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Investigating a potential geothermal play in the southern Sydney Basin

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INVESTIGATING A POTENTIAL GEOTHERMAL PLAY IN THE SOUTHERN SYDNEY BASIN

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ABSTRACT: Geothermal energy is a renewable resource that will be part of the world's transition to clean power production. Different technologies can be utilised to extract heat or produce geothermal-based electricity. The Geological Survey of NSW has identified several regions across the state where there are higher than average geothermal gradients. These regions in the southern Sydney Basin are investigated with the aim of determining if the high temperatures might be related to subsurface rocks with relatively high concentrations of radiogenic isotopes that might create a 'hot dry rock' play. Rock properties are tested that would be required to generate a geothermal resource. Existing and potential engineering technologies (i.e. geothermal-based electricity, heating and cooling applications accompanied by heat pumps, geothermal-hybrid systems, and mine-based geothermal technologies) are also further reviewed. Overall this study provides insights into future opportunities and challenges to harnessing geothermal energy in NSW.

Table 1: List of symbols and parameters in this paper

Symbol	Description
q	Geothermal heat flow (mW/m^2)
λ	Thermal conductivity (W/m•K)
A	Radiogenic heat production (W/m^3)
ρ	Density of heat producing rock (g/m^3)
C_U	Concentrations of uranium in the rock (ppm)
C_{Th}	Concentrations of thorium in the rock (ppm)
C_{K2O}	Concentrations of K_2O in the rock (%)
H	Heat extracted using heat exchangers (W)
ρ_w	Density of water (kg/m^3)
s_w	Heat capacity of water (J/kg • K)
Q	Flow rate of water (m^3/s)
ΔT	The change in temperature of water (K)
COP	Coefficient of Performance (K)
ΔT_s	Additional temperature output from the solar thermal system (K)
m	Mass of the water circulating in the pipes (kg)
W	Solar irradiance (W/m^2)
A_s	Area of the solar heat collector (m^2)

INTRODUCTION

With the compelling need to reduce fossil fuel emissions to combat human-induced climate change, the use of renewable energy in the world has expanded, and geothermal energy is increasingly considered a renewable source of sustainable energy (Soltani et al., 2021). Geothermal energy can be utilised either for electricity generation through turbine generators or direct applications related to heating and cooling. Although geothermal energy can be found anywhere in the world, it is utilised in relatively few places. This is mainly due to the necessity of a high geothermal gradient (higher heat flux) with permeable reservoir rocks for commercial energy production. Engineering techniques are adapted to geothermal resources where adequate fluid circulation and fracture permeability are not present. Locating potential sites for geothermal production and the long-term management of geothermal resources requires a detailed understanding of the local geological controls (Jolie et al., 2021). In Australia, granites have typically been considered suitable target rocks due to containing sufficient radiogenic elements (e.g.,

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potassium, uranium and thorium) that have decayed (and generated heat) over time. These low porosity and low permeability rocks need to be developed through stimulation technology to allow circulation between injection wells and production wells, and the rock mass acts as a heat exchanger. This concept is often referred to as “hot dry rock” (Moeck, 2014). These geothermal resources are dependent on the rock volume, geothermal gradient and whether the target igneous rocks are covered by rocks with low thermal conductivity (Pleitavino et al., 2021). Therefore, it is important to obtain information about these parameters to assess the potential of geothermal energy in a given area.

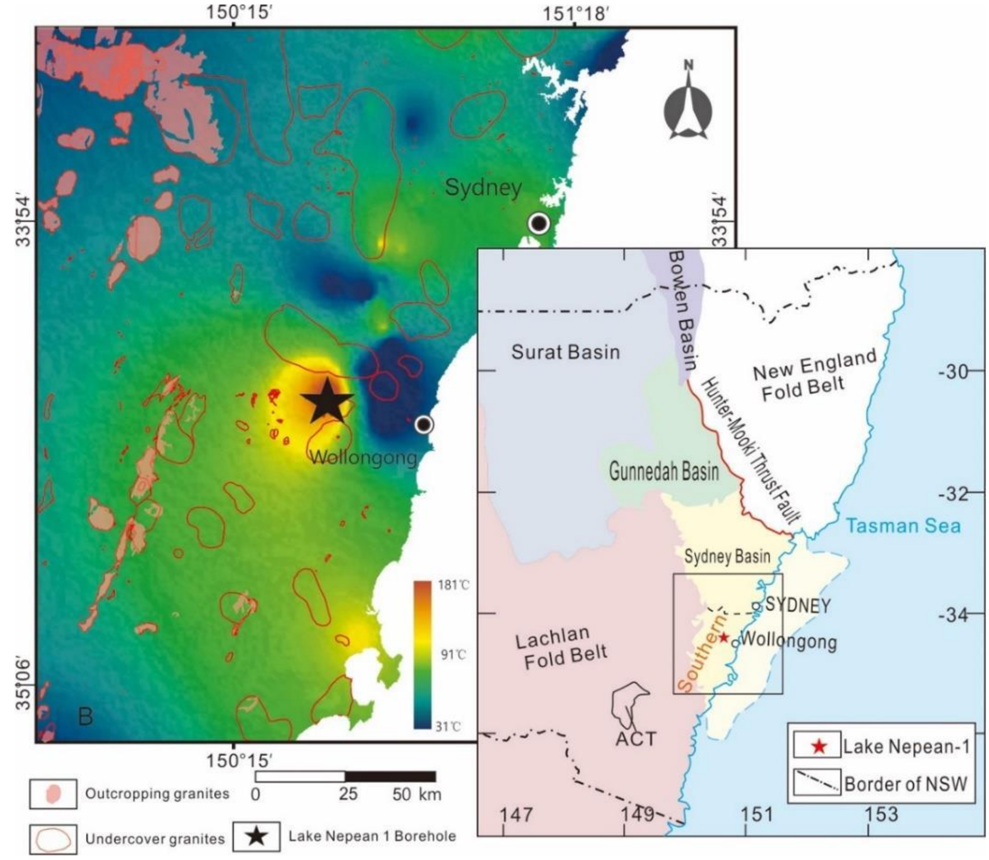


Figure 1: Estimated subsurface temperature in south Sydney Basin at 2 km depth (modified from NSW Government, 2022) and an inset map of the tectonic environment of Sydney Basin (modified from O’Neill & Danis, 2013)

The Geological Survey of NSW identified several regions with above-average geothermal gradients. This paper investigates one highlighted region surrounded by undercover granites in the southern Sydney Basin, as depicted in **Figure 1**. It was hypothesised that the high temperatures might be related to rocks below the surface with relatively high concentrations of radiogenic isotopes that might create a ‘hot dry rock’ play. The geothermal gradient was calculated by reading borehole temperatures at specific depths from the Lake Nepean-1 borehole. The thermal conductivity of the core from the Lake Nepean-1 borehole was measured using a handheld device during a site visit to the NSW Geological Survey Core Library. Radiogenic heat production was calculated based on the radiogenic heat production equation (Rybach, 1988). These data was used to model the rock properties required to generate a suitable geothermal resource. In other areas with similar geological backgrounds, the model can be used to primarily estimate the geothermal prospects by inputting the required parameters. The existing geothermal energy technologies (i.e. geothermal-based electricity and various shallow geothermal technologies, including heating and cooling applications accompanied by heat pump technologies, geothermal-solar hybrid technologies and mine-based geothermal systems) were further reviewed. It is expected that the preliminary results and discussion to be used as a reference for selecting appropriate engineering technologies and identifying critical research needs for developing geothermal-based technologies.

RESEARCH METHOD

In order to investigate the potential of the geothermal anomaly in the Southern Sydney Basin, samples from the Lake Nepean-1 borehole were examined, which occurs in the centre of the heat anomaly proposed by the Geological Survey of NSW. The model considers geothermal gradient, heat conductivity, heat flux, and radiant heat production. The borehole and core information of Lake Nepean-1 and logging and completion data were obtained through the Geological Survey of NSW Digital Imaging Geological System (https://search.geoscience.nsw.gov.au/). The well-completion report was used to obtain a detailed description of the lithological and geological characteristics of the recorded borehole temperature at a specific depth from the database. Core material from Lake Nepean-1 was also inspected at the WB Clark Geoscience Centre in western Sydney, NSW. Thermal conductivity measurements were obtained from different lithologies in a ~20 m section of core collected near the intervals where borehole temperatures were measured at the time of drilling.

Geothermal Gradient

The geothermal gradient ($\frac{dT}{dZ}$) (°C/m) was calculated by dividing the recorded borehole temperature by the depth of the temperature measurement. The completion report of Lake Nepean-1 records the temperature values at six different depths. The lithology of the Lake Nepean-1 well is simple but is relatively representative of the local stratigraphy and has therefore been used as an example to establish a simple preliminary geological model.

Thermal conductivity measurements

Thermal conductivity readings were taken using a portable Thermtest transient line source thermal conductivity and resistivity meter (“TLS-100”) using a 50mm rock probe. Measurements were collected after drilling a 60mm hole with a Ryobi hand hammer drill into 8 different sections of the rock core. The hole created by drilling was lined with Type 120 silicone paste to establish a contact between the needle probe and the rock. A conductive sample was used between each hole to keep a base point throughout the readings. Three repeat readings from each drilled hole were taken, followed by two repeat measurements of a reference sample (thermal conductivity of 0.31 W/m•K). Each measurement was obtained over a 90-second period.

Geothermal heat flow

Geothermal heat flow was calculated for the top, middle, and bottom sections of the Lake Nepean-1 well using Fourier’s law with equation (1), where (q) is the geothermal heat flow and λ is the coefficient of thermal conductivity.

$$\mathrm{q} = \lambda \frac{dT(z)}{dz} \tag{1}$$

Radiogenic Heat Production

Radiogenic heat production within the Lake Nepean-1 borehole and the expected element concentration beneath the borehole was calculated by the radiogenic heat production equation (Rybach, 1988):

$$\mathrm{A}\left(\frac{w}{m^3}\right) = 10^{-5} \times \rho \times (9.67C_U + 2.56C_{Th} + 2.89C_{K2O}) \tag{2}$$

Where ρ (g/cm^3) is the density of the rock and C_U, C_{Th} and C_{K2O} represent the concentrations of uranium (ppm), thorium (ppm), and K_2O (%) in the rock. The average U, Th, and K_2O concentrations of ‘granite’ and ‘syenite’ within Australia from the GEOROC database (https://georoc.eu/) were used, and preliminary statistical analysis was performed on the data to calculate heat production.

RESULTS ON GEOTHERMAL FEASIBILITY

Geothermal Gradient

In the Lake Nepean-1 borehole, Hawkesbury Sandstone exists from 0m to 318.5m depth. Thermally metamorphosed shale lies underneath the Hawkesbury Sandstone from 318.5m depth to approximately

333.8m. Syenite intrusives occur at 314.5m, and below this, the syenite intrudes into the Illawarra Coal Measures. The intrusives are most concentrated at the base of the hole (333.8m depth). **Figure 2** illustrates the temperature values obtained from the well-completion report (Wiltshire, 1985) with temperature with depth data of NSW sourced from OzTemp Database of Geoscience Australia (Holgate and Gerner 2010). The average geothermal gradient of NSW is shown in the black line.

The temperature remains at 17°C from the surface of the Lake Nepean-1 borehole and remains at 19.4°C from 25m until approximately 75m depth. There is a rapid increase in temperature to 29.4°C at 100m. At 127m depth in the Hawkesbury Sandstone, a temperature of 36.1°C was recorded. At 318.5m in the shale, the temperature was 28°C. There were 5 recorded temperatures at 333.8m, with a maximum of 43.3°C, a minimum of 25.5°C and an average of 33.8°C (**Figure 2**). The geothermal gradient result in the Hawkesbury Sandstone was calculated as 0.1°C/m at 25m to 75m; 0.4°C/m at 75m to 100m; 0.24 °C/m at 100m to 127m; -0.04 °C/m at 127m to 310m, respectively. In the syenite it was 0.32°C/m at 310m to 333.8m.

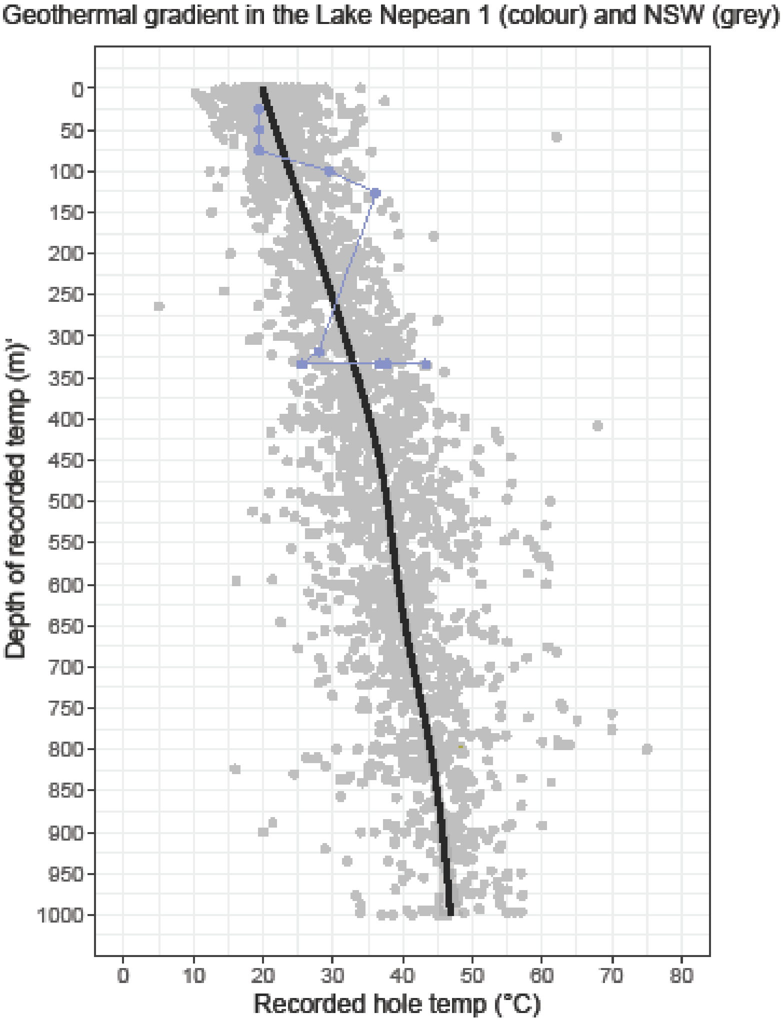


Figure 2: Temperature data of the Lake Nepean-1 borehole obtained from AGL Composite Well Log (Wiltshire, 1985) and temperature with depth data of NSW sourced from OzTemp Database of Geoscience Australia (Holgate and Gerner 2010).

Thermal conductivity

The thermal conductivity was measured between the core taken at depths of 300.75m to 316.15m below the surface. The readings for sandstone in the upper part of this section had values ranging from 1.3-1.5 (W/m°k). Measurements from coal and siltstone (“LAKENEP_04” and “LAKENEP_05”) yielded the lowest values (0.612 – 1.384 (W/mk)). The highest values (2.01 – 2.354 (W/mk)) were obtained from syenite (“LAKENEP_06 and LAKENEP_08).

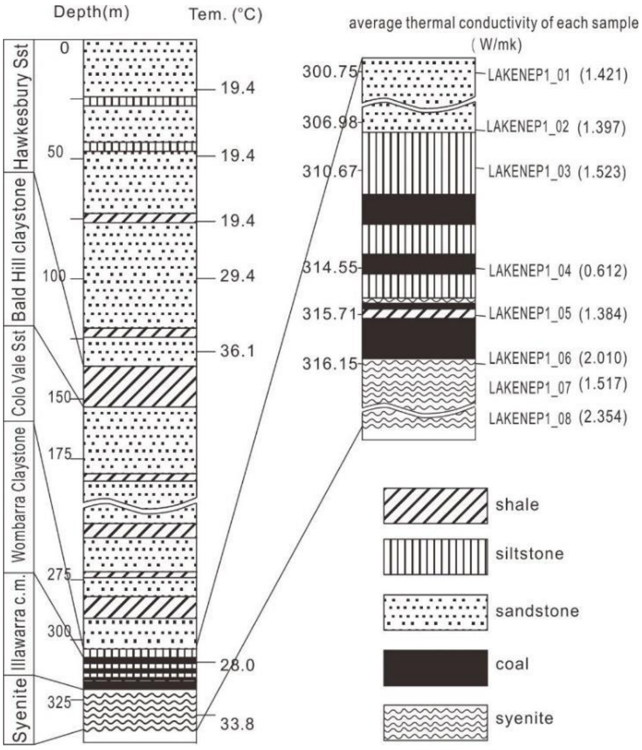


Figure 3: Lithology and temperatures recorded in the Lake Nepean-1 borehole created using data in AGL Composite Well Log (Wiltshire, 1985).

Geothermal heat flow

Based on the calculated geothermal gradient and thermal conductivity measurements, the geothermal heat flow in the Hawkesbury Sandstone at 80m was 56 mW/m^2 (average thermal conductivity in Lake Nepean-1 was applied), at the top of the coal measures at 300.74m was -60 mW/m^2, and in the syenite at 325m (average depth of syenite) was 75 mW/m^2. The reduced temperature was recorded within coal at 318.5m; thus, the calculated negative geothermal gradient resulted in the negative heat flow value. The calculated values were further compared with the South Australian heat flow anomaly. The reported heat flow rates of Adelaide Fold Belt, Western Gawler Craton, and Willyama Inliers are 92±10 mW/m^2, ~54 mW/ m^2, and ~75 mW/m^{2,} respectively (Neumann et al., 2000).

Radiogenic heat production

The heat production values for intrusive units in the South Australian heat flow anomaly region range from 4.5 to 9.9 µW/m^{3,} while the majority of values are between 5 and 8 µW/m^3 (Neumann et al., 2000). The data of K_2O (wt%), Th(ppm), and U(ppm) content of 566 granite samples and 10 syenite samples in Australia were downloaded from GEOROC database (https://georoc.eu/) on 10 December 2022, using the following parameters: Query by Geography Long.-max/min 155/110 | Lat.-max/min -10/-45, Sample Criteria (combined with AND): K_2O, Th, U; ROCK TYPE: PLUTONIC ROCK. Since syenite has only 10 samples, only the average value of three elements was calculated; the results are represented in **Table 2**. The average density of syenite was considered as 2.75 g/m^3 (Horai and Baldridge, 1972).

Table 2: Average content of heat-producing elements in syenite

Syenite	C_{K2O}(wt%)	C_{Th}(ppm)	C_U(ppm)	Number of samples
average	2.31	14.60	3.85	10

Based on the result above, radiogenic heat production of syenite in the Lake Nepean-1 area was estimated as 2.24 µW/m^3, which is lower than the common heat production values in the South Australian dataset (Neumann et al., 2000).

The radiogenic heat production of granites was further calculated employing the average density of granite as 2.65 g/m^3 for comparison (Alden, 2020). Statistical results of heat-producing elements in 566 granite samples are shown in **Table 3**.

Table 3: Statistical results of heat-producing elements in granite

Granite	C_{K2O}(wt%)	C_{Th}(ppm)	C_{U}(ppm)
average	4.27	25.48	5.96
standard deviation	1.32	15.30	4.93
median	4.50	23.00	4.79
mode	4.84	22.00	6.00
95% percentile	5.79	52.72	15.80
minimum	0.02	0.00	0.00
maximum	8.24	114.40	46.80

Using a median C_{K2O} value for granite (4.50%), and the range of Th and U content is from 0 to 52.7ppm and 0 to 15.8ppm, 95% quantile, respectively, the relationship between heat production and the concentration of radioactive trace element (U and Th) under certain content of potassium can be seen in **Figure 4**. Overall, higher heat production of granite was observed due to higher Th, U and K_2O concentrations than syenite.

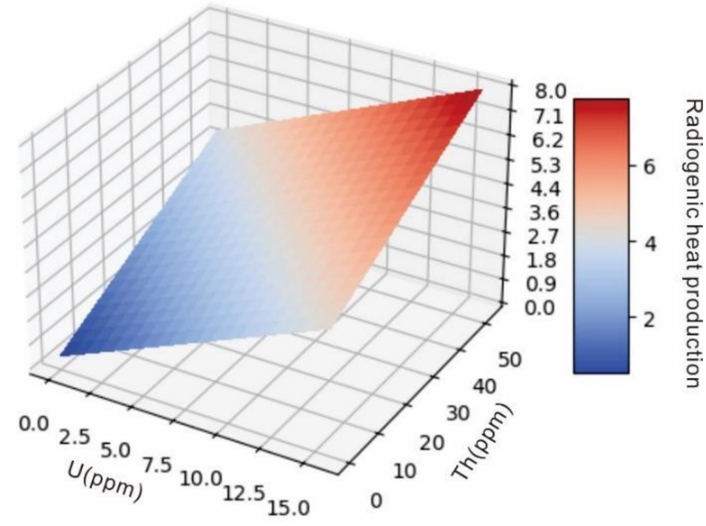


Figure 4: Relationship between the heat production and the concentration of U and Th (Granite ρ=2.65g/cm^3, C_{K2O}=4.5%)

The Sydney Basin consists of largely sedimentary rocks deposited between the Late Carboniferous and the Middle Triassic. These sedimentary rocks have been intruded by Jurassic intrusives (e.g., syenite) and overlie the metasedimentary, granitic, and volcanic rocks of the Lachlan Orogen (Herron et al., 2018). It is suspected that the radiogenic decay of K, Th and U in these igneous rocks might be the reason for the elevated geothermal gradient in the southern Sydney Basin. However, our calculation of the heat flux of syenites (as intersected in the Lake Nepean-1 well) indicates that these rocks may not be sufficient to be the source of elevated geothermal gradient alone. However, it is possible that the large volume of granites and volcanoclastic sediments that underlie the Sydney Basin might explain why some areas exhibit higher heat flow.

DISCUSSION ON POTENTIAL GEOTHERMAL HARNESSING TECHNOLOGIES

Depending on the resource potential, geothermal energy technologies range from electricity production from steam turbines to space heating and cooling applications based on ground source heat pumps and other direct-use applications. **Figure 5** illustrates different geothermal technologies applicable to the Australian context, considering various geothermal resources available. The following sections discuss potential geothermal harnessing technologies enabling understanding the most appropriate geothermal technologies considering the geothermal resources in the Sydney Basin.

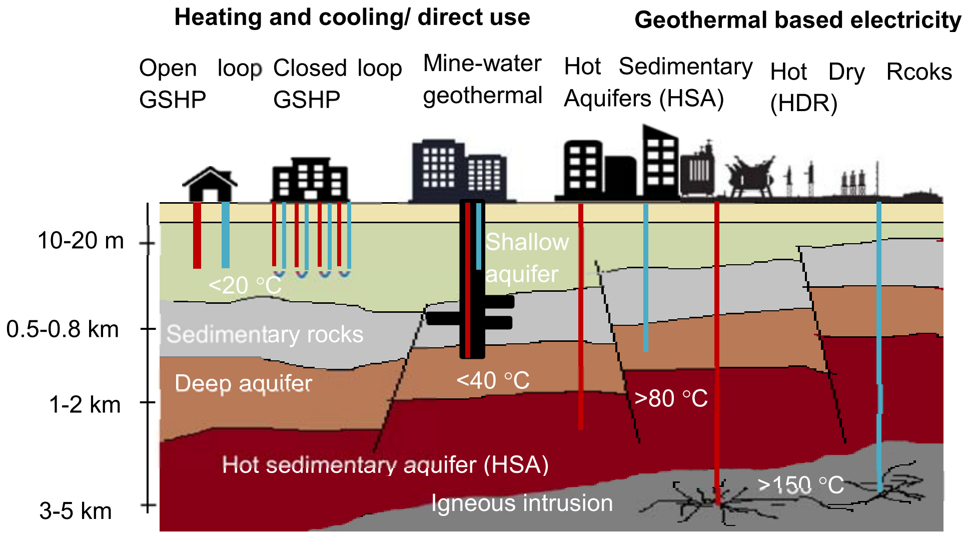


Figure 5: Conceptualised different geothermal technologies applicable to Australia (modified and re-drawn after the British Geological Survey and UK Research and Innovation)

Geothermal-based electricity

A geothermal reservoir is accessed by drilling an injection and production well system into the reservoir and circulating pressurised fluid to transport heat to the surface. There are several methods of geothermal electricity generation, including (1) dry steam (steam flows directly into the electricity-producing generators), (2) flash steam (phase changes from liquid to gas as a result of changes in temperature and external pressure, partially vaporised fluid is used to drive turbines and to power generators), and (3) binary cycle (utilises two fluids, hot underground fluid and a secondary fluid which has a lower boiling point which generates vapour and drives turbines) (DiPippo, 2016). Due to the lack of active volcanoes or surface geothermal resources, Australia is generally considered unsuitable for conventional geothermal electricity production. However, the large area of Australia is underlain by hot rocks; thus, HDR or HSA-based several projects, including the Cooper Basin project, the Paralana project and the Hunter Valley project, have been attempted. However, the Australian geothermal sector has not achieved the expected goals due to the technical challenges of developing underground fluid flow systems and failing to meet critical economic measures (Ballesteros et al., 2019).

Heating and cooling applications accompanied by heat pumps

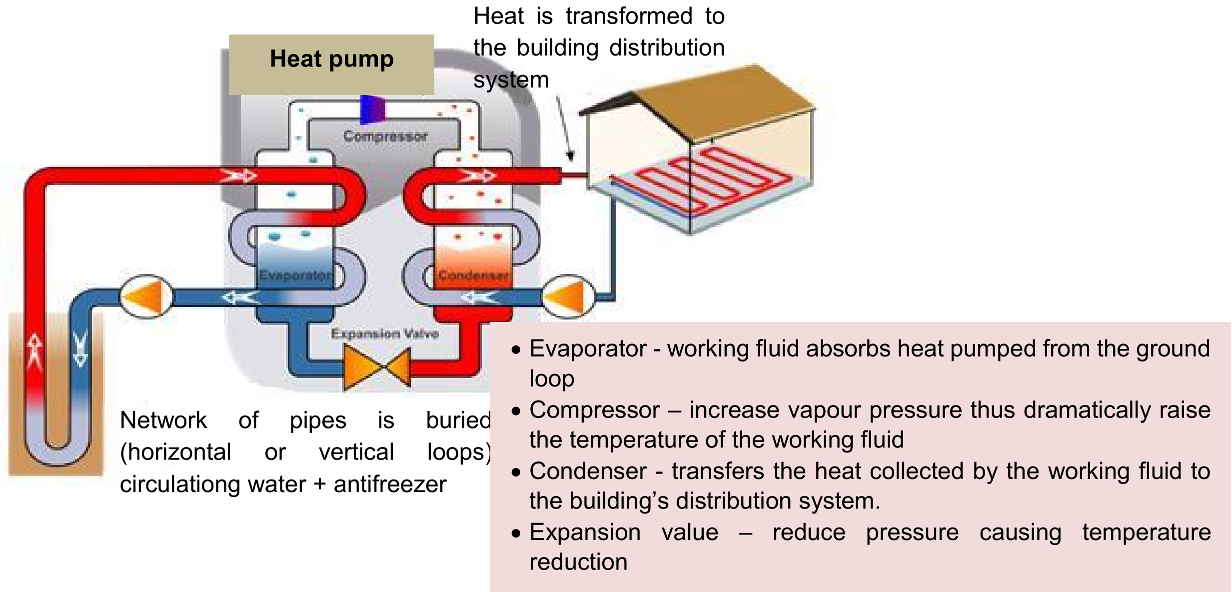
In the shallow subsurface (< 200 m), solar radiation absorbed by the ground and natural groundwater systems further influences the amount of heat stored. This energy is typically described as 'ground-source energy' or 'shallow geothermal energy. Whilst the temperature is not sufficient for electricity production, accompanied by heat pump technology; these systems offer energy for heating and cooling applications and direct thermal applications, including recreational activities, space heating, snow melting, and various agricultural and industrial applications. Using Ground Source Heat Pump (GSHP), liquids can be run through pipes underground that can absorb heat from the ground or carry heat into the ground to dissipate it (Sarbu and Sebarchievici, 2014). A GSHP can be best explained by breaking the term into two sections. A heat pump transfers heat from one place to another, while the ground is used as a heat source or sink. This heat transfer in GSHP is generally accompanied using a vapour-compression refrigeration cycle, as illustrated in **Figure 6**.

In a residential or commercial setting, pipes are laid out underground and connected to the heat pump unit. Loops can be configured in multiple ways to increase heat exchange efficiency, mainly open and closed systems. An open system extracts water from an aquifer, and a closed system is a closed fluid circulation circuit, while closed systems can be horizontal or vertical configurations. The heat transfer liquid either absorbs heat from the surrounding ground or dissipates heat from the building.

The heat (*H*) extracted using heat exchangers without heat pumps is as follows (Ochsner, 2012):

$$H = Q{*}\rho_w{*}s_w{*}\Delta T \qquad (3)$$

where ρ_w is the density of water (kg/m^3), s_w is the heat capacity of water (J/kg • K), Q is the flow rate (m^3/s), and ΔT is the change in temperature of water (K).



Heat is transformed to the building distribution system

Network of pipes is buried (horizontal or vertical loops) circulationg water + antifreezer

- Evaporator - working fluid absorbs heat pumped from the ground loop
- Compressor – increase vapour pressure thus dramatically raise the temperature of the working fluid
- Condenser - transfers the heat collected by the working fluid to the building's distribution system.
- Expansion value – reduce pressure causing temperature reduction

Figure 6: Simplified ground source heat pump system (modified after the Geothermal Heat Pump Association of New Zealand)

If the heat pump is used to extract the energy, it is crucial to consider the efficiency of the heat pump, which is stated as the Coefficient of Performance (COP), which typically depends upon the input and output temperatures. If the heat pump is used to provide cooling to the system, the heat added to the steam of water is:

$$H = (Q * \rho_w * s_w * \Delta T)/(1+[1/\text{COP}]) \tag{4}$$

If the heat pumps are used to provide heating to the houses and buildings, the heat is reduced from the water steam, and the equation for the extracted heat is as follows:

$$H = (Q * \rho_w * s_w * \Delta T)/(1-[1/\text{COP}]) \tag{5}$$

Typically COP of a heat pump is in the range of 2-3.5, meaning the heat output of the heat pump is 2-3.5 times the electricity consumption.

Geo-energy structures

Integrating heat pump technology, geo-structures (i.e., pile foundations, retaining structures, tunnels) can be transformed into energy-geo-structures harnessing geothermal energy. For example, energy piles, also referred to as heat exchanger piles have pipe circuits running through them that exchange heat with the surrounding soil. These piles are still designed to carry loads of a building while accommodating heat exchange between the fluid in the pipes and the surrounding ground. Generally, the first few meters of topsoil have fluctuating temperatures as a function of the external weather. Due to the fluctuations in temperature, energy piles that are only a few meters deep may struggle to produce ideal outputs constantly. Below this, at depths between 15-40 m, is the neutral zone, where the temperature remains relatively constant over a year. This neutral zone is the ideal place for an energy pile to be as it allows the piles to be surrounded by ideal conditions constantly (Laloui and Di Donna, 2013). **Figure 7** illustrates a preliminary model developed to capture the heat transfer mechanism of an energy pile and surrounding soil. Heat flux was applied to the bottom of the model, simulating a geothermal gradient, along with changes in temperature to the top 2.5m of the ground/soil layer in accordance with the changing average monthly temperatures of Wollongong (see **Figure 8a**). The temperature of the neutral zone was considered as 18°C. A single 10 m deep energy pile was employed, U-shape high-density polyurethane (HDPE) pipes of 25mm inner diameter and 3.5 mm wall thickness were considered for fluid circulation, and a constant flow velocity of 0.05m/s was employed.

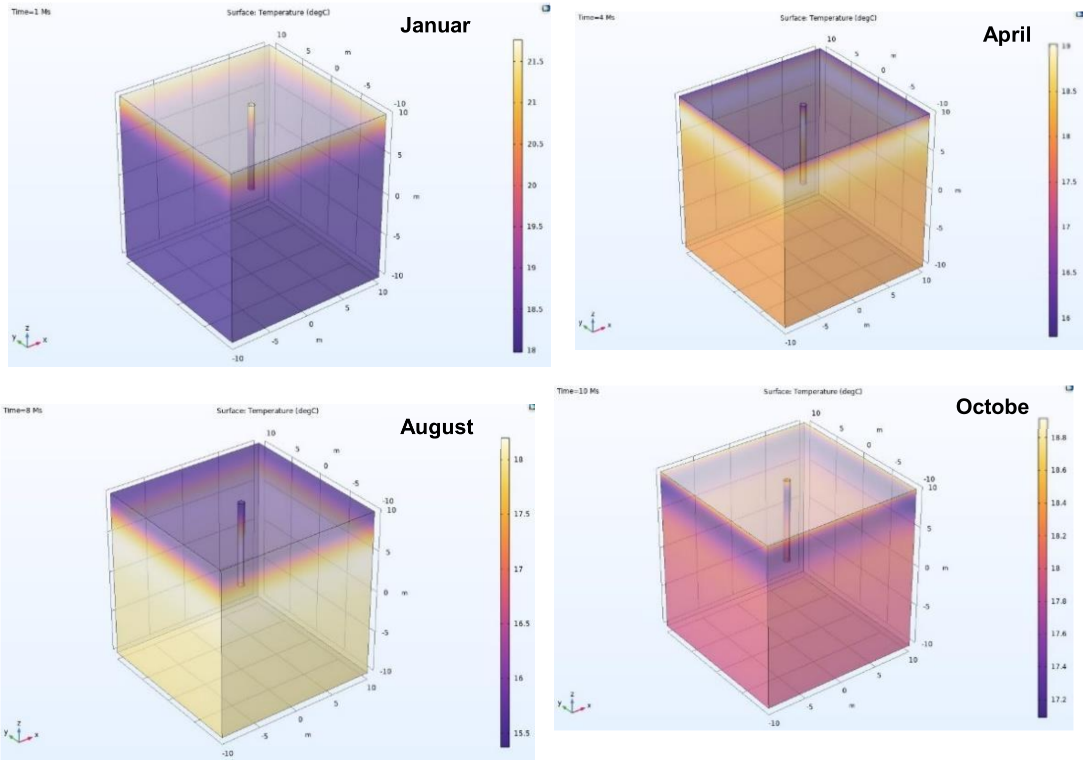


Figure 7: Modelled seasonal variation of temperature of the ground and energy pile

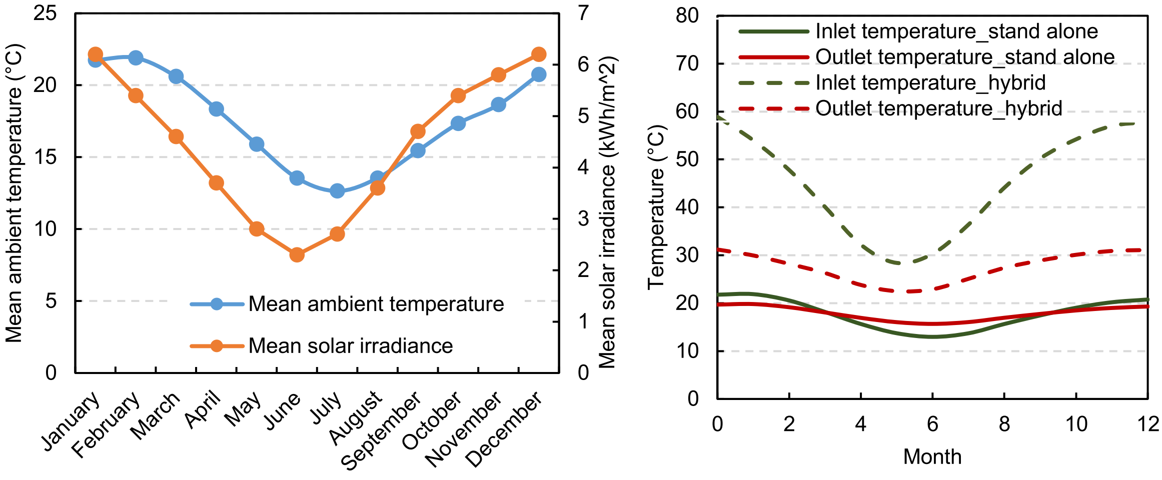
The model depicts the influence of seasonal variations on the ground profile and the temperature output from the energy pile due to fluid flow and heat transfer through the pipe. The effects of seasonal temperatures further influence the saturation and water content of the surrounding soil, thus influencing the thermal properties of the soil. For example, since the thermal conductivity of air is low, air-filled porosity critically impacts soil thermal conductivity. Soil thermal conductivity increases with water content; however, the increment is relatively low in low saturation conditions (Zhang and Wang, 2017). The volumetric heat capacity of the soil generally linearly increases with soil water content and bulk density. Soil texture, mineralogy and organic matter further influence the thermal conductivity of the soil. The fluid circulating pipes and cyclic heating and cooling loads affect the properties of the piles themselves in terms of their maximum load capacity; however, more extreme temperatures must be present to cause any significant effects on a typical reinforced concrete pile (Suryatriyastuti et al., 2012). For example, in temperatures between 5-40°C, there is very little change in the soil friction angles reported (Yavari et al., 2016). Careful selection of materials and arrangements of energy piles leads to higher output levels of the system. The use of concrete additives can change the thermal properties of the piles, favourably improving the heat transfer characteristic of the piles.

Hybrid Systems

Another technology attempting to provide a solution to this is using solar and geothermal energy in combination with each other in a hybrid system. Solar systems alone struggle to keep up with peak energy demands unless a storage system is introduced (Li et al., 2020). Hybrids of geothermal and solar power systems are a mutually beneficial combination of renewable energy sources since geothermal fluids can serve as storage systems for solar energy, while solar could be used to improve the efficiency of geothermal systems. The developed simplified finite element model discussed in the previous section was further extended to understand the thermal performance of a stand-alone and a solar-thermal integrated single energy pile. A solar heat collector with a 9 m^2 surface area was considered. The solar thermal energy was extracted through 30mm diameter 4 m long pipes with 0.1 m/s flow rate through pipes. The additional temperature output from the solar thermal system was obtained from the following equation:

$$\Delta T_s \; s_w \; m = \frac{W \;\; \Delta t}{A_s} \tag{6}$$

where *m* is the mass of the water circulating in the pipes (kg), *W* is solar irradiance (W/m^2), assuming 6.5 hours of sunshine hours and A_s is the area of the solar heat collector (m^2). The collected heat was pumped to the energy pile, which led to an increase in pile temperature and an increase in outlet temperature, as depicted in **Figure 8(b)**. These preliminary results, despite not being run through the full process of providing heating to a building, show the advantages of using a hybrid system to enhance the thermal performance of the energy pile systems.



(a)

(b)

Figure 8: (a) Ground surface temperature and solar irradiance data of Wollongong used for the model (b) Modelled temperature results of stand-alone and hybrid energy pile

Mine-based geothermal systems

Extraction of geothermal energy from underground mines is another proposed technology since mine workings created during the mine operations can be utilised with no drilling or excavation related to the geothermal system. The hydraulic conductivity of the mine reservoir is high due to artificial voids (i.e., mine galleries and shafts). Considering the enormous void space (typically several millions of m^3, depending on the extent of the mine), a very high water yield can be expected, making flooded mines a huge thermal resource. Mine water is lukewarm, typically at 15-30°C, irrespective of seasonal variations, depending on the depth, geothermal gradient, and geological characteristics of the mine. However, the temperature can be increased by integrating heat pump technologies to a more comfortable range of 40-60°C, as discussed in the previous section (Menéndez et al., 2019). In general, the temperature of the mine increases with depth due to the geothermal gradient. Interestingly, deep underground mines in Australia have reached over 40°C. For example, coal mines in the Bowen Basin have been characterised by steep geothermal gradients (Belle and Biffi, 2018). The technology offers heating, cooling, and thermal storage when coupled with heat pump technologies and shared heat networks. Depending on the fluid circulation and heat transfer mechanism, two distinctive configurations can be conceptualised for this technology, namely open and closed-loop geothermal systems (Peralta Ramos et al., 2015). Open systems directly utilise the interconnected mine workings as the fluid flow and heat transfer media where water is transferred to the surface via pumping or gravity drainage. In contrast, closed-loop systems typically use a secondary heat transfer fluid circulated through heat exchange pipes absorbing heat without abstracting mine water. Generally, open systems can provide higher thermal outputs compared to closed-loop alternatives (Al-Habaibeh et al., 2018); however, challenging water chemistry and, thus, long-term maintenance issues and potential pollution can be the decisive factor in selecting closed-loop systems over open systems (Chu et al., 2021).

Geothermal Application Summary

Geothermal power is typically considered as geothermal-based electricity generation practically utilised in hydrothermal systems close to tectonic boundaries and volcanic areas with permeable reservoir rocks and high geothermal gradients (heat flux). However, unconventional geothermal resources can be utilised for power generation through enhanced or engineered geothermal systems (EGSs) that adopt engineering techniques to enhance energy production. Apart from electricity generation, direct use of geothermal energy is an important aspect of utilising geothermal energy, mainly when the production temperature is <100 ºC. Main geothermal direct-use applications include heat pumps for space heating (and cooling) for residential, agricultural and industrial applications, recreational activities, and snow melting. Australia has the potential for geothermal utilisation for electricity generation (utilising hot dry rocks and hot sedimentary aquifer systems) and direct-use applications (employing shallow geothermal systems, ground source heat exchangers, geo-energy structures and mine-based geothermal systems). However, there is no present commercial geothermal-based electricity production in Australia. Geothermal-based direct-use applications have been emerging in the last few years, particularly ground-source heat pump technologies.

FUTURE RESEARCH NEEDS, OPPORTUNITIES AND CHALLENGES

This paper takes a single borehole as an example to illustrate and calculate the geothermal potential of a relatively small area. In the future, more specific research will be carried out on the geothermal potential of the southern Sydney Basin. This will include obtaining geochemical data from the Jurassic intrusives and older granitoids through sample collection and analysis of existing core material. It is also important to investigate the geothermal potential of shallow depths to understand the feasibility of shallow geothermal technologies, which will be most viable in the case of the southern Sydney Basin. Geothermal technologies such as mine-based geothermal systems and hybrid technologies are typically unexplored concepts in the Australian context, which can provide new opportunities. Groundwater temperature data, mine-water temperature records and thermal properties of target geological units provide important inputs for engineering designs of shallow geothermal technologies.

The major challenge associated with geothermal energy technologies is maintaining economic flow rates while acquiring sufficient thermal energy. Thus improving reservoir stimulation technologies and the overall thermo-dynamic cycle of power production is essential to meet critical economic measures of geothermal technologies. Careful selection of materials and optimal configurations of energy geostructures and hybrid systems leads to higher output levels of the system. Improved thermal properties of engineering materials can facilitate thermal storage (i.e. phase change materials) and improve the heat transfer characteristics.

Despite “geothermal power” being referred to as conventional geothermal-based electricity generation in many contexts, different geothermal technologies can fulfil local thermal needs for various applications. Therefore mapping the geothermal resource potential and the thermal needs of the locality, mainly in the agriculture and industrial sectors, allows the evaluation of the most appropriate geothermal technologies that meet techno-economical measures.

CONCLUSIONS

A geothermal anomaly identified by the Geological Survey of NSW consisting of above-average geothermal gradients was examined. Further, different deep and shallow geothermal technologies were reviewed to understand the feasibility of various geothermal technologies and critical research needs for future implementations. The following conclusions were made based on the research.

- The geothermal gradient result in the Hawkesbury Sandstone was calculated as 0.1°C/m at 25m to 75m; 0.4°C/m at 75m to 100m; 0.24 °C/m at 100m to 127m; -0.04 °C/m at 127m to 310m, respectively. In the syenite it was 0.32°C/m at 310m to 333.8m.
- According to the calculated geothermal gradient and thermal conductivity measurements, the geothermal heat flow in the Hawkesbury Sandstone at 80m was 56 mW/m^2 and in the syenite at 325m was 75 mW/m^2.
- Based on statistical results, the calculated radiogenic heat production of syenite, the major heat-producing element content in Lake Nepean-1, is 2.24 μW/m^3. Based on the K_2O median of granite, the relationship between heat production and U and Th enrichment was further simulated.
- Considering the resource potential, shallow geothermal technologies can be identified as viable geothermal technologies, including space heating and cooling applications based on heat pump technologies, geo-energy structures, mine-based geothermal technologies, and geothermal-hybrid systems. Identifying local thermal needs, designing optimal configurations through

detailed analysis and evaluating techno-economic feasibility are essential research needs for future implementations.

- Extending the database of borehole temperature logs, incorporating geochemical data of intrusive rocks and extending datasets of thermal properties of rocks, soil and other engineering materials are essential to strengthen preliminary findings of resource potential and characterise materials for geothermal applications.

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