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Canada's Geothermal Energy Update in 2023

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Abstract: Geothermal energy exploration, development, and research have been ongoing in Canada for several decades. The country's cold climate and the push to develop renewable energy sources have driven interest in geothermal energy. Despite this drive, regulatory complexities and competition with other relatively inexpensive energy sources with existing infrastructure have hindered development. As such, interest has grown and waned with changes in the energy economy over several decades, leaving many projects at a standstill. As of January 2023, there are currently no operational geothermal power projects in Canada. Many hot spring pool and spa complexes remain active, and Canada is a leading country in the installation of ground source heat pumps (GSHPs; also called geo-exchange systems). However, in the last decade, the interest in deep geothermal systems has renewed, with many new projects starting up across several provinces and territories. Moreover, projects that had shown limited progress for many years—such as Mount Meager in British Columbia—have begun to renew their development efforts. Research is also expanding within prominent research groups and universities. The areas of focus include both building upon previous studies (such as thermal gradients and the heat flow in sedimentary basins) and researching new methods and resources (such as GSHPs, closed-loop systems, integrated geothermal operations, and hybrid systems, including heat storage). The development is supported by federal, provincial, and territorial governments through grants and the development of regulatory frameworks. Although challenges still remain for Canada to develop its geothermal energy resources, several power, thermal, and co-production projects, ongoing research, funding, and regulatory acts are all moving forward to support geothermal development. This paper aims to study Canada's geothermal energy update in 2023 regarding the aspects mentioned above.

Keywords: geothermal; direct use; power generation; regulatory framework; Canada; renewable energy

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1. Introduction

Canada, the world's second-largest country, stands as one of the top per capita energy consumers on a global scale [1]. Various regions within Canada employ different energy sources for the production of both electrical and thermal energy. For example, hydroelectric power is the predominant source of energy for generating electricity in British Columbia, Quebec, Manitoba, Newfoundland and Labrador, and Yukon. In contrast, Ontario, New Brunswick, and the Northwest Territories (NWT) draw from diverse sources, including nuclear, hydroelectricity, wind, biomass, coal, natural gas, and petroleum. Fossil fuels, on the other hand, play a significant role in electricity production in Alberta, Saskatchewan, Nova Scotia, and Nunavut [2]. Therefore, there is a need to transition from carbon-based fuels to environmentally friendly or low-carbon energy sources, such as geothermal energy, whilst also adopting eco-friendly technologies and sustainable practices. Geothermal energy, either used independently or in combination with other energy sources and storage methods, has the potential to serve as a dependable and sustainable element in Canada's future clean energy systems.

Canada has immense geological diversity, including cratons, sedimentary basins, recent volcanism, mountains, and more. As such, many types of geothermal energy are being considered across the country, including conventional geothermal energy, closed-loop technology, and GSHPs, in addition to the co-production of hydrocarbons and other types of hybrid systems. Additionally, variations in existing energy sources, population density, and proximity to infrastructure throughout the country have led to a diversity of geothermal energy projects and technologies. Canada's northern climate and extensive areas of permafrost create both opportunities, such as very high heating loads and large temperature differences, and challenges, such as ground ice.

Canada is made up of ten provinces and three territories, each unique in terms of economics, population, geography, and geothermal energy development. Some of them, such as Nova Scotia and British Columbia, have been areas of development and research for several decades [3], while others are just beginning to consider geothermal energy as part of their energy mix. A map of Canada with the approximate locations of the projects and studies mentioned in this paper is shown in Figure 1.

The main goal of this paper is to provide an overview of new projects, updates to current projects, and developments in policies, funding, and other government support, as well as updates on academic research and programs in Canada.

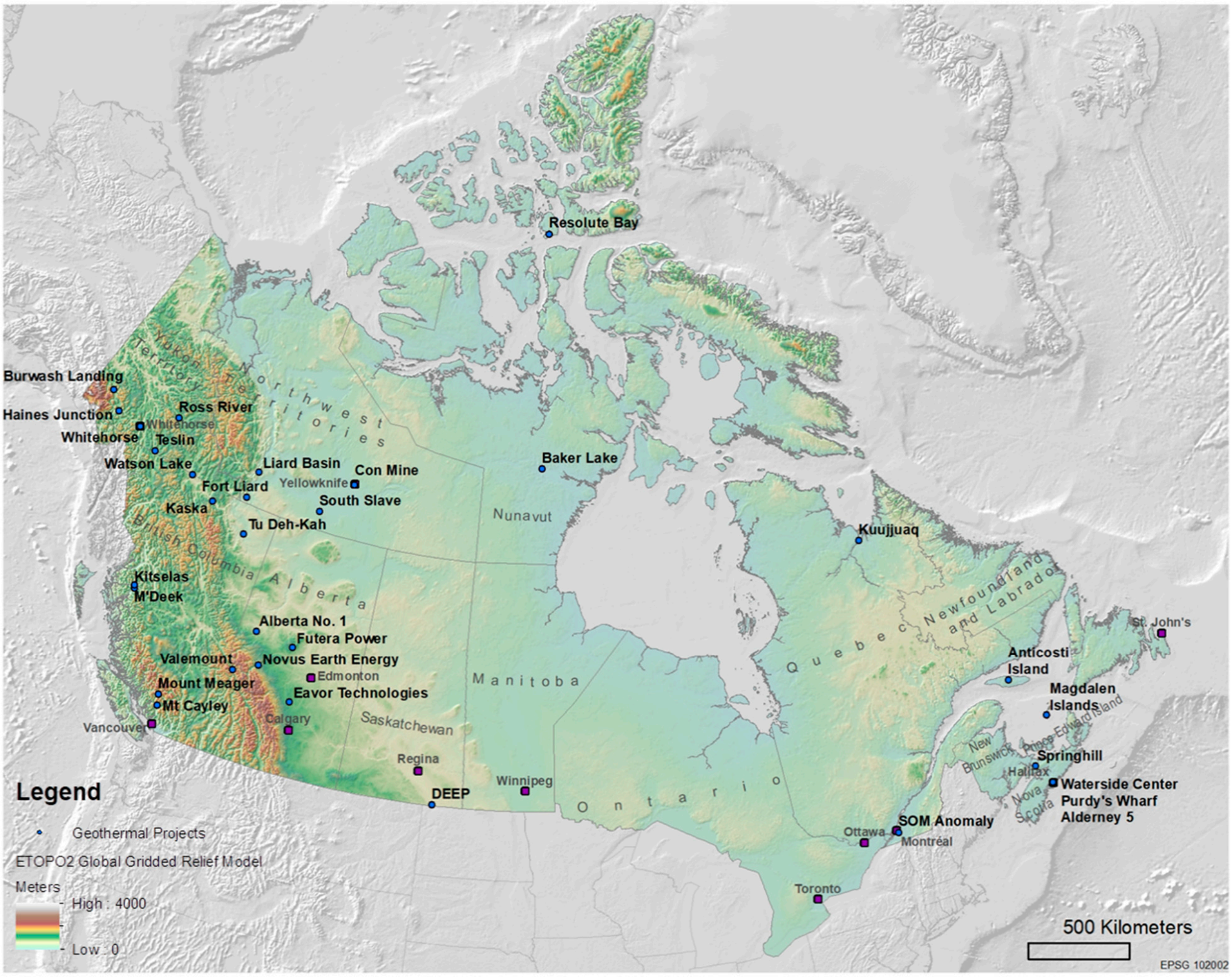

Figure 1. The approximate locations of industrial geothermal projects, research projects, and ongoing studies in this paper (modified based on the map by GEOSEIS in 2023, made for this current study).

2. Geothermal Regulatory Frameworks and Acts

Canada's geothermal energy industry is still in its infancy. Only British Columbia, Alberta, and Nova Scotia have geothermal legislation in place. One issue has been clarity regarding what is defined as "geothermal," including how to differentiate between the systems that extract naturally occurring heat and those that use either the ground, shallow aquifers, or surface (or mine) water for heat storage and extraction [4]. Geo-exchange systems have a long history of use in Canada, making the country one of the top nations per capita in terms of the deployment of geo-exchange systems. Geo-exchange system installation usually falls under groundwater regulations or other regulations dealing with surface construction and equipment, whereas geothermal systems require a more specific regulatory regime [5].

In Canada, the development of resources is controlled by the individual provinces and territories. Most of the subsurface rights in Canada are owned by the "Crown." In provinces, this is the Provincial Government, and in Territories, the federal government. In some cases, resource rights may be owned by the surface owners, but these cases are relatively rare. The subsurface rights are leased to corporations or individuals by the Crown. For this reason, each province and territory has developed, or is in the process of developing, its own regulations for geothermal development. A summary of the provinces and territories that have already established or are currently working on geothermal regulatory frameworks is briefly described below.

2.1. British Columbia

2.1.1. Geothermal Resource Definition

Geothermal resources are defined in the Geothermal Resources Act as follows: "the natural heat from the earth and all substances that derive an added value from it, including steam, water, and water vapor heated by the natural heat from the earth, and all substances dissolved in the steam, water, or water vapor obtained from a well, but does not include (a) water that has a temperature of less than 80 °C at the point where it reaches the surface, or (b) hydrocarbons."

2.1.2. Summary of Resource Tenure

- Resource is governed by fluid temperature.
- Multicommodity extraction is not permitted (e.g., hydrocarbons and/or mineral commodities, like lithium in brine).
- Rights are granted via public tender.
- Lease is one "Block" (defined by the Petroleum and Natural Gas Grid Regulation; approximately 136 km^2).
- Rights are exclusive to a single owner.

2.2. Alberta

2.2.1. Geothermal Resource Definition

Geothermal resources in Alberta are defined in both the Mines and Minerals Act and in Bill 36: Geothermal Resource Development Act as "the natural heat from the earth that is below the base of groundwater protection." Of note in this definition is the reference to natural heat from the earth and the exclusion of any reference to subsurface fluids produced from a subsurface reservoir and any constituents dissolved in those produced fluids. In addition, the geothermal resource, as defined in Alberta, occurs only below the base of groundwater protection. Alberta's geothermal act was just made into law on 31 December 2021, after a multiyear drafting and consultation process. Bill 36 is heavily based on Alberta's existing oil and gas regulations and provides limited direct support for geothermal development [4].

2.2.2. Summary of Resource Tenure

- Resource is governed by heat.
- Multicommodity extraction is permitted (but appropriate rights must be held, such as petroleum and natural gas (PNG) rights for hydrocarbon extraction).
- Rights are granted via application.
- Lease is nine sections, all of which must be laterally or diagonally adjoining.
- Rights are non-exclusive to a single owner (i.e., the current legislation has not defined how multiple geothermal operators may operate in a single locality; this is seen as a major failing of Bill 36 [4]).

In August 2022, the Alberta Energy Regulator (AER) released Directive 089: Geothermal Resource Development, which outlines the requirements for geothermal resource development below the base of groundwater protection; in other words, these are the rules for activities such as well designs and drilling activities under which geothermal development can take place.

2.3. Saskatchewan

2.3.1. Geothermal Resource Definition

Geothermal resources are not yet defined in Saskatchewan legislation. However, some guidance is available through the Government's Integrated Resource Information System—the platform through which various applications may be submitted, including Storage Project Applications, which appear to be the vehicle for a geothermal project. In the Integrated Resource Information System, a geothermal project is defined as follows: "A geothermal project means a development where geothermal energy is recovered through deep well(s). There are two main types of geothermal projects: open-loop and closed-loop. An open-loop system includes: (1) withdrawing formation water for the purpose of extracting geothermal energy as part of an industrial process, and (2) disposing of the cooling fluids into the subsurface following the extraction of its heat content. In a closed-loop system, source fluids are circulated in a sealed wellbore, heat exchange loop, and there are no formation fluids to be withdrawn or fluids to be disposed. The geothermal project application is only applied to subsurface activities."

Based on this definition, an open-loop geothermal operation is a reasonable fit with the concept of a "Storage Project Application."

In a government guidance document on the regulation of disposal wells, geothermal projects are defined as follows: "A geothermal project means a development that geothermal fluids are produced from a water source well, the geothermal energy is recovered at the surface as part of an industrial process for any purpose, and the cooling fluids are disposed of into subsurface through a waste disposal well."

Again, this definition seems to be well-suited for an open-loop geothermal scheme but not a closed-loop operation, which has no need for disposal other than while drilling operations are underway.

2.3.2. Summary of Resource Tenure

- Resource is governed by pore space.
- Multicommodity extraction is not permitted.
- Rights are granted at government discretion.
- Lease's size is not defined.
- Rights are exclusive to a single owner.

2.4. Quebec

After a period of inertia, geothermal energy, beyond GSHPs, is now receiving increasing attention within Quebec's province. The term "deep geothermal energy" was mentioned for the first time in a new Bill: "Loi visant principalement à mettre fin à la recherche et à la production d'hydrocarbures ainsi qu'au financement public de ces activités," which was adopted in 2022. This new bill is an important step taken within Quebec's energy transition plan since it aims at ending the exploration for and production of hydrocarbons and ending public financing of these activities. Furthermore, this new bill authorizes the implementation of pilot projects to acquire geoscientific knowledge related to, among other topics, deep geothermal energy potential. The Institut national de la recherche scientifique (INRS) submitted a memorandum at the time consultations were made to improve the law and suggested better-defined regulations for pilot geothermal projects [6]. The INRS continues to work in close relation to the Ministère de l'Économie, de l'Innovation et de l'Énergie to assess the potential of converting suspended oil and gas wells into ground heat exchangers to harness geothermal resources. Shallow resources associated with geothermal heat pump resources remain regulated through the Règlement sur le captage des eaux souterraines of the Loi sur la qualité de l'environnement.

2.5. Nova Scotia

Nova Scotia was an early adopter of geothermal legislation, in part because of the Springhill Mine (Figure 1) and the province's experience with oil and gas operations. In 2016, Bill No. 149: Mineral Resources Act was passed.

2.5.1. Geothermal Resource Definition

The purpose of the Act is to "support and facilitate responsible mineral resource management". Both minerals and geothermal energy are included as mineral resources. The Act defines a geothermal resource as the following: "a substance, including steam, water and water vapor, that is found anywhere below the surface of the earth and that derives an added value from the natural heat of the earth present in, resulting from or created by the earth."

2.5.2. Summary of Resource Tenure

- All minerals are reserved for the Crown.
- A "geothermal resource area" is designated by the Governor in Council.
- A royalty regime is provided for mineral resources.

2.6. Yukon

In 2020, the Government of Yukon released "Our Clean Future: A Yukon Strategy for Climate Change, Energy and a Green Economy." This document outlined actions the Government of Yukon would take to ensure Yukoners could access reliable, affordable, and renewable energy. One action the government committed to was developing a Geothermal Resources Act (Action E11) that would regulate geothermal energy development in the territory to help reduce Yukon's reliance on fossil fuels and to meet its needs for electricity and heat.

A public engagement process was hosted by the Department of Energy, Mines and Resources through an open, direct call for submissions. The purpose of this engagement was to gather feedback regarding new geothermal legislation and ensure the public had an opportunity to identify and contribute to key aspects under legislative consideration. During this phase, direct feedback was received from non-governmental organizations, industry representatives, First Nations, various levels of government, and members of the public from Yukon, western Canada, and Iceland. The engagement period ended in September 2022. Following this, the Government of Yukon will be publishing a "What We Heard" report based on the submissions from the public. Overall, the feedback received was positive, with strong support for the development of geothermal resource legislation in the territory. The policy and regulatory framework considerations that received the most interest and input pertained to the definition of geothermal resources, regulatory regime considerations, royalty structures, and issues surrounding decommissioning and reclamation. A significant number of stakeholders wanted to clearly state their willingness and interest to work with Indigenous governments and communities to ensure positive and productive collaboration in any future geothermal resource projects.

This feedback further reinforced the Government of Yukon's interest in and commitment to the development of geothermal resource legislation and ongoing governmental commitment to government discussions involving Indigenous communities that may be affected by any potential geothermal exploration and development. It also further informed and identified options to create a conducive investment environment that would encourage geothermal development in the territory. The legislative framework continued development through 2023.

2.7. Northwest Territories (NWT)

In 2010, the Government of Northwest Territories (GNWT), Department of Environment and Natural Resources, commissioned the Pembina Institute to complete an inter-jurisdictional review of geothermal energy legislation and policy [7]. However, this report did not result in further activity toward the development of a geothermal regulatory framework.

In 2018, the GNWT released its "2030 Energy Strategy," which identified geothermal energy as one potential component of the government's strategy for greenhouse gas (GHG) emission reduction and the development of secure, affordable, and sustainable energy in the NWT. In the same year, the GNWT also released the "2030 NWT Climate Change Strategic Framework," outlining the Government's goals to transition to a strong, healthy economy that uses less fossil fuels, reduces GHG emissions, increases the understanding of climate change impacts in the NWT, and builds resilience and adaptation to a changing climate. These government goals spurred renewed interest in geothermal energy in the NWT, leading to a rekindled interest in geothermal energy regulatory frameworks.

The GNWT recognizes that much has changed on the global scene in the decade since the report provided by the Pembina Institute. Therefore, in 2021, a new report was commissioned by the University of Calgary's School of Public Policy—Extractive Resource Governance Program [5]. This report is anticipated to be publicly released as a peer-reviewed Open File by the Northwest Territories Geological Survey (NTGS) and is expected to be the first step toward the development of a tailor-made geothermal regulatory framework for the NWT.

2.8. Other Jurisdictions

All other jurisdictions are currently treating geothermal and geo-exchange projects on a case-by-case basis. In most cases, existing drilling regulations under water resources acts or other resource extraction regulations (e.g., diamond drilling for mining exploration and the development of hydrocarbon extraction) are being used. In the case of geo-exchange projects, construction regulations and the regulations pertaining to boring geotechnical boreholes are typically used. Environmental regulations are also being treated on a case-by-case basis.

3. Province and Territory Updates

3.1. British Columbia

Exciting progress has been made on geothermal energy exploration and development projects across British Columbia (Figure 1). Indigenous communities and private developers are taking an active leadership role in advancing the exploration of geothermal resources in both volcanic settings and the development of sedimentary-hosted geothermal resources. In Canada, British Columbia has been leading the nation in terms of advancing geothermal investigations, building on the early research by Fairbank and Faulkner [8] in 1992, later detailed technical and economic work conducted by Kerr Wood Leidal Associates Ltd. [9] in 2015 on power generation, and Hickson et al. [10] in 2016 on direct-use applications. A summary of the progress of key projects is provided below.

3.1.1. Mount Meager

A new project in the Garibaldi Volcanic Belt [11] (Figure 1), which includes Mount Meager, is focused on efforts to reduce the risk of exploration in a regions with some of the highest geothermal potential in Canada. The project has received CAD 500,000 in funding from Geoscience British Columbia (GBC) in 2019, along with provincial and federal contributions. In 2021–2022, Phase 2 of the GBC study focused on the Mount Cayley area, including field mapping and data collection. The Phase 2 final report will summarize the geothermal potential of the Garibaldi Volcanic Belt [12]. An online community open house was hosted in August 2021 by GBC, led by Dr. Grasby of the Geological Survey of Canada (GSC) to provide an update on the Garibaldi Geothermal Volcanic Belt Assessment [12].

In addition to the research efforts by the GSC in the Garibaldi Volcanic Belt and previous studies conducted by GBC, there are currently two active geothermal leases in the Mount Meager area. This region has witnessed intermittent geothermal exploration over the past half-century, with reports of downhole temperatures exceeding 260 °C. However, the permeability found in the young rocks of the region during historical exploration efforts was insufficient to economically produce electricity. The upcoming developers plan to apply modern exploration methods and drilling technologies to increase the likelihood of discovering hot and highly permeable subsurface zones. The south lease is owned by Meager Creek Development Corporation, a private developer with the goal of producing green hydrogen from geothermal energy. The north lease is owned by Tecto Energy, which aims to generate electricity from the geothermal resources underneath.

The Meager Creek Development Corporation's project is situated 70 km northwest of Pemberton, British Columbia, in the Coast Mountain Range, as shown in Figure 2. The project is accessible via existing forest service roads, with minor upgrades slated for 2023, ahead of the drilling target timeline in Q3 2023. The Meager Creek Development Corporation holds a geothermal lease over an area of 4270 hectares, permitting the exploration and development of geothermal resources [13].

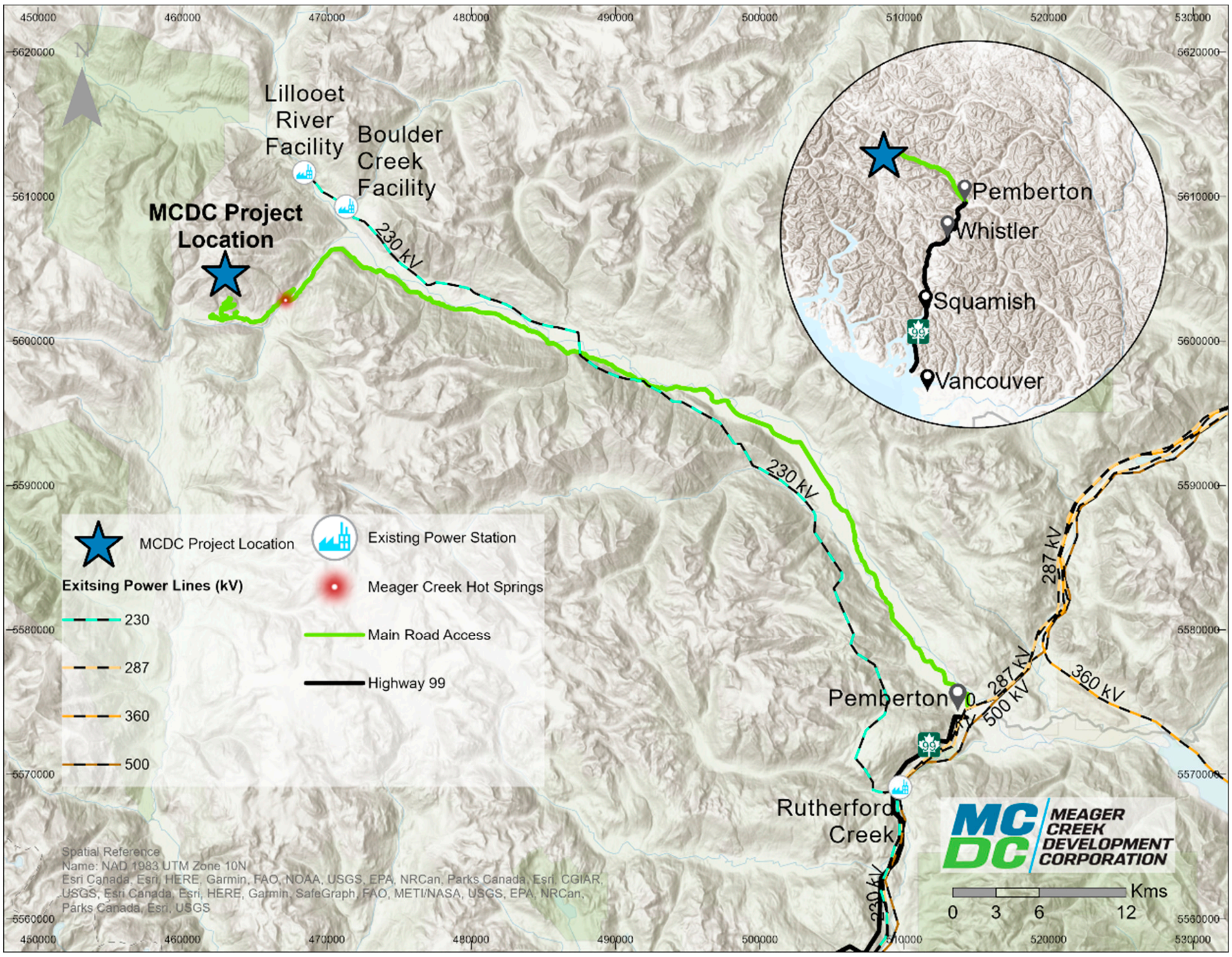

Figure 2. Mount Meager: map of Meager Creek project location [13].

3.1.2. Tu Deh-Kah (TDK)

In northeast British Columbia, the Clarke Lake depleted natural gas reservoir (Figure 1) is being re-developed for its geothermal energy potential. The Clarke Lake reservoir, located within the Western Canada Sedimentary Basin (WCSB), is the oldest and amongst the most abundant gas fields in British Columbia. After 60 years of production, it has become economically unviable due to high water cuts. The reservoir is situated adjacent to the town of Fort Nelson, a northern Canadian town known for its long and cold winters. The Indigenous people of the region, the Fort Nelson First Nation (FNFN), are the project proponents. In August 2021, the FNFN renamed the project using their traditional Indigenous language to the Tu Deh-Kah (TDK) geothermal project. The project has received significant funding support from federal and provincial grant programs, most notably the Emerging Renewables Power Program (ERPP) through Natural Resources Canada (NRCan), a federal government department.

The TDK project aims to generate 7–10 MWe in net electrical generation using the binary Organic Rankine Cycle (ORC) technology, with commercial operation anticipated in early 2026. In addition to power generation, the project is exploring direct heat use and cascading geothermal opportunities. A likely direct heat use in this northern, remote, cold community is to utilize geothermal heat to contribute to food security through agricultural and/or greenhouse development. In 2021 and 2022, the British Columbia Ministry of Energy, Mines and Low Carbon Innovation granted the TDK project proponent two Geothermal Exploration Permits, covering an area of approximately 13,400 hectares, across the extent of the target geothermal reservoir reef sequence, as shown in Figure 3. These permits grant TDK the rights to investigate and develop the geothermal resources in the area.

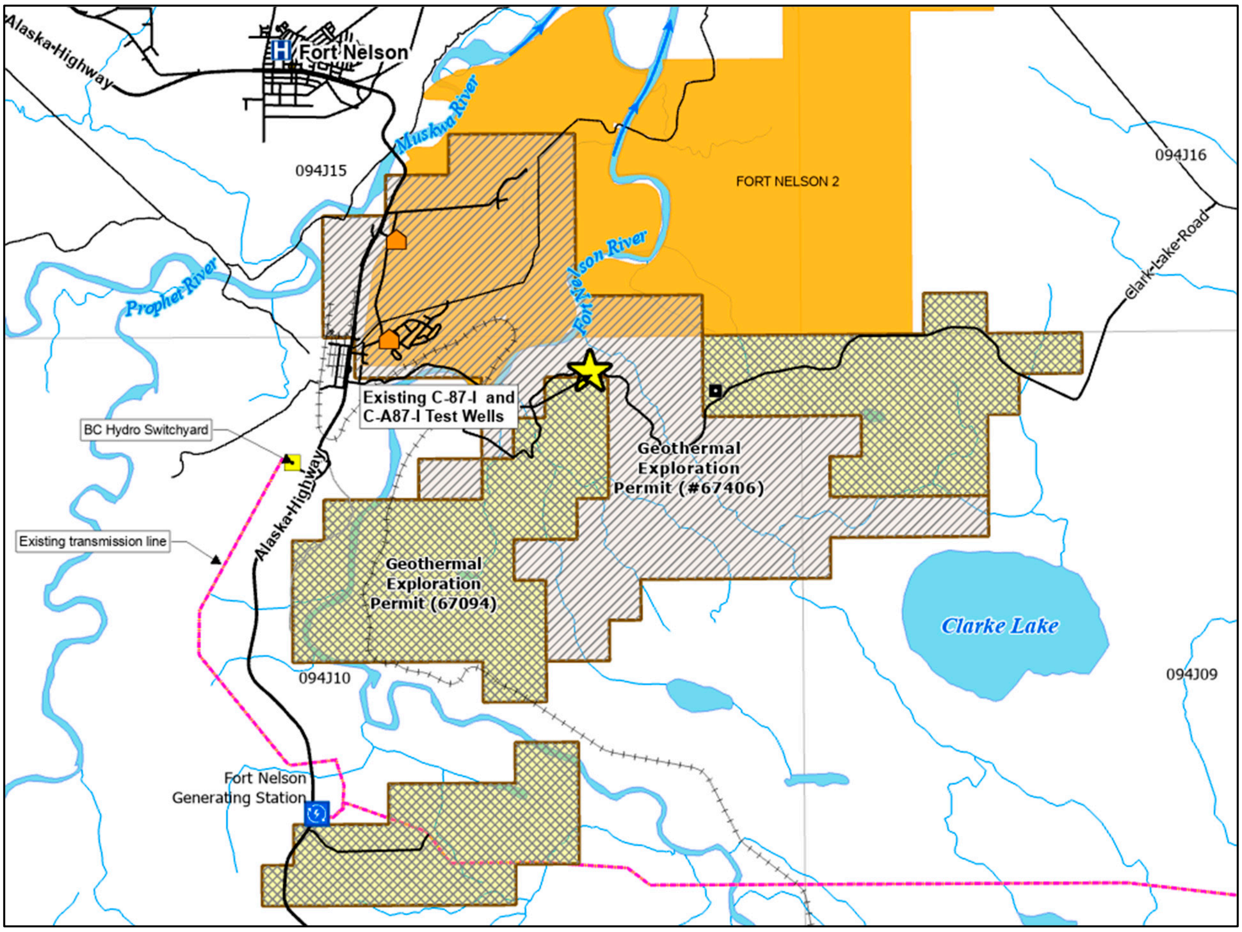

Figure 3. Tu Deh-Kah: overview of geothermal exploration permit areas and C-A87-I well test site [14].

Based on the abundance of the existing well data, Phase 1 of the project, focused on geothermal exploration, was already completed at the outset of the TDK project development in 2019. Phase 2 was finished in 2020 and included significant geoscience investigations, conceptual reservoir modelling of the geothermal resource, and background studies into the social and environmental concerns related to geothermal development. Phase 3, completed in 2021, involved drilling and completing the TDK geothermal test well, as well as deepening and refurbishing an existing gas well. This TDK well doublet comprises a full-sized geothermal producer and a re-purposed natural gas well serving as a temporary re-injection well for testing purposes. The observations and data collected so far via well logs and temperature logs indicate that the geothermal resource's temperature quality is in line with expectations, around 120 °C. Highly permeable target production intervals were encountered during drilling. The next major phases of work will include full well field drilling in 2024, followed by surface facility construction in 2025, and commissioning of the ORC power plant in 2026.

3.1.3. Kitselas Geothermal

In the coastal northwestern region of British Columbia (Figure 1), Kitselas Geothermal Inc. is advancing its "Fuel for Reconciliation" project through additional geophysical surveys and has secured CAD 500,000 in funding from the First Nations Clean Energy Business Fund. In August 2022, Kitselas Geothermal Inc. [15] formed a partnership with Shell Canada to support the de-risking and appraisal of the geothermal resource near Terrace, British Columbia, targeting the M'Deek Reservoir. The Fuel for Reconciliation project is not primarily focused on electricity generation but rather on direct heat use. This project's larger vision is to decarbonize the local industry to provide social, environmental, and economic benefits to the region and the Kitselas First Nation [15]. The project will be developed in incremental phases, with an initial emphasis on establishing industrial-scale geothermal heating. Progress has been made through the exploration and planning stages, including data collection of hot spring water (Figure 4). In 2020, four pilot core holes were drilled, and three additional core holes were drilled in 2021. Reservoir modelling is currently underway to support the production well target selection [15].

Figure 4. Kitselas Geothermal Project: conducting measurements of a hot spring in the Lakelse Lake area (from Kitselas Geothermal Inc.).

3.1.4. Kaska Dena

Led by the Daylu Dena Council of the Liard First Nation, both of which belong to the Kaska Dena people, an early-phase geothermal exploration is currently underway in the Kaska Dena territory in north-central British Columbia (Figure 1), where the heat flow and geothermal gradients are notably above average values [16] (Figure 5). This region is not well serviced by existing electrical infrastructure and relies heavily on trucked-in fossil fuels to meet the energy needs of its communities. Although geological data for this region are limited, as it has not been the focus of historical geothermal exploration programs, the presence of deep continental-scale faults, in conjunction with Quaternary volcanism and Cenozoic sedimentary basins, suggests the region may hold geothermal resources of yet unknown quality that are potentially prospective for development [17]. This exploration program will provide geothermal-specific data for this region of northern British Columbia, while creating local capacity and employment opportunities.

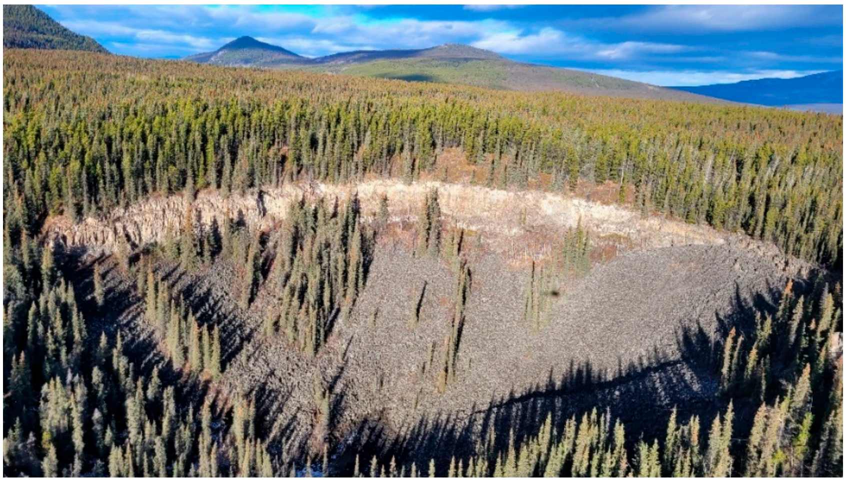

Figure 5. Pliocene-Holocene basalt outcrop in Kaska Dena territory.

3.2. Alberta

The province of Alberta continues to advance the geothermal energy industry with the progress of existing projects such as Alberta No. 1, as well as the funding and initiation of new, innovative ventures like Novus Earth Energy's Latitude 53 project. Razor Energy made strides by commencing operation of their co-produced natural gas with geothermal power project in January 2023.

3.2.1. Novus Earth Energy

Novus Earth Energy (Novus Earth), a Calgary-based geothermal company, announced the Latitude 53 Project located near Hinton, Alberta, in early 2022 (Figure 1). The project has attracted attention and support from surrounding communities, all levels of governments, and the industry. The enthusiasm for the Latitude 53 Project stems from its potential for direct-use opportunities, such as utilizing thermal and electrical energy for agricultural purposes.

Using Novus Earth's efficient closed-loop well design, the connection of geothermal direct energy use to Closed Environment Agriculture (CEA) addresses growing food security concerns and GHG reduction goals. Compared to traditional agriculture, CEA consumes less water, occupies a smaller land footprint, and mitigates the impacts of extreme weather events. However, CEA is energy-intensive, relying on LED lamps instead of/coupled with sunlight, HVAC air-conditioning for temperature control, and water-filtration systems for recycling, all of which impose a significant energy load. Novus Earth is addressing these concerns with its proprietary advanced geothermal system, extracting heat and generating electricity, thereby making CEA and food security both sustainable and cost-effective.

Novus Earth's subsurface geothermal loop system provides reliable energy, operating over 97% of the time, making it suitable for a wide range of needs and easily replicable in various global locations. Novus Earth's Latitude 53 Project is progressing, with commercial geothermal well drilling anticipated for Q3 2023. This project will combine geothermal energy with hydroponics and aquaculture to produce fresh crops and harvest seafood for the local region and the Northern Territories. Additionally, it will promote direct-use geothermal opportunities in the local region to reduce GHG emissions.

3.2.2. Alberta No. 1

Alberta No. 1 is a planned project that combines power generation and direct heat utilization, located in the Municipal District of Greenview, south of Grande Prairie, Alberta [18] (Figure 1). In 2019, Alberta No. 1 secured CAD 25.4 million in matched funding from NRCan's ERPP to develop a geothermal power plant. The target formations consist of Devonian-aged limestones with varying degrees of dolomite alteration, along with interbedded sandstone formations overlying the Precambrian Basement. They range from the top of the Winterburn Group to the base of the Granite Wash Formation.

In 2021, Alberta No. 1 conducted a temperature log on an idle disposal well, revealing that temperatures exceeding 120 °C are attainable at depths of 3500 m and below (Figure 6). Furthermore, the results suggest the presence of two distinct thermal gradients within the sedimentary sequences: the upper clastic sequences exhibit a thermal gradient of approximately 31 °C/km, while the underlying carbonate sequences display a lower thermal gradient of around 22 °C/km [19]. These findings hold significant implications for the understanding of geothermal resources within the WCSB, as well as the interpretation of oil and gas temperature data.

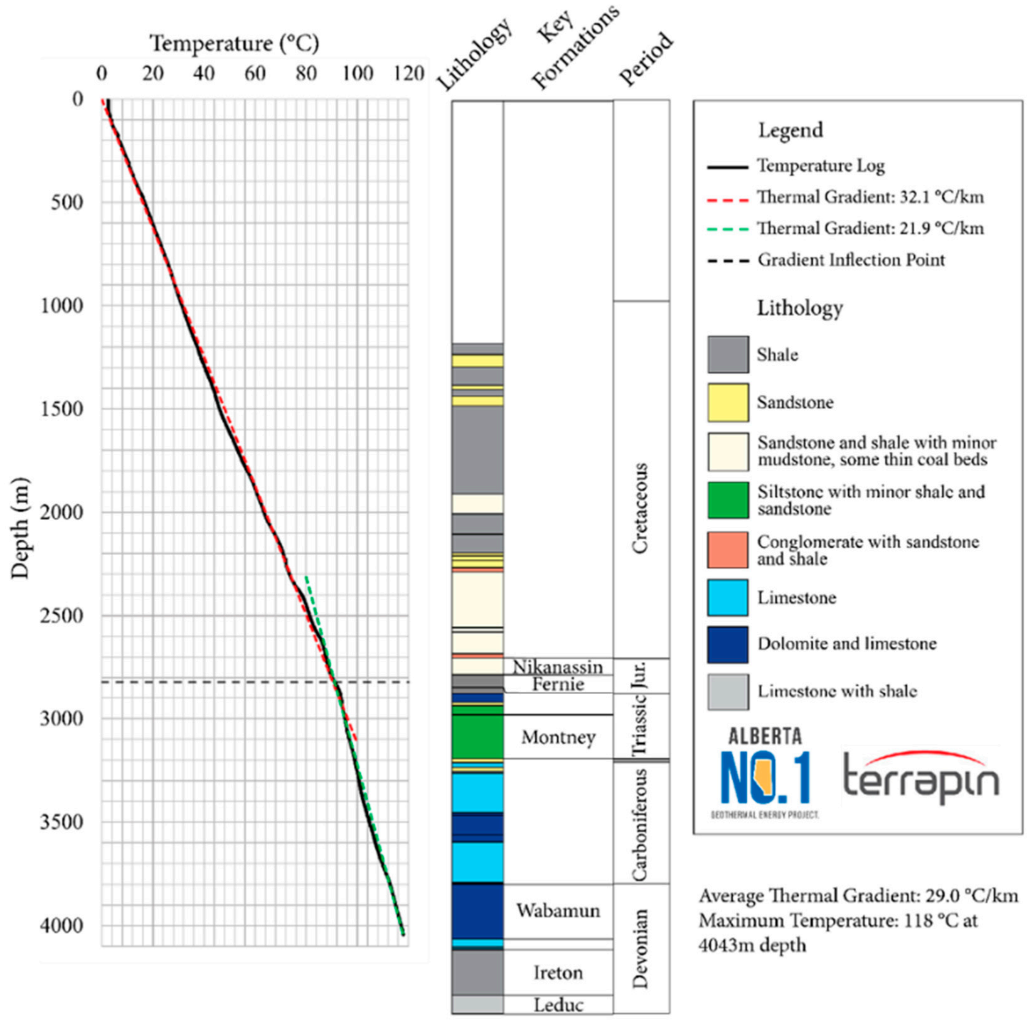

Figure 6. Alberta No. 1: the temperature–depth profile of the log and the well's lithology.

After some time working with the government and AER as they developed both Bill 36: Geothermal Resource Development Act and the AER's Directive 089, Alberta No. 1 is now in a position to apply for the necessary licenses for development [5].

3.2.3. FutEra Power

FutEra Power Corp. (FutEra), based in Calgary, AB, Canada, has constructed, commissioned, and begun operations on a co-production natural gas/geothermal power plant near Swan Hills, Alberta (Figure 1). Approximately 30% of the 21 MW power generated by the plant comes from geothermal energy. The conversion of the existing natural gas power plant to co-production utilizes only the current surface footprint. Brine with a temperature of 100 °C from the existing Swan Hills oil and gas wells is used in conjunction with the exhaust heat from the natural gas turbines to power the ORC portion of the power generation (Figure 7).

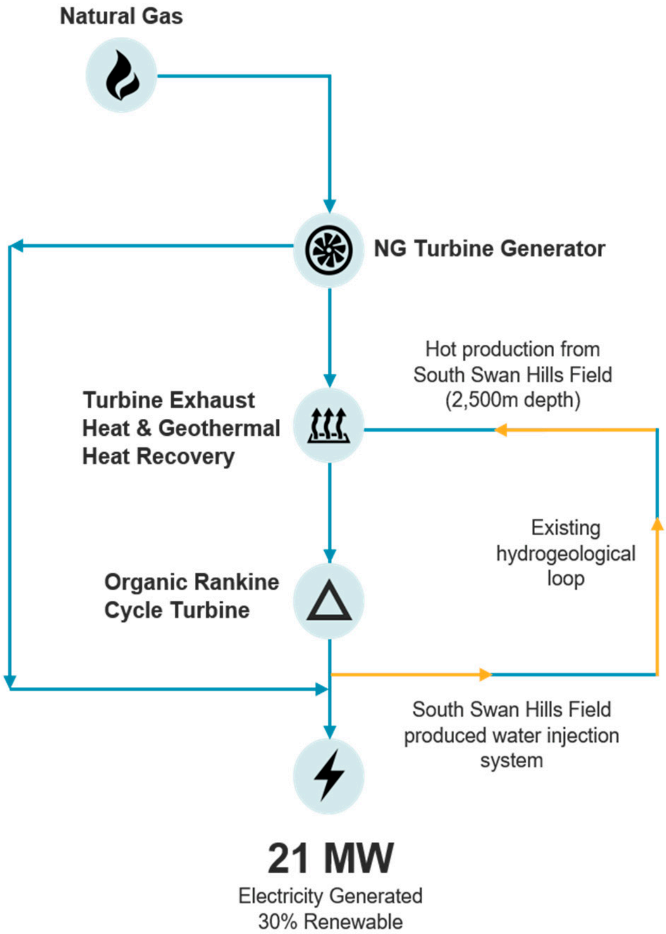

Figure 7. FutEra Power: schematic outlining the co-production power process. In this figure, the blue arrows show the direction of the exhaust heat from the natural gas turbines. The yellow arrows show the point in the process where brine from existing wells is added to the system.

3.2.4. Eavor Technologies Inc. (Eavor)

Eavor is an Alberta-based geothermal technology company and the developer of Eavor-Loop™ technology, a closed-loop geothermal system, enabling scalable, baseload or dispatchable, and emissions-free electricity generation located close to the demand. This closed-loop technology comprises a buried-pipe system, akin to a deep radiator or heat exchanger. The working fluid is composed primarily of water added at the surface, which is then circulated to extract heat from the earth to generate electricity, provide direct commercial heating, and/or serve cooling applications.

Eavor's technology demonstration project in Central Alberta, near Hinton (Figure 1), continues to operate with less than 0.3 m^3/day of leakage and remains within 2% of the predicted thermal output of 800 kW_{th}. Eavor broke ground on the first commercial implementation of its technology in October 2022 and is predicted to start in June 2023 in Bavaria, Germany. This project will tie into the electric grid and has the potential to become a combined heat and power project once the necessary heat infrastructure is established in the nearby town of Geretsried. In addition to the Bavaria project, Eavor has signed a heat purchase agreement with Enercity AG in Hannover and is in the design phase of that project.

In December 2022, Eavor completed the 'Eavor-Deep™' test well in New Mexico, reaching depths > 5 km and temperatures surpassing 200 °C, validating numerous aspects of the second-generation technology. This technology focuses on drilling deeper and hotter compared to the horizontal drilling technologies being deployed in the Bavaria or Hannover projects.

On the Canadian front, Eavor is collaborating with Enwave on a district heating project in Toronto, Ontario, and with Eavor Yukon on an electricity project. The Yukon project also involves partnerships with the Little Salmon Carmacks First Nation. Eavor Yukon has been actively engaged in data-gathering, re-entering numerous deep mining holes to obtain bottom-hole temperature data. They have also drilled one diamond drill well near the Whitehorse Trough in late 2022.

3.3. Saskatchewan

While sedimentary basins such as the Williston Basin may not offer the higher temperatures found in volcanic-hosted geothermal resources, they possess several advantages relative to other geothermal regimes. These advantages include a better understanding of the reservoir properties and extents, thanks to decades of oil and gas development, which reduces the risk associated with early-stage exploration. Furthermore, sedimentary reservoirs often have the appropriate permeability thickness and storage for the high fluid production volumes needed for binary ORC geothermal power plants.

Currently, there is one geothermal project in the province, operated by Deep Earth Energy Production (DEEP) Corporation, situated in southeast Saskatchewan, a few kilometers north of the Canada–United States border (Figure 8).

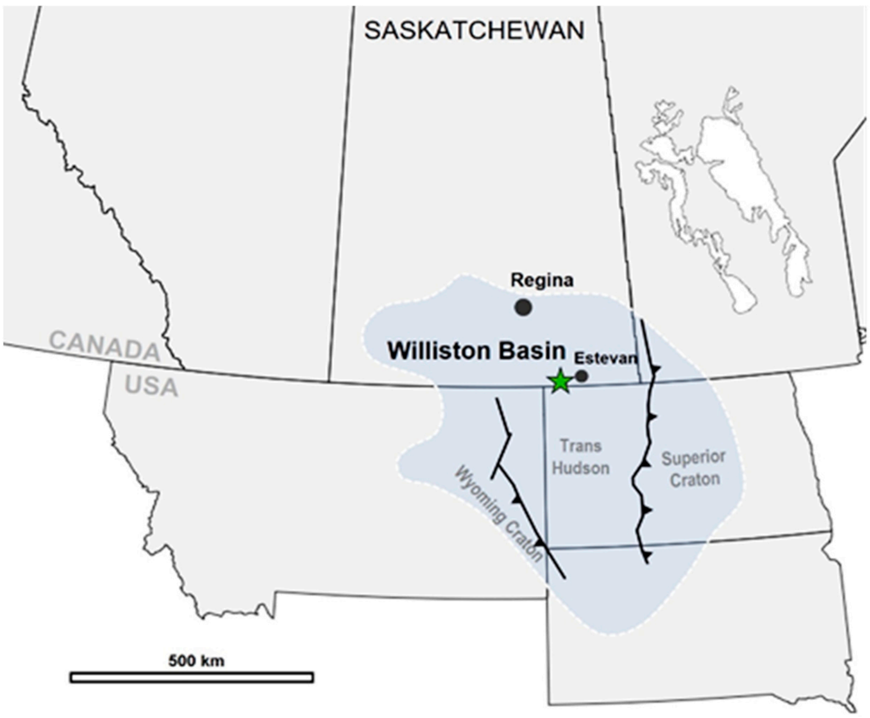

Figure 8. DEEP: map showing location of the DEEP project (green star) within the Williston Basin in southern Saskatchewan.

Deep Earth Energy Production Corporation

After more than a decade of preliminary work and preparatory engineering, supported by CAD 25.6 million ERPP NRCan funding, DEEP is at the forefront in Canada, with plans to construct a geothermal power facility (Figure 1). This project will introduce baseload renewable power generation for the first time to the SaskPower grid. With a focus on innovation, proven technology, and a highly skilled workforce, DEEP is dedicated to developing and building Canada's premier geothermal power facility, with ample room for future expansion. DEEP has geothermal rights within 39,120 hectares (approximately 100,000 acres) with the potential for approximately 200 MWe of geothermal power.

The geothermal resource is a naturally occurring >120 °C and 3450 m deep aquifer at the base of the Williston Sedimentary Basin. DEEP's drilling and extensive well testing of six of the deepest wells ever drilled in Saskatchewan, conducted from 2018 to 2021, have demonstrated that the basal sands of the Deadwood Formation can serve as a viable source of geothermal electrical generation and direct heat for the province. It is a made-in-Saskatchewan energy opportunity, and the province has a highly supportive and streamlined regulatory environment, shaped by six decades of oil and gas development and mining operations.

In 2021, the extended well testing of the geothermal system was completed. Hot brine was produced from the horizontal well and injected into the previously drilled vertical wells. This extensive production and injection loop test aimed to refine the reservoir model and determine the optimized horizontal well lengths and spacing. In September 2023, GeothermEx completed a review of DEEP's thermal numerical reservoir model, which supported DEEP's geothermal resource estimation.

DEEP has developed a unique geothermal field design to manage the reservoir, balancing the reservoir pressure, heat extraction, and subsequent re-heating of the injected brines using horizontal production and injection wells (Figure 9). DEEP's 'ribcage' geothermal well field design is globally unique and builds off of modern oil and gas drilling and completions techniques, applied for the first time in a renewable energy project. DEEP will tap into the geothermal energy stored in a permeable sandstone layer within the Deadwood Formation. This sand was deposited on the Precambrian basement rock during the Cambrian Period, approximately 500 million years ago.

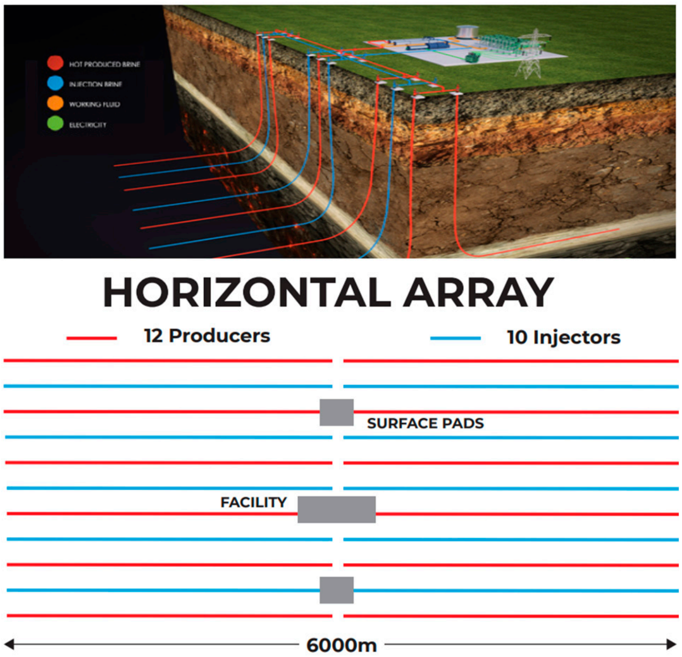

Figure 9. DEEP: ribcage geothermal well design.

3.4. Quebec

GSHPs (geo-exchange systems) are the sole geothermal technology used in the province of Quebec at the present time [20]. Although the Institut de recherche d'Hydro-Quebec (IREQ) and the INRS made efforts to assess the electricity production potential of deep geothermal energy in southern Quebec and eastern Canada [21,22], the conclusion was that the identified sites were generally unsuitable for a large-scale pilot project in the current context of low electricity prices. This unsuitability primarily arises from the required depths, as well as uncertainties regarding the temperature and the associated risks related to deep reservoirs (Figure 10). Nevertheless, the IREQ's report highlights that a significant reduction in the deep drilling costs and the development of expertise in creating geothermal reservoirs could potentially open a path for growth in the deep geothermal sector in Quebec.

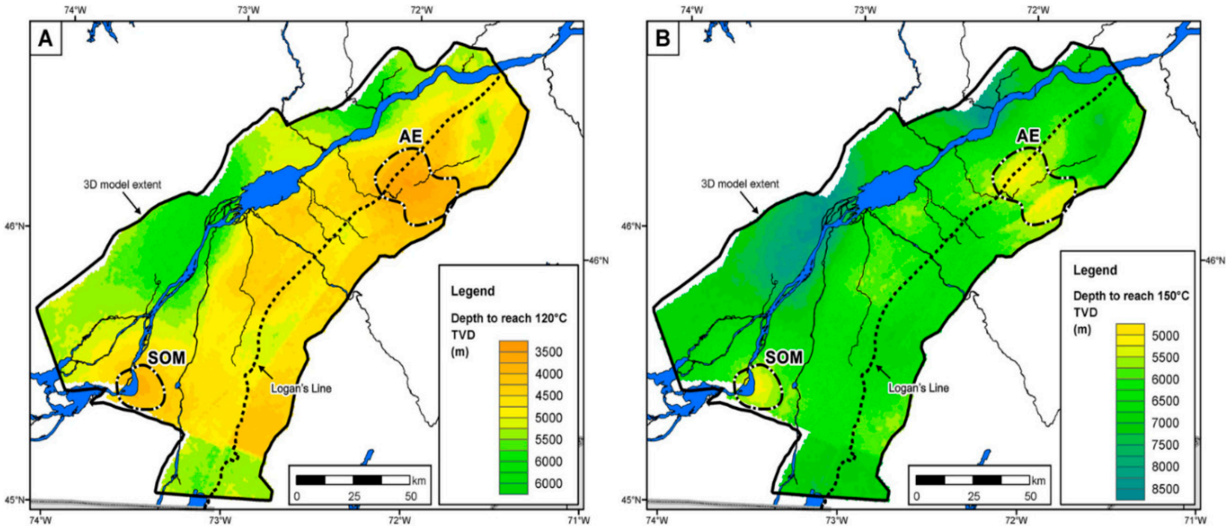

Figure 10. Quebec research: (**A**) depth to reach 120 °C, and (**B**) depth to reach 150 °C [23]. In this figure, SOM, AE, and TVD represent the southeast of Montreal anomaly, the Arthabaska-Erable anomaly, and true vertical depth, respectively.

In October 2022, Acti-Cité drilled a 400 m deep well in the town of La Prairie, located to the south of Montreal. This site falls within the boundaries of the southeast of Montreal (SOM) anomaly (Figure 1). An eco-neighborhood is being developed in an old quarry site in La Prairie, and geothermal energy is being considered as an option for providing space heating through either a deep geothermal district heating system or geothermal heat pumps. The INRS is currently assessing the geothermal gradient and the geothermal potential of the site. Furthermore, this 400 m slim hole well enables the collection of more information to support the existence of the SOM anomaly.

Another important venture in Quebec is the first geothermal pilot project installed in Kuujjuaq, the regional capital of Nunavik (Figure 1), which is the Inuit region in northern Quebec (above the 55th parallel). This project is a 30-kW horizontal GSHP system (Figure 11) installed for the community's swimming pool facility [24].

Figure 11. Kuujjuaq, Quebec: geothermal pilot project, 30 kW horizontal GHSP system for the community's swimming pool.

This geothermal pilot project is a result of "Generating New Opportunities: Indigenous Off-Diesel Initiative (IODI)." This initiative aims to support remote Indigenous communities in developing and implementing plans to reduce diesel consumption for heating and power purposes. IODI is a program funded by NRCan to support Clean Energy Champions and their communities by providing tailored clean energy training, access to expertise, and financial resources for developing and initiating ambitious diesel reduction plans. Notably, this project serves as the first demonstration of a GSHP operation in a subarctic climate.

Within the same IODI program, a 240 m deep slim hole was drilled near Kuujjuaq's Forum building. This well was drilled as part of a drilling training class supported by Avataa Explorations Logistics Inc., with the goal of installing a 145 m deep vertical closed-loop GSHP. The Kuujjuaq Forum, operated by Kuujjuamiut Inc., features an ice arena, a gymnasium, and a fitness center, and is primarily heated by diesel. The shallow geothermal system is expected to extract 9.4 $\pm$ 0.8 MWh of energy annually [25]. This 240 m deep well also made it possible to advance the state of knowledge about Kuujjuaq's deep geothermal energy potential. A geothermal gradient of about 21 °C/km was assessed, indicating a surface heat flux of 57 mW/m^2 [26]. These values suggest that at a depth of about 2–3 km, the thermal energy in-place may be sufficient to provide space heating for this community.

3.5. Nova Scotia

A number of homes, institutional buildings, and commercial facilities throughout Nova Scotia have groundwater and GSHPs in operation. One of the most famous geothermal systems under operation in Nova Scotia is the one installed in the abandoned mines of Springhill (Figure 1). These flooded former coal mines contain about 4,000,000 m^3 of water, recovered at the surface at a temperature of about 18 °C [27]. The water is used as the input to heat pumps for heating and cooling industrial buildings. Such a system offers lower heating costs than heating with fuel oil, while also reducing CO_2 emissions. The systems, initially deployed in Springhill in 1989 for a single building, have expanded in recent years to cover a geothermal business park servicing many buildings [28]. Beyond Springhill, Purdy's Wharf in Halifax was the province's first large-scale project to leverage temperate differences in the ocean for cooling [29]. Additionally, the new Waterside Centre in Halifax will also employ seawater to heat and cool [29].

Since 2020, Net Zero Atlantic has been running a collaborative program in Nova Scotia to assess deep geothermal resources close to the shore of the province. Phase 1 of this project had four main objectives [30]. The first objective was to provide an overview of the general types of geothermal resources in Nova Scotia (excluding shallow resources used by GSHPs), with reference to key regional, national, and global examples. The second objective was to provide a preliminary evaluation of the potential and favorability of geothermal electricity generation and heat production across the province. The third objective was to recommend the next steps to further reduce risks in targeted areas. The last objective was to summarize the economics of geothermal resource exploration and development in the province.

The Phase 1 report concludes that there are areas in Nova Scotia with relatively high geothermal potential for electricity generation and that most of the province's sedimentary basins may have potential for direct heat use (Figure 12). Additionally, the Phase 1 report suggests that new and emerging technologies may hold promise for expanding the areas of Nova Scotia that may be considered for direct-use and electricity geothermal development. Finally, interesting opportunities can also be found within abandoned coal mines for space heating and cooling.

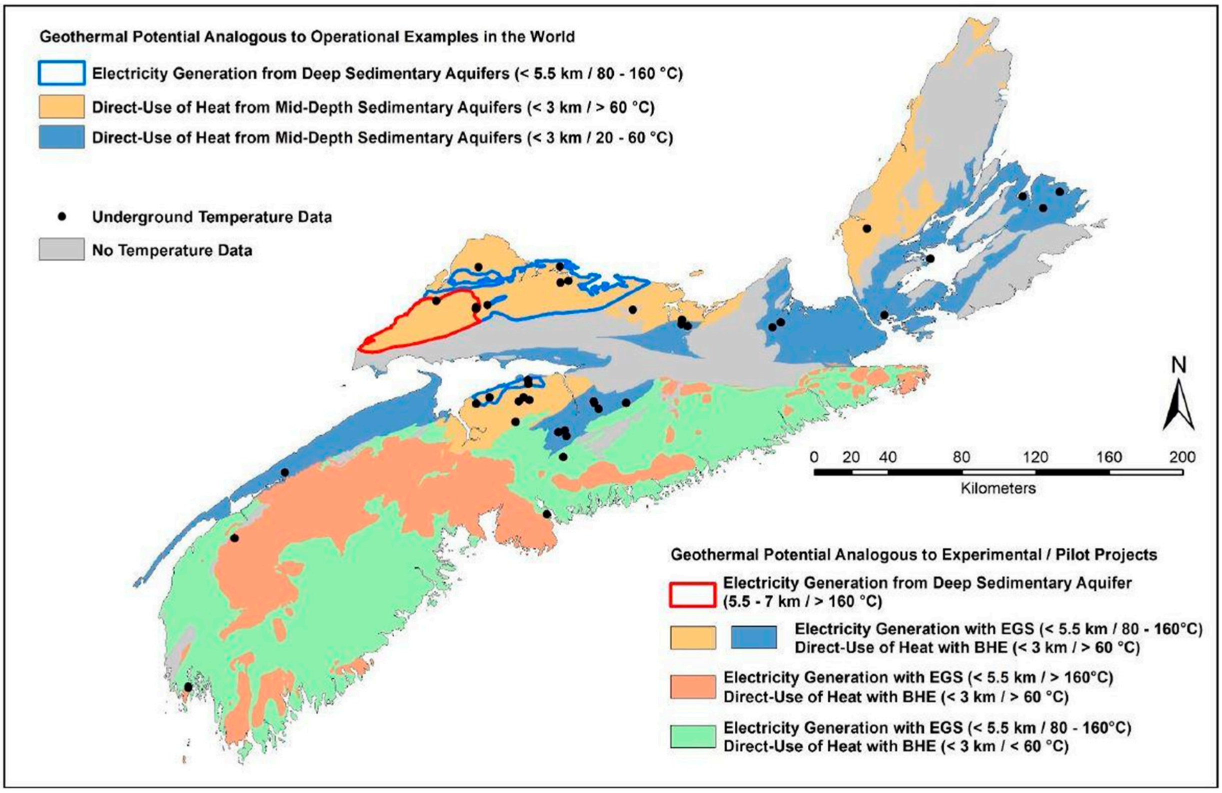

Figure 12. Net Zero Atlantic: geothermal potential in Nova Scotia for electricity generation and direct heat use, based on similar operational examples around the world [30].

Phase 2 of Nova Scotia's geothermal collaborative program aimed to evaluate the technical and financial suitability of deep geothermal systems for specific heating applications in three specific potential areas in the province [31]. The report suggests that, under base case scenarios, deep geothermal systems may not be cost-effective for the archetypal buildings studied (greenhouses, aquaculture, and district heating). However, many uncertainties still exist. Both Phase 1 and Phase 2 emphasize the need for more subsurface data collection in Nova Scotia to comprehensively assess the province's potential. The reports propose that exploration wells drilled in geologically preferred settings and commercially viable locations are required to de-risk the province's mid-depth geothermal resources. Thus, in 2022, Phase 3 of Nova Scotia's collaborative program was initiated to provide a forward-thinking strategic planning study with recommendations for specific activities to support a successful drilling campaign [32].

3.6. Yukon

The Yukon Geological Survey (YGS) initiated a geothermal research program in 2016 with the goal of evaluating the geothermal energy potential of Yukon (Figure 1). While the majority of Yukon's power is currently generated from renewable sources (primarily hydroelectricity, with a growing contribution from solar and wind), the region's rapid population growth and potential new mining developments are increasing the demand for power, and reliance on hydrocarbon-powered generators to meet this demand is also growing. Although the power grid is currently over 90% renewable, four communities in Yukon remain off-grid. Moreover, a significant number of Yukon homes and businesses still rely on hydrocarbons for heating, which are transported from the south.

Yukon Geological Survey Research

The initial studies by the YGS involved mapping the Curie Point Depth (CPD) using aeromagnetic data [33–35] and calculating the potential heat generation of granitoid plutons from lithogeochemical data [36,37]. The CPD mapping indicates that a higher heat flow can be expected in parts of southern Yukon (Figure 13A). The potential heat production calculations show that a number of granitoids have values in excess of the average granite (~2.5 μW/m^3), with Late Cretaceous granites yielding strongly anomalous values >10 μW/m^3 (Figure 13B). Direct measurements of the thermal gradient were obtained from the two wells drilled by the YGS near Takhini Hot Springs in the Whitehorse area and within the Tintina Trench near Ross River (Figure 1).

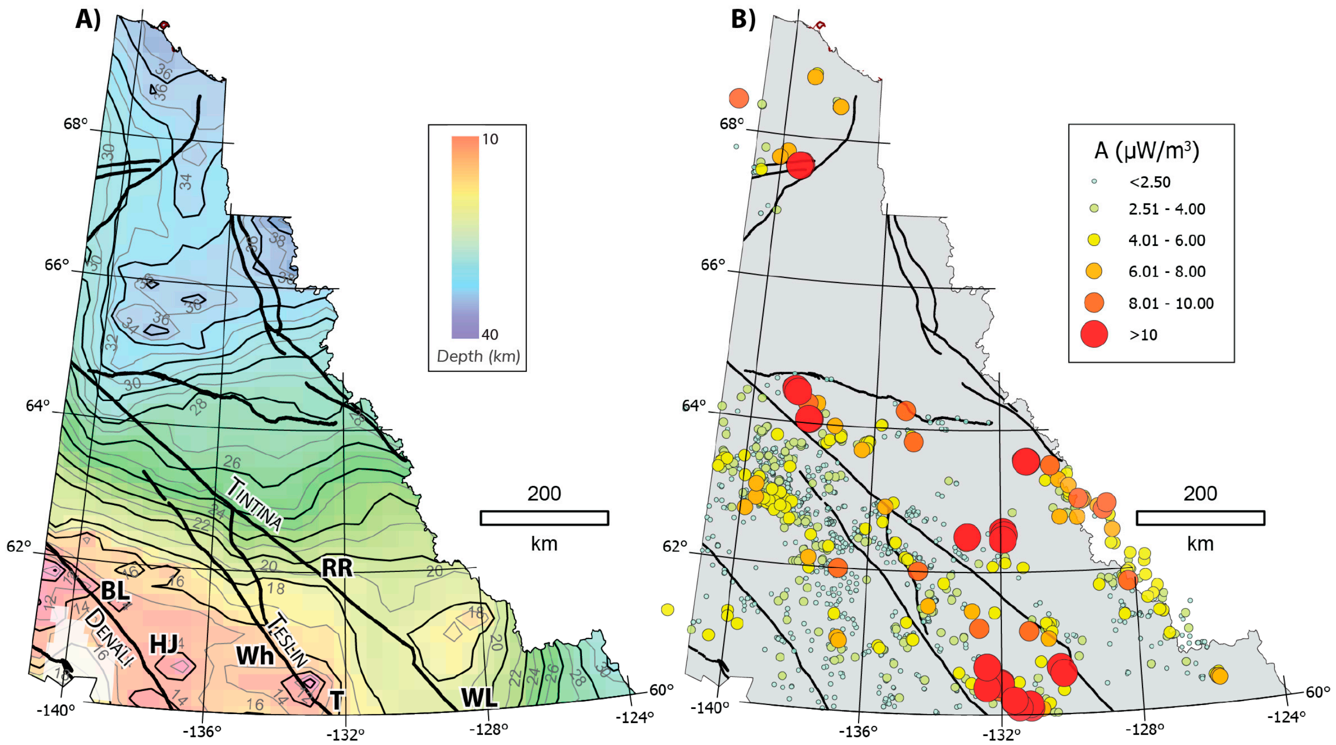

Figure 13. Yukon Geological Survey Research: (**A**) map of the Curie Point Depth in Yukon (data from [35], and (**B**) the potential heat generation from granitoid plutons. Contour labels are in kilometers. Bold black lines show major faults, and those that are the current focus of the YGS studies are labeled. Communities mentioned in the text are indicated: BL (Burwash Landing), HJ (Haines Junction), RR (Ross River), T (Teslin), Wh (Whitehorse), and WL (Watson Lake).

Current research by the YGS is focused on evaluating the geothermal potential along major crustal faults in southern Yukon. The activities are concentrating on the Denali, Teslin, and Tintina faults near the towns of Burwash Landing, Haines Junction, Teslin, and Watson Lake. The study areas are first evaluated using a series of geophysical methods, including magnetic, electromagnetic, magnetotelluric, gravity, and passive seismic surveys. These methods are combined to create 3D geological models across the fault structures (Figure 14). The data from these studies are then used to determine the locations for future temperature gradient wells [17,38]. The studies along the Denali Fault are the most advanced, with drilling scheduled for completion in 2023. The objective is to install a long-term, downhole monitoring site for temperature, stress, and seismicity along the active Denali Fault zone. Additionally, an analysis of the LiDAR imagery is being conducted to identify the neotectonic features along the Denali Fault, and petrophysical studies are in progress with the aim of modelling the regional hydraulic system in southwest Yukon. Finally, the YGS is in the process of compiling existing geothermal indicators, including previously unpublished studies commissioned by the Yukon Energy Corporation. These data will be made available through a web interface. The overall findings of this research program indicate that there is an elevated heat flow in southern Yukon and along the Tintina Trench near the Ross River, while the results of geothermal favorability along the Denali Fault are still being assessed.

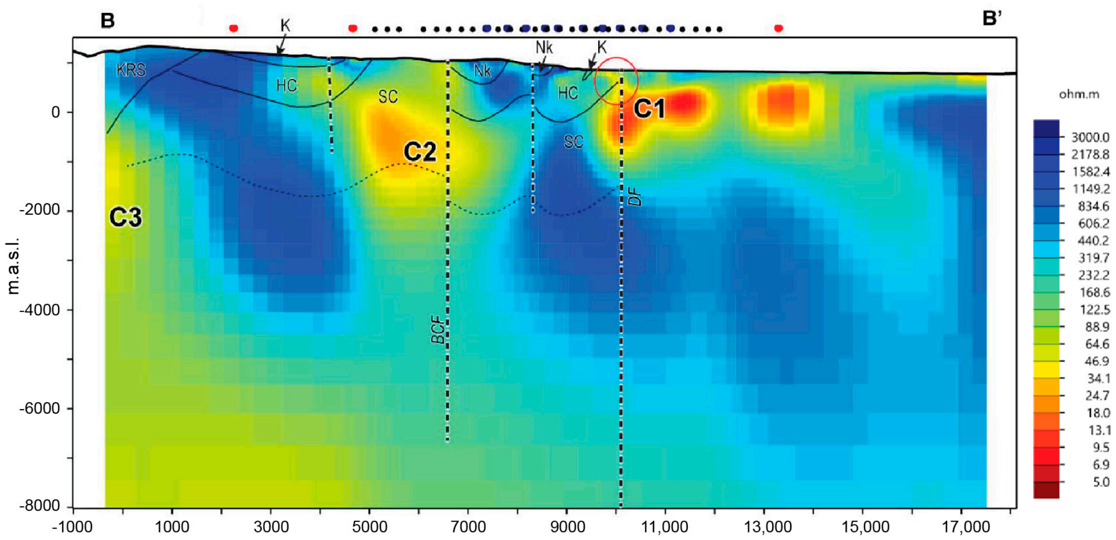

Figure 14. Yukon Geological Survey Research: cross section through a 3D resistivity model for the Burwash Landing area, Yukon (after Tschirhart et al. [38]). Red circle shows the location of the conductor to be investigated by drilling a temperature gradient well.

The YGS geothermal research program is conducted in collaboration with communities and First Nation governments with funding from NRCan's ERPP and the Yukon government's Our Clean Future initiative. This work is being conducted in collaboration with researchers from the GSC, the United States Geological Survey, and Canadian universities.

3.7. Northwest Territories (NWT)

The GNWT has developed several strategies to reduce GHG emissions in the NWT, diminish the reliance on fossil fuels for its energy needs, increase energy security and affordability, and enhance sustainable energy development. Although a large portion of the territory's electricity needs is supplied by hydroelectricity, diesel and gas are still the main components of electricity generation in remote and isolated grids; hydrocarbons are also the main source of building heating. Geothermal energy is identified as one potential solution to satisfy future energy demands in the territory.

The southeastern region of the NWT has been recognized to have elevated geothermal gradients [39] and has been the focus of renewed research interest by the NTGS and NRCan. Currently, several concurrent research projects with different foci are underway to characterize the region's geothermal energy potential. A research project investigating the geothermal energy potential of the Con Mine in the city of Yellowknife has recently been completed.

3.7.1. Fort Liard

The researchers at CanmetENERGY-Ottawa, one of the federal government's energy research laboratories, investigated a hybrid geothermal system for the remote Indigenous off-grid community of Fort Liard in the NWT (Figures 1 and 15), which is situated above a region of the WCSB [40,41].

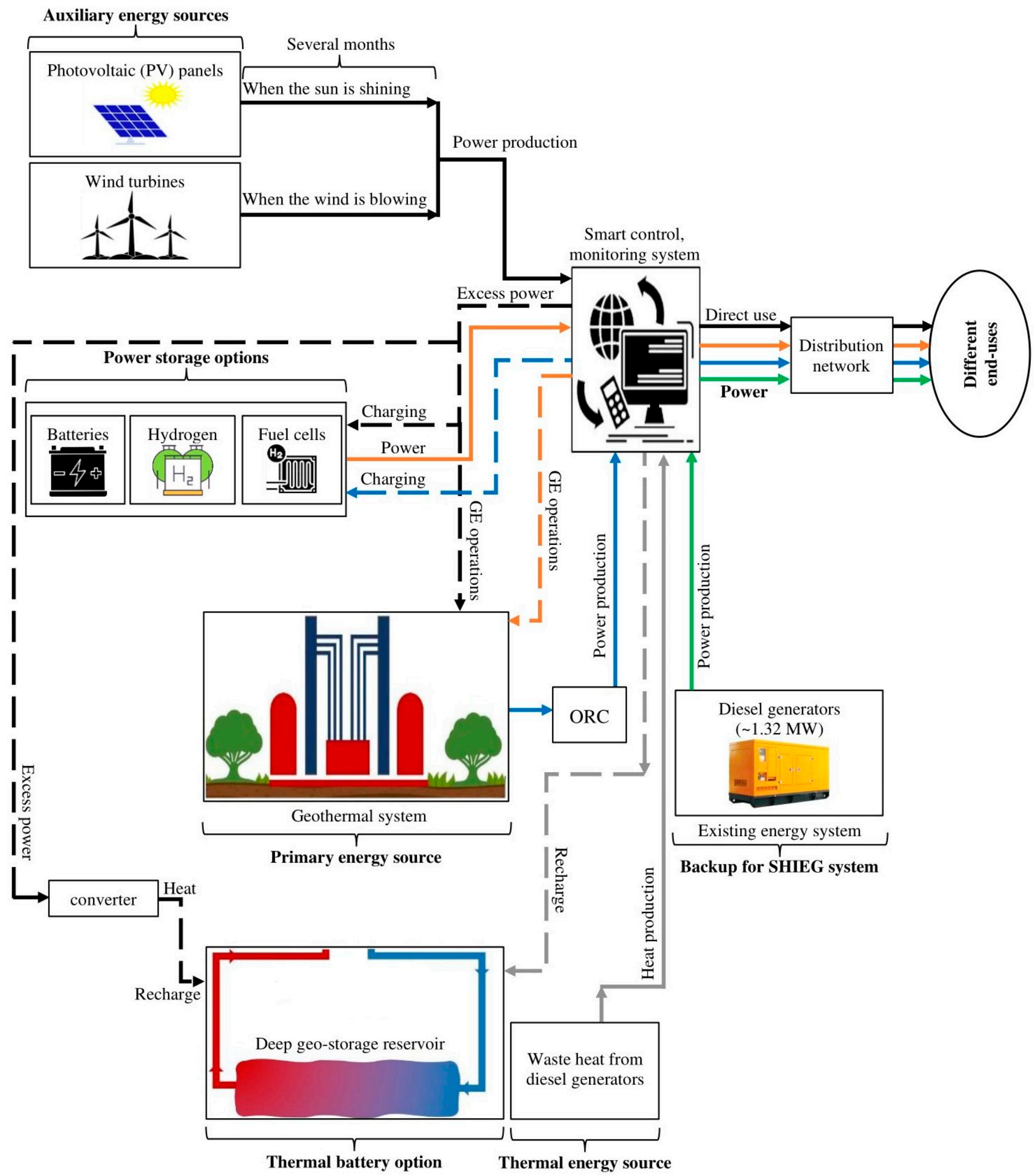

Figure 15. Fort Liard: a proposed hybrid geothermal system for Fort Liard, NWT [40].

They considered six different scenarios—three considering a geothermal system only and three considering a hybrid system—and conducted a techno-economic feasibility assessment using HOMER and COMFAR software to determine the optimal design and operation that can reliably meet the community's energy needs over the 30-year project lifespan. In addition, they carried out sensitivity analyses for factors such as the inflation rate, internal rate of return, and return on investment.

Their results indicate that the cost of energy (COE) for these six scenarios ranged from ~0.074 to ~0.36 CAD/kWh, much lower than the COE (~0.70 CAD/kWh—no northern subsidy diesel) for the existing diesel generators in Fort Liard. Among these six scenarios, the one comprising a geothermal system, a backup diesel generator (for emergency situations only), wind turbines, photovoltaic (PV) panels, a battery bank, a hydrogen system, and an inverter, which considered the most optimal capacity of wind turbines and PV panels to supply ~50% of the community's annual production, was found to be the best optimized system in terms of technical, economic, and environmental aspects for a variety of reasons. The primary reasons were that the geo-reservoir had time for recovery, since the binary cycle geothermal plant did not need to run continuously to produce electricity; it provided a more stable and reliable energy supply by using multiple systems; its COE was ~0.26 CAD/kWh, 2.7 times less than the COE for the present diesel facility; and its annual electrical energy generation (~2.35 GWh/y) was almost equal to the community's yearly electricity needs (~2.14 GWh/y), meaning that the excess electrical energy generation was negligible.

3.7.2. NTGS: Liard Basin Geothermal Reservoir Characterization

The Liard Basin project (Figure 1), led by the NTGS, aims to gather baseline geologic data and fill knowledge gaps related to the reservoir quality of the prospective deep and hot geothermal reservoir rocks of the Nahanni Formation limestone and its regionally extensive dolomitized Manetoe Facies. The project was initiated in 2019 in collaboration with the Department of Infrastructure—Energy Division. For this study, eight cores and nine field sites from the region were sampled in 2019 and 2021, respectively (Figure 16). The samples were analyzed for porosity and permeability (a routine core analysis), an XRD mineralogy, an SEM pore-space characterization, and a thin-section petrography. In 2022, the NTGS entered into a collaborative partnership with researchers from the INRS, who are in the process of compiling and interpreting the analytical data. The results of the study will be combined with legacy core analysis data from well files, and the study will expand to include other prospective formations. The majority of the strata is composed of fine-grained and well-cemented limestone and crystalline dolomite. Permeability and porosity values in the order of 0.01–0.1 mD and <<1% porosity suggest a limited overall reservoir quality. However, dolomitization has increased the vuggy pore space (1 to ~40 mD and 1–7% porosity) locally, suggesting a moderate reservoir quality in these sections. The patchy nature of the facies' fabric is supported by field observations.

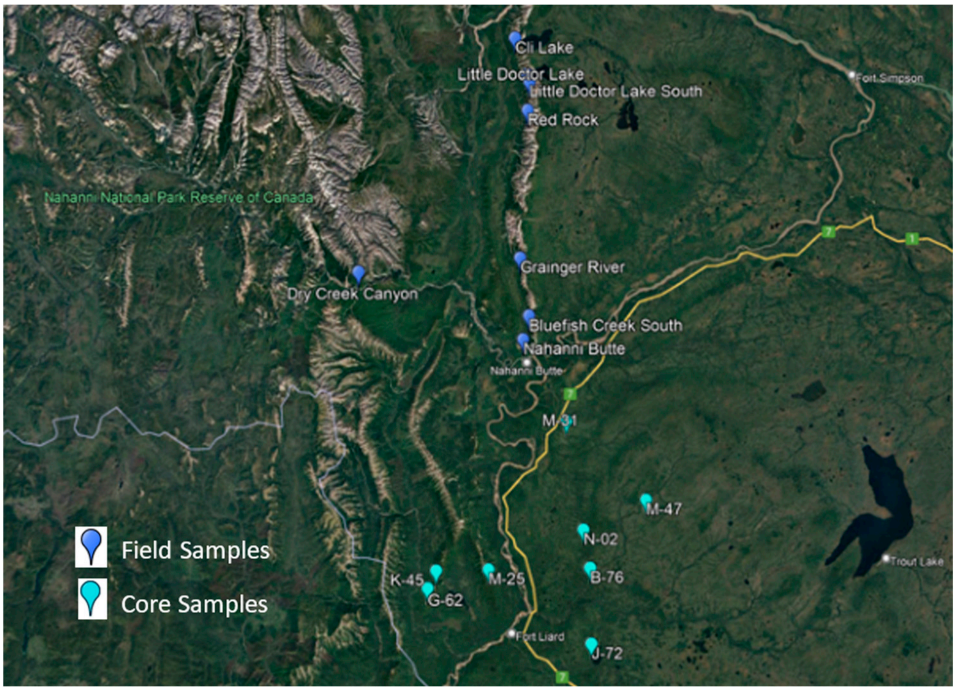

Figure 16. Liard Basin Geothermal Reservoir Characterization: field and core sampling locations in the Fort Liard area of the NWT.

3.7.3. NTGS: South Slave Geothermal Potential

This collaborative project between the NTGS and the INRS aims to evaluate the geothermal resources in the South Slave region of the NWT to help inform future decision making on local geothermal heat for the communities of Kakisa, Hay River, Fort Providence, and Enterprise (Figure 1). The project's first phase comprises the measurement of the thermophysical properties of the main lithologic formations of the study area, with the objective of identifying potential targets for further exploration. Eighty-four samples were collected from forty-three wells that cover eight formations (Figure 17). The preliminary results show that the average thermal conductivity of the rock samples ranges from 2.8 $Wm^{-1}K^{-1}$ to 5.6 $Wm^{-1}K^{-1}$. The thermal diffusivity varies between 1.1×10^{-6} m^2s^{-1} and 2.2×10^{-6} m^2s^{-1}, and the volumetric heat capacity falls within the range of 2.3 MJ $m^{-3}K^{-1}$ to 3.6 MJ $m^{-3}K^{-1}$. When using a cut-off value of 3.5 $Wm^{-1}K^{-1}$, the results indicate that the Slave Point and Horn Plateau Formations limestones and the Watt Mountain Formation shales are conductive to insulating, while the remaining formations are heat conductors. The Keg River Formation dolostone and the Chinchaga Formation anhydrite may have the best heat storage potential, although there is some variability among the lithologies. Forthcoming results will include the hydraulic properties, as well as a geochemical and mineralogical analysis of the samples. The aim is to define the thermofacies to evaluate the study area's geothermal potential, considering the strata's thickness and lithological heterogeneity.

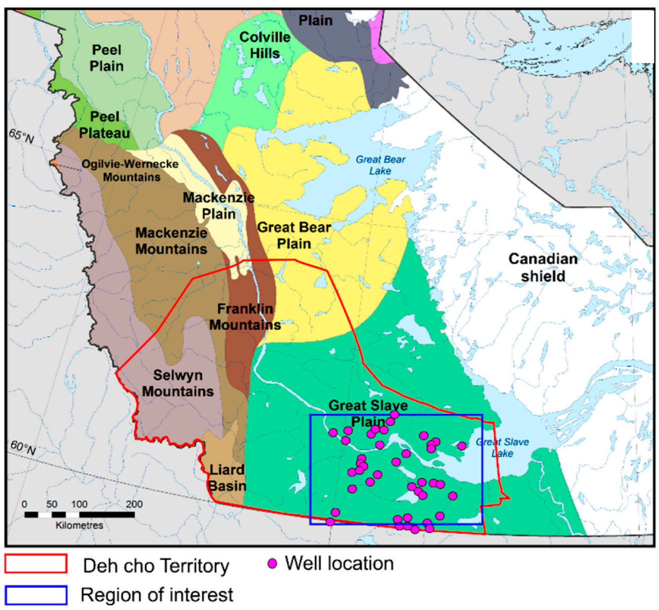

Figure 17. South Slave Geothermal Potential: location of the 43 wells sampled for the South Slave geothermal study.

3.7.4. NTGS: Con Mine

From 2019 to 2021, the NTGS collaborated with the INRS and the GSC to model the geothermal energy potential of the flooded Con Mine in the city of Yellowknife (Figure 1). The Con Mine is an abandoned gold mine that operated from 1938 to 2003, with a depth exceeding 1800 m. The data for this study consisted of (1) water temperature measurements in the mine shafts and one nearby borehole to obtain a reliable temperature gradient; (2) regional fracture measurements along scan lines to determine bedrock hydraulic conductivity using Cubic's Law; and (3) a water quality assessment to determine the potential for scaling and corrosion. The results were used in analytical and numerical models to estimate the Con Mine geothermal system's ultimate energy potential. This work revealed that the Con Mine holds enough thermal energy to sustainably heat and cool buildings using a heat pump for over 25 years. The energy delivered to the buildings can annually reach

2510 MWh with a pump depth of 300 m for a flow rate of 0.06 m^3s^{-1}, while it increases to 3770 MWh when the flow rate is 0.08 m^3s^{-1}. In both cases, the thermal power extracted from the mine water during peak conditions is 562 kW and 843 kW. Installing the pump at a greater depth also increases the thermal energy delivered to buildings, which can reach up to 18,048 MWh with a pump located at a 1 km depth, providing a heating capacity of 3.9 MW during peak conditions.

3.8. Nunavut

Because all communities in Nunavut rely on diesel, the Qulliq Energy Corporation (the energy utility company in Nunavut) has been interested in evaluating the territorial geothermal potential and assessing some target communities for future geothermal development. Phase 1 of the Nunavut geothermal feasibility study estimated that the technical power generation potential could be between 59 MWe and 64 GWe in the Canadian Shield and between 662 MWe and 96 GWe in the sedimentary basins of the Arctic Islands [42]. However, important data gaps make this assessment uncertain, and additional data collection with drillings at target communities (e.g., Resolute Bay and Baker Lake—Figure 1) is necessary to properly define the resource potential [42].

4. Academic Research

4.1. Geothermal Research and Programs at Canadian Universities

Many Canadian universities are actively involved in geothermal programs and research, development, and innovation (RD&I) projects. Many of these programs receive partial funding from Canadian federal grants provided by the National Science and Engineering Council of Canada (NSERC), as well as university, provincial, and territorial support. Beyond those universities listed in Table 1, several other Canadian universities offer undergraduate and/or graduate programs that provide opportunities for research in the field of sustainable energy, including work related to geothermal energy.

Table 1. Summary of Canadian universities with active geothermal research and development (R&D) projects.

University	Geothermal Research Program
University of Alberta	→ Multi-disciplinary research for geothermal energy involving specialists working in geophysics, geology, geochemistry, mechanical engineering, risk management, safety and the built environment, energy law, and energy policy. → Geothermal and alternative energy. • Imaging, characterizing, and modelling Canada's geothermal resources; • Fluid/rock interactions in Canada's geothermal systems; • Optimizing geothermal energy, production, and utilization technology; • Socio-economic roadmaps to commercial geothermal energy production in Western Canada.
University of Calgary	→ GeoS (Energi Simulation Centre for Geothermal Systems Research). • Multi-disciplinary research spanning the development cycle of geothermal energy from exploration geology to facilities to regulation and social acceptance; • Thermal and fluid flows in reservoirs; • Drilling, well design, and completions; • Thermodynamics and energy conversions; • Sustainability, social license, and Indigenous perspectives; • Geothermal policy and law.

Table 1. *Cont.*

University	Geothermal Research Program
Institut national de la recherche scientifique (INRS)	→ Geothermal program. • Northern geothermal potential research chair; • Aquifers: a natural infrastructure for energy-efficient cooling to fight the urban heat island; • Geothermal resources and technologies for active and closed mines; • Analysis of heat transfer processes in favorable geothermal environments; • Geothermal potential of sedimentary basins; • Geothermal heat pump systems to heat greenhouses; • Underground energy storage: heat, compressed air, and hydrogen. → Laboratoire ouvert de géothermie (LOG)—open access laboratory. → Master in Earth Sciences—joint program between INRS and Reykjavik University. • Earth Science Master program with a focus on renewables.
Polytechnique Montreal	→ Geothermal program. • Thermal response test interpretation; • Rapid and accurate simulation of ground-coupled heat pump systems; • Operation of standing column wells. → Geothermal Research Chair. • Integration of standing column well in commercial and institutional buildings. → Low-temperature geothermal. • Graduate course that mixes notions of hydrogeology and geothermal.
Concordia University	→ Sustainable Energy and Infrastructure Systems Engineering (SEISE) Lab. • Techno-economic feasibility analysis of geothermal systems; • Environmental risk/impact assessment of borehole thermal energy storage (BTES); • Integration of geothermal energy into district heating systems; • Reliability engineering for geothermal energy facilities management; • Modelling, simulation, and optimization of hybrid renewable energy systems at building, district, and community scales.
University of Waterloo	→ Waterloo Institute for Sustainable Energy (WISE). • Tools for analyzing the power flow of modern microgrids at various scales; • Compressed air offers energy storage insights using steel-cased wellbores or geostorage; • Solutions for greener energy and potable water distillation and compressed air storage; • Integrating local community knowledge into the transition from fossil fuel to renewable energy systems; • Geothermal energy systems for remote, isolated communities; • Low-grade heat scavenging, storage, and utilization for power and district heating; • New technology for massively reduced CO_2 oilsands exploitation; • Deep liquid and solid waste injection and energy harvesting.
University of Saskatchewan	→ Geothermal Research in the Department of Civil, Geological, and Environmental Engineering. • Geothermal energy, groundwater modelling, heat transport in porous media, hydrogeology, and geochemistry.

Table 1. *Cont.*

University	Geothermal Research Program
University of Regina	→ Petroleum Technology Research Centre (PTRC) announced funding for the University of Regina research project evaluating geothermal heat and the integration of different energy sources at a proposed greenhouse facility in Estevan. • Joint initiative between the University of Regina, PTRC (a research agency that aims to make all forms of subsurface energy more efficient and environmentally sound, which receives funding from Innovation Saskatchewan, a government agency that fosters innovation, research, and the development of technology across Saskatchewan), Evolution Growers (a First Nations-owned startup working to improve food security and support for produce in southern Saskatchewan), and Mitacs (a Canadian not-for-profit organization committed to funding partnerships between academic and industrial institutions to support innovation and job opportunities for students and postdocs).

4.2. University of Calgary

The University of Calgary's Energi Simulation Centre for Geothermal Systems Research (GeoS) is a multi-disciplinary collaboration involving professors, students, and researchers from various departments, including Chemical and Petroleum Engineering, Mechanical Engineering, Civil Engineering, and Geosciences, as well as the Faculty of Education and the Faculty of Law. The GeoS collaborates with industry partners and provincial and federal funding agencies for research opportunities for undergraduate, graduate, and postgraduate students in support of the Energi Simulation Centre's vision of "geothermal anywhere through improved exploration, drilling efficiency, well layouts, reservoir management, surface facilities, energy conservation, heat re-use, and close collaboration and buy-in from the community."

4.3. University of Alberta

Geothermal research at the University of Alberta began in the 1970s and 1980s, focusing on the WCSB [43,44]. However, this research declined over the following two decades as federal research funding was largely suspended. Geothermal research was reinitiated between 2010 and 2015 with the Helmholtz–Alberta Initiative. This initially focused on investigating the role that geothermal heat could play in providing heat for the oilsands industry [45]. It later diversified into quantifying other geothermal resources within the WCSB and its surrounding areas [16,46] (Figure 7). Since 2016, geothermal research has further diversified with support from Alberta Innovates and the Future Energy Systems program at the University of Alberta, funded by the Canada First Research Excellence Fund with matching and in-kind support from provincial and local municipal agencies, along with contributions from several industry partners. Cumulatively, the research program has secured over CAD 7.5 million in funding through 2023. The research program is divided into the following areas.

4.3.1. Western Canada Sedimentary Basin (WCSB)

The University of Alberta has continued to investigate the geothermal potential in the WCSB using data from the oil and gas industry to map hot sedimentary aquifers [47]. A new, state-of-the-art fluid–rock interaction laboratory has been established at the University of Alberta. Related studies have explored a number of the practical aspects of developing low-enthalpy geothermal resources within a sedimentary basin environment. These studies have examined potential geothermal applications for Stirling engines, which are externally heated, closed-cycle heat engines capable of running with small temperature differences, converting heat energy into electricity. Utilizing Stirling engines for geothermal applications in locations such as the WCSB poses challenges due to fluid temperatures under 150 °C. The progress is summarized by Stumpf [48], Michaud [49], Nicol-Seto [50], Hasanovich and Nobes [51], and Lottmann et al. [52]. Eghbali et al. [53] have developed a model for heat extraction from a WCSB-type geothermal reservoir using a multi-component, multi-phase approach.

The applications of direct heat use have included heating cattle feedwater [54] and heating water for processing oilsands to extract bitumen [55]. The potential role of re-purposed deep oil wells in geothermal development within the WCSB, including the performance of deep borehole heat exchangers, has also been investigated [56–59].

The partnership in the commercial TDK project at Fort Nelson began with the construction of the reservoir and simple flow models [60] and is now in the process of securing funding for integrated geophysical, geological, and engineering studies. Socio-economic studies of how geothermal development can economically benefit the community are also in progress. In addition, a reservoir study was also undertaken at the South Swan Hills oil field to delineate favorable zones in the reservoir for long-term hot water production [61].

4.3.2. Canadian Cordillera

Several fault-hosted and volcano-hosted geothermal resources have been identified in the Canadian Cordillera in British Columbia and Yukon. The University of Alberta has been collaborating with both commercial developers and government agencies to better define these resources. Some research has taken a regional-scale approach, seeking to identify the factors that control the distribution of resources. Hanneson and Unsworth [62] developed a regional-scale resistivity model based on an array of magnetotelluric soundings in the southern Canadian Cordillera and investigated the spatial relationship between the thermal springs and mid-crustal fluid content. Finley et al. [63] investigated the state-of-stress on major fault systems in the southeastern Canadian Cordillera to determine which faults might have elevated permeability and act as conduits for transporting high-temperature fluids from the depths to the surface. Other studies have focused on specific geothermal resources located on major fault systems. The areas studied include Valemount [64], the M'Deek geothermal area near Terrace [65], and Watson Lake. Finally, the University of Alberta has contributed to studies of high-temperature geothermal resources in the Garibaldi Volcanic Belt. The research has concentrated on defining the deeper parts of the hydrothermal and magmatic system beneath the Mount Meager geothermal prospect. The fieldwork took place in 2019–2021, and the resulting data were used to generate a 3D resistivity model [66,67]. This project now focuses on Mount Cayley, where a similar approach is being used to determine the location and size of the heat source beneath this volcano.

4.3.3. Northern Canada

This region of Canada currently relies on diesel and other hydrocarbons for both heat and electricity generation. This dependence is associated with high shipping costs and contributes to several environmental challenges. In collaboration with the Nunavut government and other university researchers, a program is under development to evaluate how geothermal energy could contribute to heat generation and electricity production. The research focus to date has centered on innovative approaches to geophysical imaging of the upper 1–2 km of the subsurface, with the aim of understanding both the thermal conditions and the groundwater characteristics.

4.3.4. Socio-Economic Studies

Additional research has been dedicated to examining the socio-economic factors associated with supplying the remote, isolated northern communities with geothermal power. This research aims to support communities seeking to diversify and decarbonize their energy sources, re-purpose existing hydrocarbon infrastructure, and address reclamation liabilities by harnessing geothermal power for heat and electricity. Jurisdictional reviews of regulations and royalties in mature economies assist Canadian authorities in determining the most effective ways to promote geothermal energy production through regulation, networking, incentives, and other resourcing. Moreover, by assessing the economics, researchers also help mediate negotiated settlements between municipalities and geothermal energy developers. This provides an opportunity for longitudinal studies on the best approaches to support communities in adopting renewable technologies. Examples of such studies include the results presented by Percy [68], Schiffner et al. [54], and Nadkarni et al. [69].

4.4. Institut National de la Recherche Scientifique (INRS)

The Centre Eau Terre Environnement at the INRS, based in Quebec City, has developed a geothermal research program over the past eight years with the goal of improving the understanding of heat transfer mechanisms that impact the performance of geothermal energy systems. This knowledge can help to reduce installation costs and foster the development of competitive geothermal technologies. A core laboratory, named LOG (Laboratoire Ouvert de Géothermie), was also established to characterize the thermal and hydraulic properties of geological materials with major funding from the Canadian Foundation for Innovation and has been operated in an open-source manner. In addition, a research chair supported by the Institut nordique du Québec to study the geothermal potential in the northern regions was awarded to the INRS.

Research within the INRS geothermal group has been focused on improving thermal response tests (TRTs), improving methods to characterize in-situ thermal properties (e.g., oscillatory TRTs), and finding new approaches to estimate terrestrial heat flux. The group has also been active in untapping the geothermal potential in the St. Lawrence Lowlands, Anticosti Island, the Magdalen Islands, Kuujjuaq, Nevado del Ruiz in Colombia, Madagascar, and Djibouti.

4.5. Polytechnique Montreal

The Department of Civil, Geological, and Mining Engineering at the Polytechnique Montreal hosts an NSERC Industrial Chair in geothermal energy, specifically focused on geothermal standing column wells in industrial buildings. This Geothermal Research Chair aims to rapidly overcome barriers to the use of permanent column wells (PCPs) in institutional buildings, thus reducing their heating and cooling costs, decreasing the demand for electrical power from the grid, and minimizing the GHG emissions resulting from fossil fuel usage. The Chair's numerous research activities are grounded in three demonstration projects conducted in the schools over a five-year period. The objectives of the research activities and demonstration projects are to (1) reduce peak power demand and operate PCPs efficiently; (2) acquire, design, validate, and demonstrate the potential of PCPs; (3) monitor groundwater quality in the vicinity of PCPs; and (4) train, change perceptions, disseminate, and transfer knowledge.

4.6. Geological Survey of Canada (GSC)

The GSC has been conducting geothermal research in Canada since the 1970s, including some of the first studies that defined the geothermal potential across the country. Recently, several projects have been operating in an integrated fashion with other provincial and territorial research organizations, as well as academia. Early research in the 1980s identified the highest temperature geothermal resources known in the country (over 250 °C) in the Garibaldi Volcanic Belt of British Columbia. Ongoing research has focused on reducing exploration risk in these volcanic systems by developing new tools to predict the occurrence of permeability at depth.

A second focus has been on the northern communities that are largely off-grid and rely on imported hydrocarbons for heat and electricity. These can be offset by local geothermal resources. However, subsurface geothermal resources are challenging to identify, even more so in northern Canada where thermal data are limited and regions of thick permafrost can hide thermal anomalies. To tackle these challenges, this project is developing new geophysical, geochemical, and remote sensing techniques to identify 'blind' geothermal resources. This project closely aligns with the geothermal research activities in Yukon and the NWT. Part of the work led by the INRS examines the potential of abandoned mines, often flooded, which then make a large reservoir that can have water production at an extremely high volume.

Hot sedimentary basins have been another focus, primarily within the WCSB and its sub-basins. The activities include regional studies of heat potential and focused research on specific abandoned or end-of-life petroleum fields. In addition, long-term planning and design are being considered for tight unconventional gas (TUG) formations containing additional energy, such as geothermal, compressed gas, and abandoned gas flows, toward the end of production. The economic value of these resources may surpass that of natural gas itself, and many of them remain untapped. An innovative solution that makes proper use of these untapped resources and existing wellbores could potentially double the energy value when compared to the outcome of production from the TUG or the geothermal energy resources alone, such as helping accelerate the low carbon transition. The feasibility of converting active and abandoned oil and gas wells into CO_2 geological storage sites and geothermal energy producers is also being examined. Converting these oil and gas wells for CO_2 storage and geothermal energy producers can result in the storage of more CO_2 in geological formations, reducing the CO_2 emission into the atmosphere while generating renewable energy to offset field operation needs. In addition, the conversion could significantly reduce the cost of the well cleanup and reclamation, extend the life of existing field infrastructure, employ out-of-work petroleum sector workers, and diversify the economic portfolio of petroleum-dominated oil and gas provinces.

Additional work is being conducted to examine the potential for enhanced geothermal system (EGS) development in basement rocks underlying sedimentary basins, particularly focusing on the nature of water–rock interactions and how they can affect the permeability of the fracture-dominated systems.

The lower-temperature sedimentary basins are also being examined for their potential for heat production, specifically in the Bécancour area, Quebec. This project consists of two components: (1) a modelling study that investigates the use of geothermal heat for building heating and exploring the utilization of deep borehole heat exchangers (DBHEs, which can be installed in new boreholes or re-purposed oil and gas wells) and doublets, and (2) a combined lab and modelling study that uses 3D pore network images from CT-scans (medical and micro) to simulate fluid flow and heat transfer.

The GSC is also undertaking conceptual modelling studies of closed-loop systems, including horizontal and inclined systems, to assess the thermodynamic feasibility of these concepts. The results have shown that closed-loop systems are viable, but only in rock types with sufficient thermal conductivity.

5. Conclusions

The pursuit of geothermal energy in Canada has been highly dependent on external factors, such as the strength of the economy, the prevalence of other energy industries, and the interest in developing renewable energies. Consequently, the development of the industry has started and halted several times since the 1970s. However, interest has renewed over the last decade, as evident from the involvement of provincial and federal governments, increased research, and new projects across the country. The provincial governments of Alberta and Quebec recently developed geothermal framework acts, while British Columbia and Nova Scotia have had acts in place for many years. Yukon and the NWT have not yet created frameworks specifically for geothermal development but have released plans to develop more renewable resources. Several provincial and federal governments have also provided grants and supported research.

Many new geothermal projects have progressed across several provinces, including British Columbia, Alberta, Saskatchewan, Quebec, and Nova Scotia. Research and analyses have been conducted in the territories of Yukon, the NWT, and Nunavut with the hope of diversifying their energy sources. There are several universities across Canada with strong geothermal research programs. The research is highly variable, covering a wide range of topics, including deep geothermal resources, GSHPs, energy engineering, direct heat use, and many more.

The progress of the geothermal industry in Canada has been significant in recent years. With many projects in development and extensive research being conducted, many Canadians hope to see the completion of geothermal projects and a greater understanding of the resources.

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Abbreviations

AE	Arthabaska-Erable
AER	Alberta Energy Regulator
BTES	Borehole Thermal Energy Storage
CEA	Closed Environment Agriculture
COE	Cost of Energy
CPD	Curie Point Depth
DBHEs	Deep Borehole Heat Exchangers
DEEP	Deep Earth Energy Production
ERPP	Emerging Renewables Power Program
EGS	Enhanced Geothermal System
FNFN	Fort Nelson First Nation
GSC	Geological Survey of Canada
GBC	Geoscience British Columbia
GeoS	Geothermal Systems Research
GNWT	Government of Northwest Territories
GHG	Greenhouse Gas
GSHPs	Ground Source Heat Pumps
IODI	Indigenous Off-Diesel Initiative
IREQ	Institut de recherche d'Hydro-Quebec
INRS	Institut national de la recherche scientifique
LOG	Laboratoire Ouvert de Géothermie
NSERC	National Science and Engineering Council of Canada
NRCan	Natural Resources Canada
NWT	Northwest Territories
NTGS	Northwest Territories Geological Survey
ORC	Organic Rankine Cycle
PCPs	Permanent Column Wells

PNG	Petroleum and Natural Gas
PTRC	Petroleum Technology Research Centre
PV	Photovoltaic
R&D	Research and Development
RD&I	Research, Development, and Innovation
SOM	Southeast of Montreal
SEISE	Sustainable Energy and Infrastructure Systems Engineering
TRTs	Thermal Response Tests
TUG	Tight Unconventional Gas
TDK	Tu Deh-Kah
TVD	True Vertical Depth
WISE	Waterloo Institute for Sustainable Energy
WCSB	Western Canada Sedimentary Basin
YGS	Yukon Geological Survey

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