Geothermal Energy Technology Solutions Based on Canada's Geological Provinces

Katherine Huang, Catherine Hickson

Alberta No. 1

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ABSTRACT

The increased demand for energy, commitment to develop more renewable energy, and need for baseload renewables has pushed geothermal energy development in Canada in recent years. The country's geological diversity, as well as population distribution and infrastructure, require a variety of geothermal systems. Conventional geothermal systems need heat, fluid, and permeability, however, only portions of Canada's orogen and platform provinces have all 3 parameters. Unconventional methods and shallow geothermal systems have been/are being developed to produce geothermal energy in areas that lack one or more of the conventional requirements. As well, new innovations allow for re-purposing existing end-of-life wells and creating heat storage and utilization for use in conjunction with intermittent renewables. This paper outlines seven classes of geothermal energy systems and suggests where each class is suitable for development in Canada. Geologically, Canada is made up of a number of geological "provinces", the most aerially extensive is the Canadian Shield. The Shield, which is comprised of crystalline Precambrian rock and characterized by lower temperatures and low permeability, cannot produce geothermal energy from conventional means; alternative technology is required. This region is potentially suitable for ground source heat pumps south of the permafrost zone (and possibly with heat augmentation within permafrost zones), shallow subsurface hydrological systems, Advanced Geothermal Systems (AGS), Enhanced/Engineered Geothermal Systems (EGS), and heat capture and storage. On the other hand, conventional geothermal development is possible in some sedimentary basins within the platform geological provinces, and there are already several projects being developed. In Canada's orogenic geological provinces, conventional geothermal projects are possible in fault-hosted systems, especially within the volcanic belts that have been shown to have high subsurface temperatures. In both the platform and orogen provinces, AGSs and EGSs are options in areas that lack permeability and/or subsurface fluid, and can also support the shallow systems, borehole heat exchangers, and heat capture and storage.

1. Introduction

The geothermal landscape in Canada continues to be shaped by both challenges and successes, emulating many similar setbacks that projects have faced over the past several decades, such as regulatory hurdles, limited funding, and geological challenges. Despite this, the geothermal industry in Canada is still growing as commercial projects in several provinces and territories continue to develop, while new projects are entering planning phases. Research in many fields of geothermal energy, such as direct heat use, co-production, Enhanced/Engineered Geothermal Systems (EGS), and more, is also very strong across universities and research groups. The continual increase in interest and drive to develop the industry shows strong promise as geological and energy conferences grow their focus on geothermal energy. This is a strong preparation for Calgary, Alberta to host the World Geothermal Congress in 2026.

Development of geothermal energy projects is especially critical since the announcement of the 2030 Emissions Reduction Plan which pledges to reduce emissions of 40% below levels from 2005 and reach net zero greenhouse gas emissions by the year 2050. This plan includes reducing emissions from oil and gas development, lowering energy costs for homes and buildings, and investing in renewable electricity. The Government of Canada plans to invest $600 million for renewable electricity support and grid modernization through the Smart Renewables and Electrification Pathways Program as well as $250 million to support predevelopment work of large-scale, clean electricity projects (Environment and Climate Change Canada, 2022).

The increasing need for renewable energy has in part driven companies and researchers to develop novel technologies, including geothermal energy systems that generate electricity and heat, collaborate with the oil and gas industry, and work with other existing renewables like solar and wind. As well, the variation in geology across the country, the population distribution, infrastructure, and climate lends itself to different requirements and needs. The country's 14 onshore geological provinces (plus 3 offshore) can be divided into orogens (which include mountain and volcanic belts), platforms (hosting sedimentary basins), and the Canadian Shield (Precambrian rock) (Figure 1). These provinces generally outline which technologies may be suitable for development.

This paper provides an overview of the geological provinces in Canada, outlines seven different geothermal classes, attributes which technologies are being used and could be used in each area, and provides examples of each class.

2. Regions and Provinces of Canada

Canada is comprised of 17 geological provinces based on their general rock type, age, and history (Geological Survey of Canada, 1981; Figure 2). The Canadian Shield, characterized by crystalline Precambrian rocks, includes seven geological provinces. Extending beyond the Canadian Shield are platforms where these Precambrian rocks are overlain by younger strata; these are known as the Interior, Arctic, Hudson, and St. Lawrence Platforms, and there are several sedimentary basins within them. At the western, northern, and eastern edges of Canada are the Cordilleran Orogen, Innuitian Orogen, and Appalachian Orogen, respectively. These geological provinces are comprised of mountains, volcanic belts, and other sequences that have undergone significant metamorphism, folding, faulting, and uplift. Finally, there are three continental shelves (not shown on Figure 1).

The use of varying classes of geothermal energy is dependent on many factors. Where favourable geology is present, population density plays a role. The population distribution map of Canada shows that the majority of the country's population lives within the Interior Platform, St. Lawrence Platform, Appalachian Orogen, and Cordilleran Orogen, which has led to progress of several conventional geothermal projects (applicable mostly in platforms or orogens) and ground source heat pumps (GSHPs) (Figure 2). Smaller populations within the Canadian Shield not only have geological challenges, but also limited infrastructure, requiring innovative solutions.

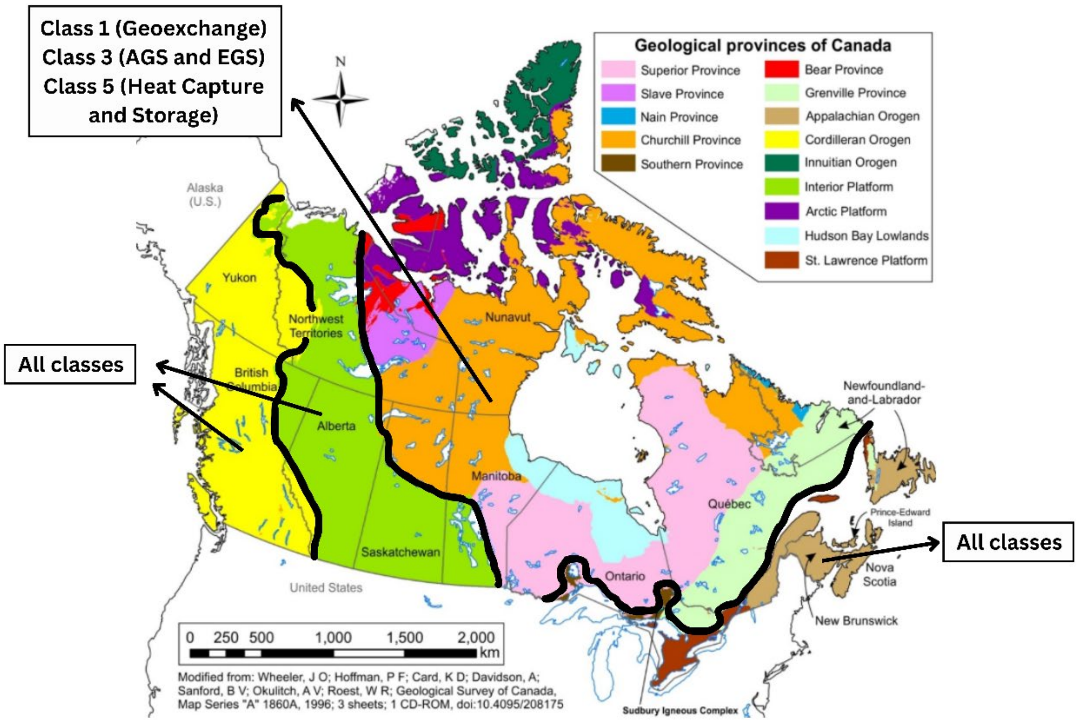

Figure 1: Geological provinces of Canada with suggestions of each geothermal class that could be developed in each (modified from Mercier-Langevin, 2017 and Wheeler et al., 1996).

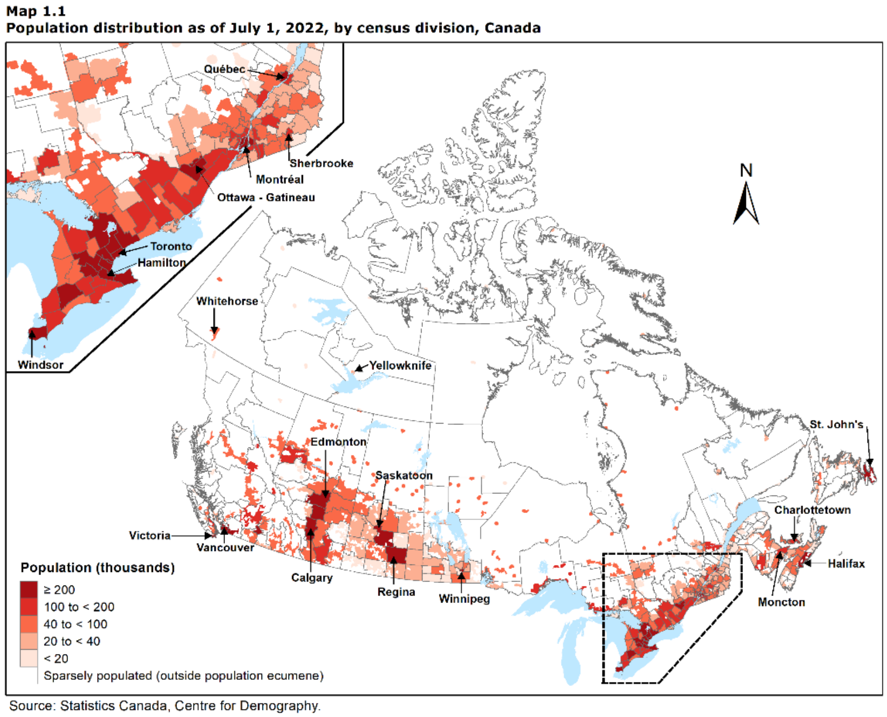

Figure 2: Population distribution map of Canada (Statistics Canada, 2022). The Canadian population reached 40 million in 2023.

3. Classes of Geothermal Systems

This paper divides the potential available geothermal systems into seven classes (Figure 3; Hickson and Smejkal, 2024). Class 1 utilizes the shallow ground/water as a battery for heating and cooling and is divided into 2 subclasses: Class 1 A: Ground Source Heat Pumps (GSHP) and Class 1 B: Shallow Subsurface Hydrological Systems. The most widely known system is Class 2: Conventional Geothermal, which uses a hydrothermal system. Class 3 encompasses 2 types of unconventional geothermal system technology. Unconventional systems are gaining traction in both research and utilization in many areas globally because they provide a solution to "geothermal anywhere". Class 3 systems are defined here as Advanced Geothermal System (AGS) and Enhanced Geothermal System (EGS). Both of these classes have also been referred to as Petrothermal Systems (Hickson et al., 2022) because they are well suited for reservoirs with insufficient permeability and/or fluid volumes for conventional geothermal. Class 4: Deep Borehole Heat Exchangers utilize similar technology to GSHP systems but are deployed down hole into deeper wells. Finally, Class 5 G: Heat Capture and Storage describes an emerging technology which use a subsurface reservoir for artificial heat storage much like those in Class 1, but is capable of storing excess heat at higher temperatures from other energy sources.

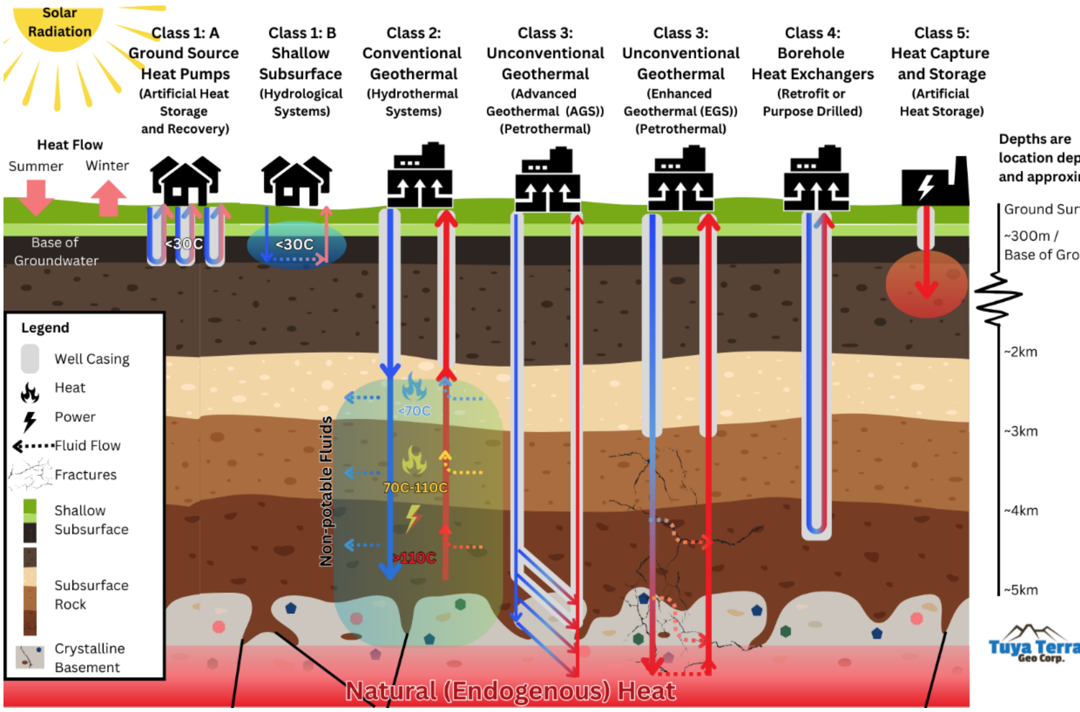

Figure 3: The 7 classes of geothermal systems that are described in this paper as possible solutions in various geological provinces and areas in Canada (Hickson and Smejkal, 2024).

3.1 Class 1: Ground Source Heat Pumps (Artificial Storage and Recovery)

<u>3.1.1 Overview</u>

Ground Source Heat Pumps (GSHP), also called GeoExchange®, are HVAC (heat, ventilation, and air conditioning) systems which use the ground temperature at shallow depths (generally above the base of groundwater) for heating and cooling. The technology extracts temperatures from the soil through closed-loop pipes, a borehole heat exchanger, and a ground source heat pump (Khodayar and Björnsson, 2024). These systems can also be used for artificial heat storage and recovery by storing heat in the shallow ground through heat pumps, then extracted at a later time (Khodayar and Björnsson, 2024).

<u>3.1.2 Potential Areas in Canada</u>

GSHPs can be used anywhere in Canada and have particular importance within the Canadian Shield where the geology limits use of other geothermal systems. However, permafrost zones in Canada's north create challenges for use of GSHPs due to permanently frozen ground and challenges balancing of the heat requirements in the winter months with the ability to store heat in the summer at shallow depths. In general, GSHPs can be easily utilized within the 'No Permafrost' zone (yellow-brown in Figure 4) and may be feasible within the permafrost zone by using heat augmentation and careful load balancing.

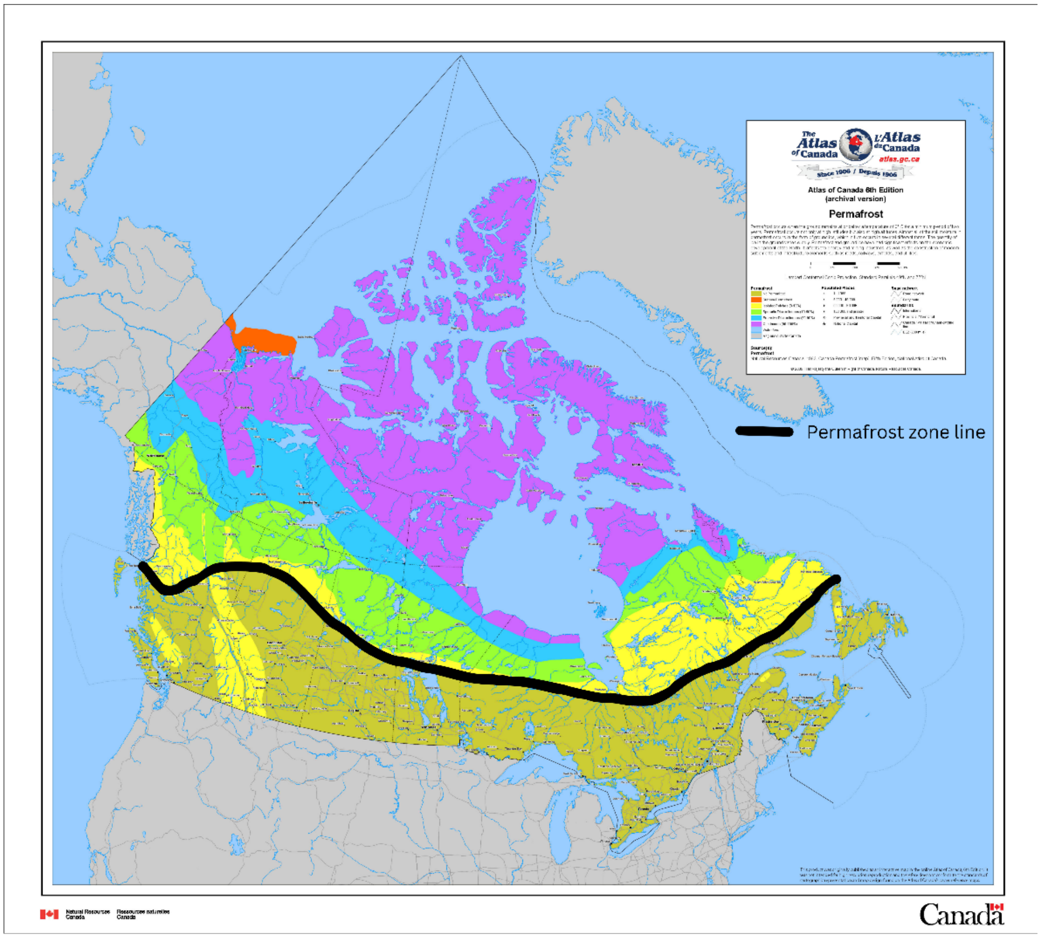

Figure 4: Canada's permafrost zones. The black line separates the zone of no permafrost (yellow-brown region) and zones of isolated patches, sporadic, and continuous permafrost zones to the north of the line. GSHPs can be used below this line but require heat augmentation for use to the north of the line (modified from Natural Resources Canada, 1993).

3.1.3 Examples

There are many GSHP operations in Canada. In Northern Quebec, within the Canadian Shield, the town of Kuujjuak has installed a 30-kW horizontal GSHP system for the community's swimming pool facility (Giordano and Raymond, 2020). A 240-m deep slim hole has also been drilled with the goal of installing a 145-m deep vertical closed-loop GSHP (Geothermal Solutions Inc, 2022). GSHP use is not limited to the Canadian Shield- in the St. Lawrence Platform, for example in Toronto and surrounding towns, GSHPs are becoming popular for district energy systems. The University of Toronto is constructing a large GeoExchange® system on its St. George campus for heating and cooling (University of Toronto, 2022). GeoExchange® systems are already constructed and utilized for select buildings at University of Toronto Mississauga and University of Toronto Scarborough campuses. Additionally, companies like Subterra Renewables partnered with Enercare Inc. plan to provide heating and cooling systems to homes in Canada through GeoExchange® systems.

3.2 Class 1:B Shallow Subsurface (Hydrogeological System)

3.2.1 Overview

Class 1 B systems are very similar to Class 1 A but instead of the ground being used to store heat captured by the GSHP, these systems utilize water sources at shallow depths such as aquifers, lakes, ponds, seas, or even flooded mines (Khodayar and Björnsson, 2024). Generally, these systems work more efficiently for cooling than heating, for example, Toronto's Deep Water Lake Cooling (DWLC) system, but are currently operational in Canada for both uses.

3.2.2 Potential Areas in Canada

In Canada, Class 1 B systems can be installed anywhere with shallow water sources with temperatures that remain relatively consistent throughout the year. They are not suitable for areas of permafrost, but there may be some limited energy gains using deep large lakes or ocean water. Deep mine shafts in areas of permafrost are also potential sources of energy (see below).

3.2.3 Examples

There are several operations in Canada which use shallow hydrogeological systems for heating and cooling. In Nova Scotia, which lies within the Appalachian Orogen, the abandoned coal mines of Springhill are flooded with approximately 4,000,000 m^3 of water. The system pumps this water to the surface (recovered at around 18°C) and through heat pumps where it is used for heating and cooling of many buildings in the nearby geothermal business park (Jessop, 1995; Saltwire, 2019).

Within the Canadian Shield, the City of Yellowknife, Northwest Territories is home to the Con Mine, an abandoned and flooded gold mine. A 2019-2021 study by the Northwest Territories Geological Survey concluded that the thermal energy within the water in the Con Mine contains thermal energy sufficient for heating and cooling buildings for several decades (Huang et al., 2024).

3.3 Class 2: Conventional Geothermal (Hydrothermal Systems)

3.3.1 Overview

Conventional geothermal (hydrothermal) systems utilize the heat and fluid from relatively deep in the earth to create electricity and/or for direct heat use. These systems require permeability and as such do not involve stimulation of the reservoir like EGSs (Khodayar and Björnsson, 2024). As well, conventional geothermal uses open loop technology, in contrast to Advanced Geothermal Systems (AGSs).

3.3.2 Potential Areas in Canada

Conventional geothermal energy production has potential in the sedimentary basins within Canada's platform provinces as well as in the Cordilleran Orogen through fault-hosted and volcanic settings. Several projects are being developed within the Interior Platform, while research is being conducted for potential within the St. Lawrence Platform. Potential for development within the Arctic Platform is also being assessed (Figure 1).

3.3.3 Examples

Conventional geothermal projects in the Interior Platform throughout British Columbia, Alberta, and Saskatchewan are pushing forward. Examples include the Deep Earth Energy Project (DEEP) in southern Saskatchewan that targets the Williston Basin. In the Western Canada Sedimentary Basin (WCSB), Alberta No. 1 near Grande Prairie, Alberta, and Tu Deh Kah outside Fort Nelson, British Columbia, are in various development stages. Near Swan Hills, Alberta, Futura Power has begun operations on their geothermal and natural gas co-production plant where geothermal energy powers approximately 30% of the 21 MWe power plant (Huang et al., 2024).

In the Arctic Platform, several studies have been conducted to assess the geothermal potential in Nunavut. In 2018, a feasibility assessment by the Qulliq Energy Corporation indicated that power could be produced within the sedimentary basins of the northern Arctic Islands (Minnick et al., 2018), but noted major data gaps that still must be addressed. In 2023, researchers from the University of Alberta assessed the potential for geothermal energy development in Resolute Bay and Cambridge Bay (both within the Arctic Platform) as data from oil wells drilled in the 50s and 60s suggest slightly higher than average temperatures; they also found that heat might be sufficient to generate electricity (The Weather Network, 2023). As all communities in Nunavut rely on diesel for power generation, geothermal energy could drastically change the territory's energy usage.

In the Cordilleran Orogen, Geoscience BC is studying the Kootenay Lake, British Columbia area for direct heat use potential within a deep-seated fault system. The 2023 summer and fall research phase found evidence of a geothermal reservoir of over 70 °C within the fractured rock (Geoscience BC, 2024). The Kitselas project is also assessing for potential for direct heat use near Lakelse Lake, British Columbia and has recently received funding. Within the Garibaldi Volcanic Belt of British Columbia, Mount Meager has seen multiple rounds of geothermal investigations, including drilling of several wells in the 1990s. These wells discovered high-temperature resources exceeding 250 °C but found that permeability was insufficient for economic geothermal energy production (Jessop, 2008; Witter, 2019; Grasby et al., 2022). The Garibaldi Volcanic Belt has recently been the focus of a geothermal study by GeoscienceBC, with Phase 1 focusing on developing methods to more accurately map high permeability zones in the reservoir (Grasby et al., 2022).

3.4 Class 3: Unconventional Geothermal (Advanced Geothermal (AGS), Petrothermal)

3.4.1 Overview

Unconventional geothermal describes systems that utilize technology to extract heat from the subsurface in geological settings that lack fluid and/or permeability. This paper describes two sub-classes of unconventional systems- Advanced Geothermal Systems (AGS), and Enhanced (or Engineered) Geothermal Systems (EGS). These systems have also been referred to as "petrothermal" (Hickson et al., 2022).

AGSs utilize long drilled wells that are connected and closed to the formation rocks into which they are drilled. Heat is extracted by proprietary fluids (working fluids) circulating through the radiator like system of connected wells. Heat is transferred by conductive heat transfer from the surrounding rocks into the working fluid (IRENA 2023). Because these systems rely on conductive heat transfer, long and/or many well bores are required which can increase drilling and total project cost, however, they have the potential to successfully extract heat in almost any location globally, fulfilling the dream of "geothermal anywhere" (IRENA 2023).

3.4.2 Potential Areas in Canada

These systems are most efficient in areas of high rock conductivity, high heat flow and tight crystalline rocks that do not require casing or synthetic "rock pipe" to prevent escape of the working fluid. They can potentially be installed anywhere depending on how the technology develops and the investment limits. The deeper and cooler the system the more expensive the installation due to drilling costs. Within Canada, there is potential within the platforms and orogens where local permeability and fluid volumes are limited, and especially within the Canadian Shield where outcrop and subsurface is Precambrian granite.

3.4.3 Examples

Canada-based company, Eavor, has developed two AGSs- Eavor Loop 1 for sedimentary rocks and Eavor Loop 2 for igneous rocks. Eavor Loop 1 includes vertical production and injection wells drilled 50 – 100m apart to around 4.5 km depth. At this depth, the wellbores bend and 24 lateral wells are drilled to maximize surface area for conductive heat transfer (Khodayar and Björnsson, 2024). If the temperatures are high enough, water is circulated then heat is converted to power at the surface using an Organic Rankine Cycle (ORC); otherwise the system operates to provide thermal energy through a heat exchanger system. Eavor Loop 2 is very similar but the wellbores are drilled deeper to reach hotter temperatures. Their demonstration project for Eavor Loop 1 near Hinton, Alberta (in the Interior Platform) is operating at a thermal output of approximately 800 kWth (Huang et al., 2024; Toews et al., 2020).

3.5 Class 3: Unconventional Geothermal (Enhanced Geothermal (EGS), Petrothermal)

3.5.1 Overview

EGSs utilize stimulation, either by hydraulic, chemical, or thermal means, to increase the permeability of a geothermal reservoir (IRENA 2023). They are viable options in reservoirs with limited permeability and/or subsurface fluid. They generally require elevated temperatures but can be drilled very deep to access hot, deep rocks.

3.5.2 Potential Areas in Canada

Almost all areas in Canada are potentially viable for EGS development. There are reservoirs within the platform and orogenic provinces where subsurface temperatures are sufficient for conventional geothermal, but permeability in the target formations have been shown to be too low, such as in the Liard Basin of the Northwest Territories, which lies within the Interior Province (Huang et al., 2024). EGSs also have potential within the Canadian Shield if drilled deep enough. EGSs have advantages over AGSs in that they require significantly less drilling and thus have a much lower CAPEX compared to AGSs. However, the CAPEX for EGSs is still higher than conventional Class 2 systems. Currently there is significant research funding being directed towards these systems in jurisdictions such as the US as they are seen as the most likely solution to "geothermal anywhere", notably, the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) initiative.

3.5.3 Examples

U.S.-based company Fervo Energy has developed and tested an EGS technology which uses pairs of horizontal injection and production wells (Norbeck et al., 2023). In 2023, they announced the completion of "Project Red", a 3.5 MW test plan in Nevada which now delivers power to the local grid (Fervo Energy, 2023). They have also begun development of a 400 MW power plant in Utah which plans to be operational by 2026 (Fervo Energy, 2024). In Canada, E2E Energy Solutions is planning to use a new technology called Enhanced Geothermal Reservoir Recovery System (EGRRS) to provide power and heat in the community of Rainbow Lake, Alberta, which lies within the Interior Platform. The EGRRS plans to combine conventional and EGS technologies by injecting the reservoir fluid into a deeper, stimulated reservoir to increase the temperature (E2E Energy Solutions, 2024). Utah FORGE, sponsored by the US Department of Energy, is an 'underground field laboratory' dedicated to developing and testing EGS technologies. The research and development initiatives are focused on basement fracture networks and how they can be initiated and sustained (Office of Energy Efficiency and Renewable Energy; Utah FORGE, 2024). The goal is to understand and develop EGS technologies and resources to make geothermal development possible anywhere.

3.6 Class 4: Borehole Heat Exchangers (Retrofit or Purpose Drilled)

3.6.1 Overview

Borehole heat exchangers are a part of GSHP systems, however, this class refers to installation of borehole heat exchangers in deep wells to extract the heat from circulating fluids. A borehole heat exchanger is comprised of a heat exchanger inside a borehole where fluids are heated up through conductive heat transfer from the rock and circulated. This is a closed-loop system that does not involve production of fluid to the surface (Toth, 2017). As well, they are drilled to shallower depths than conventional geothermal and generally only used for direct heat purposes. Two possibilities with this technology are to repurpose existing wellbores and/or to drill purposed-drilled new wells. The former option is attractive because it has the potential to utilize dry, unsuccessful or end-of-life wells, however, most existing oil and gas wellbores lack the diameter to allow for sufficient heat transfer.

3.6.2 Potential Areas in Canada

Deep borehole heat exchangers can be utilized almost anywhere with sufficient thermal conductivity and have high potential in areas with high heat flow. One example is in the Dehcho Region near Nahanni Butte, Northwest Territories in the Interior Platform, as the thin sedimentary cover overlaying the rocks of the Canadian Shield in the area make conventional geothermal development challenging, but its elevated heat flow suggests potential for deep borehole heat exchangers (Grasby et al. 2021; Smejkal et al., 2023).

3.6.3 Examples

One example of this developing technology is the GreenLoop Closed Loop Geothermal system, developed by Greenfire Energy, which consists of several closed-loop borehole pipes in a single well with various working fluids to produce either electricity or heat. Their 2019 field test in Coso, California indicated that their technology installed in an idle well could produce approximately 1.2 MWe (Scherer et al., 2023).

3.7 Class 5: Heat Capture and Storage (Artificial Heat Storage)

3.7.1 Overview

Class 5 describes a heat capture and storage system that creates an artificial reservoir to store excess heat from other energy sources for later use. In the cases of wind and solar power, the power would be stored as hot water or steam, then brought to the surface for electricity production when wind and solar are not producing (World Economic Forum, 2022). This emerging technology has potential to provide a storage solution for excess wind and solar energy as Canada looks to decarbonize its grid with intermittent renewable power sources.

3.7.2 Potential Areas in Canada

In Canada, heat capture and storage systems can be used anywhere that there is excess heat and/or power production. Based on results of pilot projects and new studies (described below), there is potential for storage in EGS reservoirs and depleted oil and gas reservoirs.

3.7.3 Examples

Vantaa Energy is planning the construction of an innovate heat storage system in Finland. The project plans to build underground caverns to store hot water. When renewable electricity production is cheap or production is in excess of load, it will power electric boilers to heat water which will then be stored in the underground caverns (pv magazine, 2024).

U.S.-based company Sage Geosystems has developed a system called EarthStore™ for heat capture and storage. The pilot project in Texas involved initially creating a large vertical reservoir (over 3 km deep) using fracturing technology then pumping and storing water in the 3,200-foot vertical reservoir deep underground using its novel fracturing technology. Demonstrating long-term and short-term storage capabilities, the pilot produced 200 kWe for over 18 hours and 1 MWe for 30 minutes (Sage Geosystems, 2023).

In 2023, the National Renewable Energy Laboratory (NREL) announced a new project to evaluate the potential of heat capture and storage systems. This will involve a case study to assess using depleted oil and gas reservoirs for solar thermal storage in California, and another case study for storage of excess wind power into water reservoirs in Texas to explore using legacy oil/gas reservoirs with solar thermal hybridization in California (NREL, 2023).

4. Conclusions

The increasing global demand for renewable energy has birthed innovations within geothermal energy systems, making geothermal energy production possible in reservoirs with limited permeability, low heat flow, and inadequate fluid volume. Geothermal energy is a viable solution to help meet Canada's emissions reductions goals, however, unconventional methods must be considered for energy production within many of the country's geological provinces. The seven different classes of geothermal systems described in this paper include two types of shallow, GeoExchange® systems (GSHPs and hydrological systems; Class 1), conventional geothermal (Class 2), two types of unconventional systems (AGS and EGS; Class 3), borehole heat exchangers (Class 4), and heat capture and storage (Class 5). While many areas within Canada's interior platform and orogenic provinces host reservoirs capable of producing conventional geothermal energy (in both sedimentary basins and fault-hosted volcanic systems) at lower cost, the geology of the rest of the country lacks one or more of permeability, heat flow, and fluid volume. In the Canadian Shield, where Precambrian rock outcrops, geothermal energy production is possible through AGS, EGS, GeoExchange®, and heat capture and storage, although environmental implications in zones of permafrost must be considered for GeoExchange®.

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