Department, Institute of Renewable Energy of the National Academy the Sciences of Ukraine—geotherm@ukr.net.

2.8.5. Tunisia

Tunisia occupies 164,000 km² between Algeria and Libya in northern Africa (Figure 35), with arable land making up only 30% of the country. In spite of its location in one of the hottest and most arid parts of the world, Tunisia is today the largest consumer of geothermal energy for greenhouses in the world, and the only region to use geothermal energy for greenhouses in an arid zone. Most of the greenhouses are in the arid south of the country. The following information is drawn from Ben Mohamed (2010)[97] unless otherwise cited.

***Figure 35**. Tunisia lies between Algeria and Libya in northern Africa.*

The geothermal reservoir is the ‘Continental Intercalaire’ aquifer, which produces 30–80°C water from depths as great as 2,800 m. The aquifer underlies about one million square kilometres of southern Tunisia, Algeria and Libya; comparable in scale to the Great Artesian Basin in Australia. Bore flow rates range from 70 L/s to 200 L/s.

The use of geothermal energy for greenhouses in southern Tunisia began with a one hectare experimental facility in 1986, financed by the United Nations Development Program. The facility quicky demonstrated that it could produce better quality and higher yield crops than non-heated greenhouses or open air crops. This early success led to rapid and ongoing duplication of the concept, with 21 Ha of greenhouses heated with geothermal energy by 1988, 111 Ha by 2005, 194 Ha by 2010, and, as recently reported[98], 237 Ha in 2020.

The spent geothermal water is not reinjected, but rather used entirely for irrigation. The greenhouses themselves use only 10–15% of the water passing through their heating systems, with the remainder used to irrigate large tracts of outdoor oases. Many other bores produce water only for outdoor irrigation. Agoune (2021)[99] sounded an alarm bell about this practice based on satellite derived gravity data over the period 2002 to 2016. The data suggest that between 45,000 and 63,000 GL of groundwater is being lost from the regional aquifers every year due to the large scale production of groundwater without reinjection—arguably the most rapid loss of groundwater from any comparably sized region in the world. While only a small fraction of the loss can be attributed to the geothermal systems, the findings indicate that current practices are probably unsustainable.

The geothermal greenhouses have, however, stimulated local economic growth in the dry southern parts of Tunisia. Farmers earn a premium for the produce of geothermal greenhouses, and excess produce feeds into a growing export market. Tunisian tomatoes earn a good price in Europe because of their superior quality and taste. Each hectare of geothermal greenhouse in 2010 generated revenue of 40,000–50,000 Tunisian dinars (c.AU$18,900–23,600 in April 2021), employed seven permanent staff, and provided about 400 days of seasonal work.

2.8.6. Even more examples

The twelve examples described above in varying levels of detail do not constitute an exhaustive list of all the direct uses of geothermal energy from aquifers in the temperature range 30–70°C. Rather, they represent the major examples uncovered through a search of English language literature sources and English-speaking contacts of the author. The review uncovered references to geothermal systems in Russia and other former Soviet republics, Japan, Algeria (across the border from Tunisia), states other than Idaho in the USA, Latin America, and elsewhere. Further details about those systems can be sought at a future date if deemed of interest.

3. Key Findings

3.1.General observations

Arguably the most striking conclusion from the global scan detailed above is that the geothermal energy reservoir(s) beneath the Latrobe Valley and greater Gippsland represents a truly world-class resource. Similar temperature aquifers have been economically developed in many parts of the world from much greater depth and lower productivity rocks.

The global scan provides enlightening insights into how other regions have nurtured the birth and sustainable growth of local geothermal economies. While the circumstances and experiences of each individual region are instructive in themselves, some overarching patterns become apparent when all of the regions are considered collectively.

A feature of geothermal development in many regions is a dominance of one particular end use for the geothermal energy. Greenhouses are the dominant consumers of geothermal energy in the Netherlands and Tunisia; aquatic centres dominate the geothermal landscape in Perth; Paris, Boise and the Polish Lowlands utilise their geothermal resources almost exclusively for district heating systems; bathing and relaxation resorts are the preferred geothermal business model in Brazil; beyond Veresegyház, most geothermal resources in Hungary are applied to therapeutic health spas (balneology).

The reasons for the evolution of ‘geothermal monocultures’ described above are not immediate obvious. In some regions, the characteristics of the geothermal resource might particularly suit a specific purpose (e.g. higher temperatures for greenhouses; beneficial chemical composition for balneology) to the exclusion of others. In other locations, however, there might be a ‘copycat’ element. The author found no evidence that ‘geothermal monocultures’ are planned, but might instead develop as a natural result of ‘user driven’ growth of the local geothermal economy. This could arise, for example, from the expansion of a commercially successful concept by the original project developer, or replication by colleagues or competitors in the same sector. There is evidence for this in the growth of the hot spring spa sector in Victoria (stimulated by the commercial success of Peninsula Hot Springs), the replication of geothermal aquatic centres throughout Perth (where local councils and schools have copied earlier successful projects), district heating systems throughout Paris, and greenhouse heating in Tunisia.

Even though it might not make the most efficient use of the geothermal resource, a ‘geothermal monoculture’ still provides its region with substantial economic benefits through cheap energy and the growth of a network of local specialist entities to service the monoculture. The specialist network could, in fact, provide a positive feedback mechanism by reinforcing and facilitating the further growth of the monoculture. The risk (as for any monoculture) is of catastrophic collapse of the sector if the business model for the geothermal application is fundamentally unsustainable (propped up by temporary government subsidies, for example, as were early solar installation businesses), or if external forces disrupt the sector (for example, a pandemic forces the closure of all hot spring spas for an extended period).

Monocultures appear to be an outcome of user-driven development, which also appears to be the most common development model around the world. Heat consumers make the long term capital investments to drill their own wells and develop their own surface infrastructure. This limits accessibility to large heat consumers or self-organised joint enterprises of heat consumers.

Veresegyház in Hungary provides an alternative model for growing a geothermal economy. There, the town council effectively owns and operates an energy utility company. The council invests capital into drilling wells and building a heat distribution (pipes) network, earns a direct return on its investment through energy sales to customers, and indirectly stimulates the local economy by providing access to cheap energy. The cost of connection to the geothermal network for individual customers is relatively low, allowing equal access for small, medium or large consumers. The result is a broad cross section of end users in Veresegyház, from individual houses to large global companies. This is arguably a more resilient development model for a geothermal economy, less exposed to the fortunes of any single consumer sector.

For both development models (user-driven versus public utility), central government's role is to provide a coherent, enabling and persistent policy and legislative framework to promote and facilitate secure access to, and sustainable use of, the geothermal reservoir.

The rest of this section summarises other key findings from the global scan within the framework of Smart Specialisation Strategy design principles.

3.2.Global markets

Geothermal energy drawn as heat from aquifers in the 30–70°C temperature range is, by its very nature, non-fungible. That is, the heat itself cannot be sold into a global market but must be used locally and soon after production, or else the heat dissipates to the surroundings and its value is lost. The early stages of successful geothermal developments, therefore, tend to deliver value primarily to the local environment, community and economy.

Strong local success, however, can build gateways into global markets. These might be export markets for products or produce generated using geothermal energy (e.g. greenhouse produce from the Netherlands and Tunisia; aviation products from Hungary); national or global tourism markets for hot spring spas (e.g. Slovakia, Poland, Brazil); national or global markets for knowledge-based services (e.g. Perth based geothermal consultants in demand around Australia; Dutch geothermal greenhouse expertise exported around the world; training courses attracting international students to Hungary.) Through the development of its geothermal resource, Gippsland can position itself to take advantage of growing global demands for low-emissions products, wellness experiences, and sustainable development.

The global scan identified global centres of state-of-the-art geothermal energy knowledge, experience and expertise. Specifically, the Netherlands is the clear global leader for geothermal greenhouses and geothermal energy research; Paris leads the world for implementing geothermal district heating; Hungary delivers world-leading education programs in geothermal energy; Perth hosts world leading expertise in geothermal aquatic centres; Beijing is home to arguably the world's most successful cascaded geothermal energy system. By building personal, institutional and/or inter-governmental linkages with those regions, Gippsland can gain access to world-leading knowledge and state-of-the-art equipment to ensure optimal development of its geothermal resource. In time, Gippsland could itself become a centre of geothermal knowledge and expertise for a global market.

3.3. Collaboration and inclusion

The global scan confirms that regions in which government, industry, academia and the community collaborate to define and achieve a common goal are those that most successfully develop sustainable geothermal economies. The most striking examples are the village of Nangong in the suburbs of Beijing, where the entire village evolved from a traditional agrarian lifestyle to a geothermal economy over a period of about 10 years; and in the Netherlands, where Geothermie Nederland provides a forum for a broad range of geothermal stakeholders to identify and address barriers to development. Collaboration between regulators, project proponents and local communities is also assured in the Paris Basin through mandated public hearings for all new geothermal heating systems proposals, while local institutions provide targeted research and training services. It is particularly enlightening, also, that a European commission study into the possible transition from a coal-based economy to a geothermal economy in Slovakia recommended the adoption of a smart specialisation strategy.

In contrast to the examples above, the former Soviet republics of Ukraine and Georgia demonstrate the negative consequences for geothermal development when governments, academia, communities and industry operate in isolation. Both countries lost most of their early geothermal energy investments after the withdrawal of central government control following the disintegration of the Soviet Union in the early 1990s.

The Geothermal Innovation Group assembled and coordinated by the Latrobe Valley Authority already provides the nucleus of an inclusive forum to define and implement the scope of a transition to a geothermal economy in Gippsland. The Geothermal Innovation Group could be further strengthened by broadening representation to include (for example) the financial sector, industrial heat consumers, the Victorian Department of Earth Resources, additional community groups (e.g. indigenous representation), the pre-tertiary education sector (e.g. high school science teachers), environmental groups, media companies, and others.

3.4. Regional growth potential

The global scan reveals that successful transformation of a region to a geothermal economy is best driven by a local, visionary, committed and enduring leader or leadership group with a strong personal connection to the region. This is most clearly illustrated by the example of Veresegyház in Hungary, where the Mayor has held his position for over fifty continuous years. Once the Mayor of Veresegyház was convinced of the benefits that geothermal energy could bring to his town and region, his continuity of leadership ensured an ongoing municipal commitment to developing the geothermal energy distribution network. Nangong village on the Beijing plains provides another example, where the successful transformation to a geothermal economy was conceived, initiated and managed by the village council. And at Uniejów on the Polish Lowlands, regional economic growth based on geothermal energy was envisioned, and ultimately realised, by “a group of people with a high degree of awareness of the potential”[89] who developed and drove “an innovative, strategic and long-term development plan.”[89]

The former Soviet states of Ukraine and Georgia, however, provide alternative examples of what happens when continuity of local leadership is suddenly lost. Development of geothermal resources in those regions not only ceased, but existing systems fell into disuse and disrepair when the Soviet Union collapsed in the early 1990s.

These findings indicate a crucial role for local government(s) in any transition to a geothermal economy for Gippsland. More specifically, the findings highlight the importance of an individual champion or group of champions with close connections to the local community, personal devotion to driving positive outcomes for Gippsland, and the power to influence and implement a long-term regional transition plan.

3.5.Sustainability

The global scan identified geothermal systems that have delivered sustained energy output for a hundred (e.g. Boise district heating system) or hundreds (e.g. Slovakian health spas) of years with little impact on the underlying geothermal reservoir. Other examples, however, illustrate the negative impact that unregulated, or poorly regulated, geothermal development can have on the sustainability of the resource. The Beijing Plains provides a prime example of the rapid reduction in groundwater level that can accompany a rapid increase in production of geothermal energy if cooled water is not reinjected. In Slovakia also, non-reinjection of cooled water from new geothermal projects is beginning to reduce the level of an aquifer that has sustainably supplied geothermal heat and water to a spa facility for hundreds of years. Dire predictions for the health of the groundwater system in Tunisia due to over-extraction for irrigation, however, is arguably the most poignant example of the need to sustainability manage groundwater systems through reinjection.

The global scan also highlighted the importance of financial sustainability. For example, many of the first generation of geothermal district heating systems in Paris failed commercially when the cost of servicing capital loans and maintaining equipment against corrosion and scaling from the saline water become higher than the cost of natural gas option for heating. In Georgia and Ukraine, also, geothermal systems failed commercially because they could not meet the cost of maintenance. The Parisians learned from their experiences and today incorporate rigorous monitoring, maintenance and insurance policies into their geothermal energy business models.

The sustainability of a geothermal economy is well illustrated by the examples of the village of Nangong (Beijing Plains), where the entire village is connected in some way to geothermal enterprises, and Veresegyház (Hungary), where "everybody think of using thermal water as the first alternative. It is simply wonderful!"[47] Perth, also, seems to have achieved a self-sustaining geothermal energy industry, with enthusiastic local councils developing a growing number of geothermal systems, which are actively monitored and sustainably managed within an enabling policy and regulatory framework.

A key finding for Victoria and Gippsland is that geothermal reservoirs can be sustainably managed through reinjection, and with ongoing monitoring of the fluid characteristics (temperature, pressure and chemistry) in the production and injection bores. Surface systems can be sustainably managed through regular monitoring and maintenance programs. A self-sustaining geothermal economy can flourish if nurtured by government through its early growth phase and subsequently supported by a comprehensive, persistent and enabling legislative and policy framework.

3.6. Dynamic business model

By its nature, the delivery of heat as an energy commodity lies within the fairly staid world of public utilities. The context and circumstances of heat demand tend not to vary rapidly in areas of established businesses and housing, so business models tend to remain static. The growth, contraction, and renewed growth of a geothermal heating industry in Paris over the past decades, however, provides an example of business models adapting to changing commercial conditions. The introduction of a geological risk management fund by the French Government dramatically changed the business model for geothermal district heating systems in Paris, freeing up lower-cost finance and allowing relatively small co-operative developers to embrace the inherent geological risk of geothermal projects. At the project scale, mandatory public hearings before the granting of development licences also often require developers to incorporate specific conditions into their plans at relatively short notice. And there are documented instances in Paris of innovations such as crowd-funding for geothermal projects, and rejuvenating old geothermal systems with new materials and boreholes.

The geothermal energy distribution network in Veresegyház, Hungary, has continuously adapted and expanded dynamically in response to changing national legislation (mandating reinjection) and demand. Its business model of building an ever-growing network of hot water pipes to which public and private enterprises, and even individuals, can connect at an affordable price via heating substations is itself a business innovation.

The key lesson for Gippsland is to remain open minded about possible business models for geothermal energy developments. While a large facility such as the Gippsland Regional Aquatic Centre might justify drilling its own geothermal bore, alternative energy supply business models might offer many smaller users access to geothermal energy at acceptable cost and risk levels.

3.7. Active learning and discovery

Regions that nurture a transition to a geothermal economy also seem to encourage and embrace active research and development into the geothermal resource itself, surface plant, business systems, environmental and social impacts, and more. Examples include state government funding for the Western Australian Geothermal Centre of Excellence in Perth; successful trials of cutting edge horizontal drilling techniques in the Paris Basin; investigations into the economic impact of geothermal developments on the Polish Lowlands; development of an innovative business model and heat offtake units in Hungary; a specialized geothermal borehole research facility in The Netherlands; and many others. Common characteristics of these active learning and discovery programs include a clear collective vision for the development of the geothermal opportunity; broad deployment of sensing and monitoring systems; close cooperation between project developers, regulators, and local research institutes; and integration of monitoring data into management and planning structures.

Through the Latrobe Valley Authority, Gippsland has already demonstrated a commitment to active learning and discovery about its geothermal energy resource, as evidenced by the commissioning of this report and parallel studies. A continued commitment to investigate the characteristics of the geothermal resource and the optimal pathways for its social, environmental and economically sustainable development will provide the best foundation for a successful transition to a geothermal economy.

4. Recommendations for Gippsland

The lessons from the investigations presented in previous sections are here amalgamated into a series of recommendations for the Latrobe Valley Authority to foster the efficient, effective and sustainable growth of a geothermal economy in Gippsland.

- Expand the Geothermal Innovation Group to broaden the range of stakeholders. New members could be invited from the financial (including risk management) sector, industrial heat consumers, the Victorian Department of Earth Resources, indigenous leaders, high school teachers, environmental groups, media companies, and others.
- Identify and empower one or more permanent ‘champions’ within local government(s) to influence and implement a long-term transition to a geothermal economy.
- Facilitate personal, institutional and/or inter-governmental linkages with experts in regions around the world that have made the transition to a geothermal economy in order to gain access to world-leading knowledge and state-of-the-art equipment. Specific targets could include the town council of Veresegyház (Hungary), Geothermie Nederland (Netherlands), European Geothermal Energy Council (Belgium), Nangong village council (China).
- Perform an opportunity and gap analysis to assess the potential for Gippsland to become a centre of geothermal training for a global market.
- Highlight the sustainable management of the geothermal reservoir(s) and surface systems as the core of any policy and legislative framework for geothermal energy. This could include a points-based risk assessment framework; reinjection where deemed appropriate; ongoing monitoring of reservoir characteristics (temperature, pressure and chemistry) using production and injection bores; and systematic monitoring and maintenance programs for surface plant.
- Consider appropriate incentive schemes (e.g. geological risk mitigation) to nurture the growth of a geothermal economy through its early growth phase.
- Explicitly investigate the feasibility of an energy utility model for delivering geothermal energy to small, medium and large consumers in Gippsland.
- Encourage coordinated research into environmental, social and economic issues associated with a transition to a geothermal economy in Gippsland.

5. Concluding Remarks

The geothermal aquifer(s) beneath Gippsland represent(s) a potential world-class resource of cheap, sustainable heat. Gippsland has an opportunity to deliberately and responsibly realise the potential by nurturing a transition to a ‘geothermal economy.’ Such a transition would help position Gippsland as a clean energy hub for generations to come.

Global experience suggests that such a transition would require a coordinated effort by government, industry, academia and the community to define and execute a shared transition plan. The Latrobe Valley Authority is ideally placed to coordinate that effort.

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