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Decarbonizing Heat in Canada's North

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Abstract

The majority of Canada's current energy usage (more than 50%) is for space and water heating at both the commercial and residential scale. Where geothermal heating systems can be deployed there is the opportunity to offset heat provided by natural gas (or electricity on carbon intense grids), thereby reducing GHGs. This offsetting potentially could liberate some of Canada's cleaner hydrocarbons to be used in Canada's North, replacing diesel, or sold to foreign, coal-dependent markets. This would enable Canada to decarbonize locally while also contributing to global decarbonization. There are many ways to locally decarbonize, but they must be evaluated on a case-by-case basis. Shallow geoexchange systems are suitable in more temperate areas where permafrost or other ground stability issues are not an issue, as is the concept of heat storage from various sources, such as waste heat recovery from diesel generators. In communities where there is an enhanced geothermal gradient, it may be cost effective to install shallow (one to two kilometer) deep, single borehole heat exchangers. In other areas with larger power draws, higher gradients and more built infrastructure, power generation might be an achievable goal. For the north it is not "one-size-fits-all", but rather hybrid systems that combine several technologies to create innovative solutions that are "right sized" for the community.

Background

Geothermal energy has long been talked about; through history, enthusiasm has waxed and waned for this baseload, ubiquitous source of energy. Periods of enthusiasm have been closely linked to the price of crude oil (Figure 1). Prior to the oil crises of the 1970s, geothermal was a niche energy source, most commonly installed for direct-use applications where thermal waters flowed to the surface and were clearly visible and usable. The use of surface hot pools is typically part of every indigenous culture where such thermal features are present. The first electrical generation from geothermal happened in Lardarello, Italy (1904) when Piero Ginori Conti, Prince of Trevignano, created the first geothermal electrical generator that powered 5 light bulbs. It was there, in 1913, that the first geothermal power plant was built. However, despite promising beginnings, few places in the world took up the challenge of creating electricity from natural thermal sources as cheap energy became available through hydro and fossil fuel sources.

In the early days, when promulgation of electrical energy generation to power growing cities and industry was at the forefront of civic responsibility, generation from hydropower was first on the list for large scale exploitation, coal-fired steam turbines weren't far behind, and then natural gas as the network of pipelines expanded in the post WWII era (Figure 1). Only in areas like

Lardarello where there was an abundance of dry steam to tap did geothermal for electrical generation make much headway.

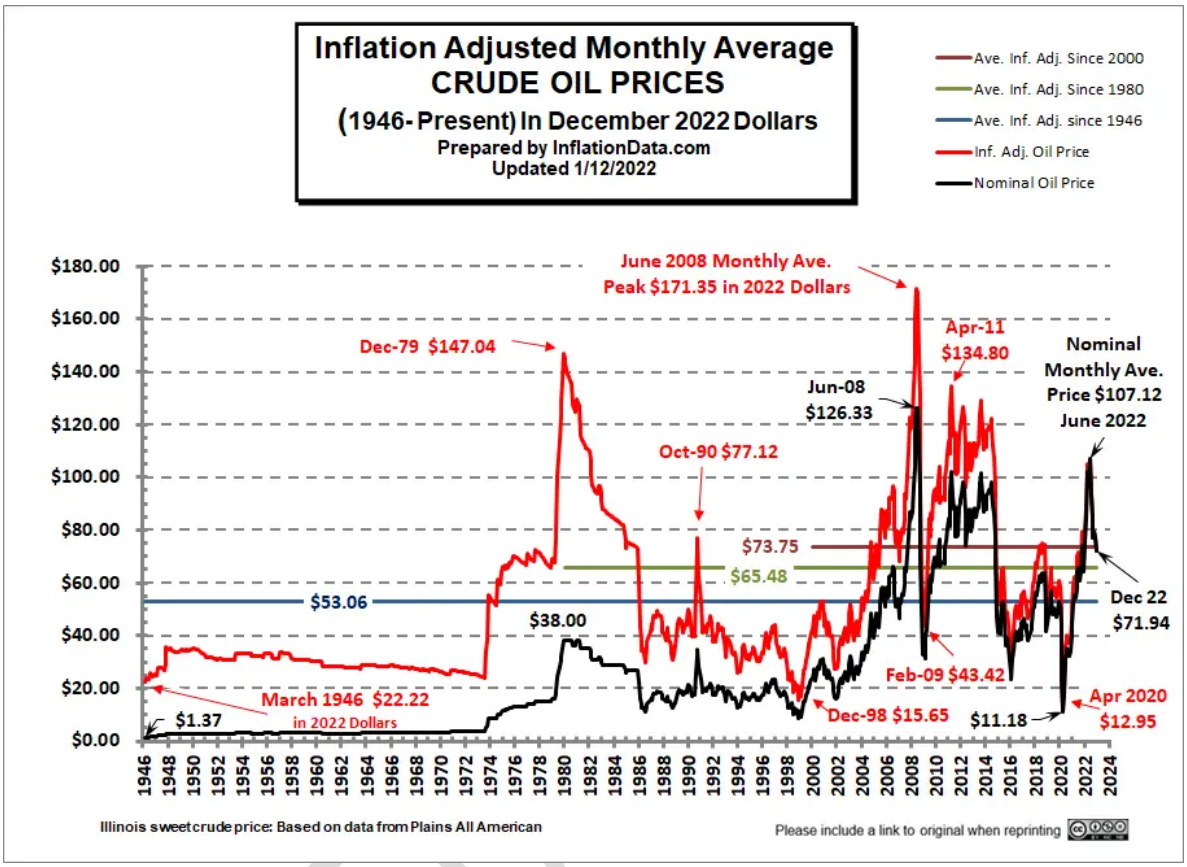

Figure 1: Crude Oil prices from 1946 to December 2022.

It was not until the mid-1970s when the world thought it was entering into an oil crisis that interest in geothermal energy began to see investment from governments and the private sector. Most of the world's major electrical generation projects stem from the exploration that took off in earnest in 1972. Many of these early projects were supported by the World Bank and governments concerned about the potential collapse of hydrocarbon-based electrical power generation. Those jurisdictions with high quality (high enthalpy) resources paved the way for technological advancement. However, as the crude oil price fell after 1979 (Figure 1) along with Natural Gas (NG) prices, only projects with high quality geothermal resources in areas where hydrocarbon resources remained expensive and were imported continued to go forward (Iceland, Indonesia, New Zealand, Philippines). In other jurisdictions, geothermal was viewed as not cost competitive or too complex to pursue for baseload power. And in any case, particularly in Canada, an abundance of energy resources, including hydro and almost unlimited access to inexpensive natural gas, led to expanding electrical grids while new pipelines furnished the majority of Canadians with power and clean burning NG for heating. Combined

cycle natural gas turbines soon became major sources of baseload and load-following electrical power in many Canadian grids.

As the world entered the early 2000s, population growth (Figure 2), economic growth, regional conflicts, and expansion of electrification to supply the burgeoning population, again led to soaring hydrocarbon prices (Figure 1).

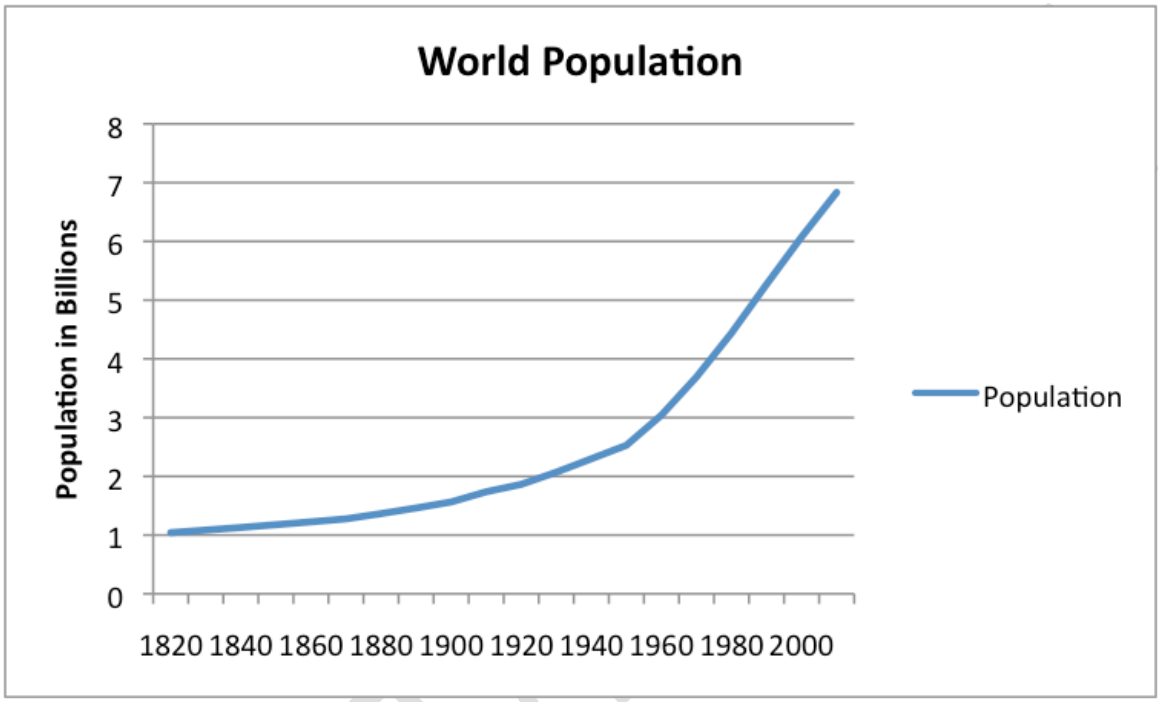

Figure 2: Population growth mirrors continued energy demands of society.

With escalating prices for NG, many countries, especially those dependent on imported NG, began to look for alternatives to hydrocarbon-sourced electrical generation. Coal generation remains a significant energy source (Figure 3) for many countries, and only in a few countries have there been efforts to convert from coal to NG or to scrub emissions to reduce GHG outputs (for example, Saskatchewan's Boundary Dam coal-fired plant and the Aquistore project (2023).

Thus began the second wave of geothermal development.

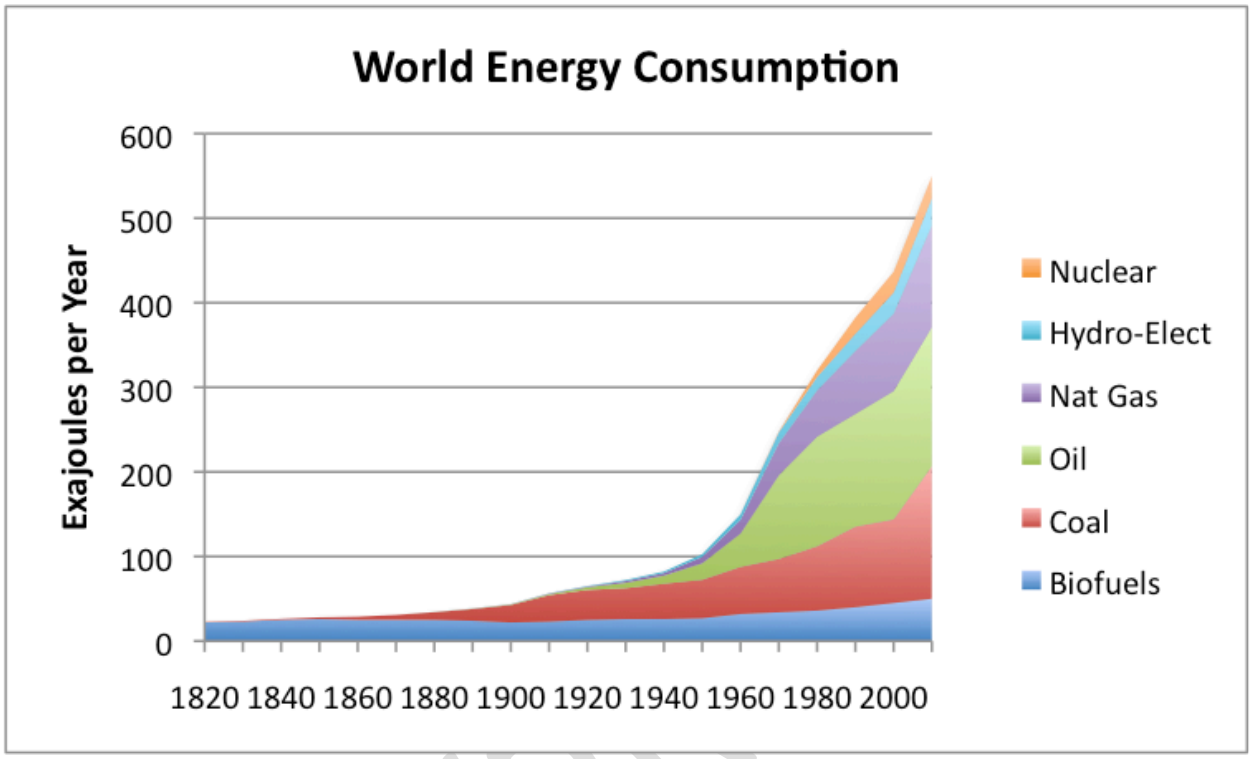

Figure 3: World energy consumption, showing exponential growth after 1960 as well as continued and expanding use of coal.

In this period, in Canada, increasing demand for electrification is supplied largely by legacy hydro, development of run-of-river hydro, increasing solar and wind generation, and NG plants to replace coal-fired plants as well as to provide the baseload generation required for stable grid functioning. Also, in remote communities isolated from large electrical grids, diesel (fuel oil) and propane continue to provide electrical and heating needs. Yet globally this "second wave" of escalating hydrocarbon prices spurred on significant exploration and development. Many companies "were born" and there was a significant land rush in the US and even to some extent in Canada. The resurgence quickly vanished as oil prices dropped, commensurate with plummeting costs of solar project CAPEX. By 2014 the geothermal industry underwent a contraction and reorganization.

The "third wave" is now upon us, spurred by sky-rocketing NG prices and lack of security of source markets. Indirect evidence suggests that this current wave is much more about fuel costs than about GHG reduction. However, GHG reduction remains an important goal and is being implemented via the "stick" (i.e., taxes) rather than the "carrot" method. Although the majority of the general population in the western world has recognized the need to reduce GHGs, it is through the pocketbook that western corporations are recognizing the need to reduce GHGs. As an example, the Alberta No. 1 project (Hickson *et al*. 2021) is a small

conventional geothermal project projected to produce 10 MWe gross power. However, the unsung aspect of the project is the potential thermal energy output of the project.

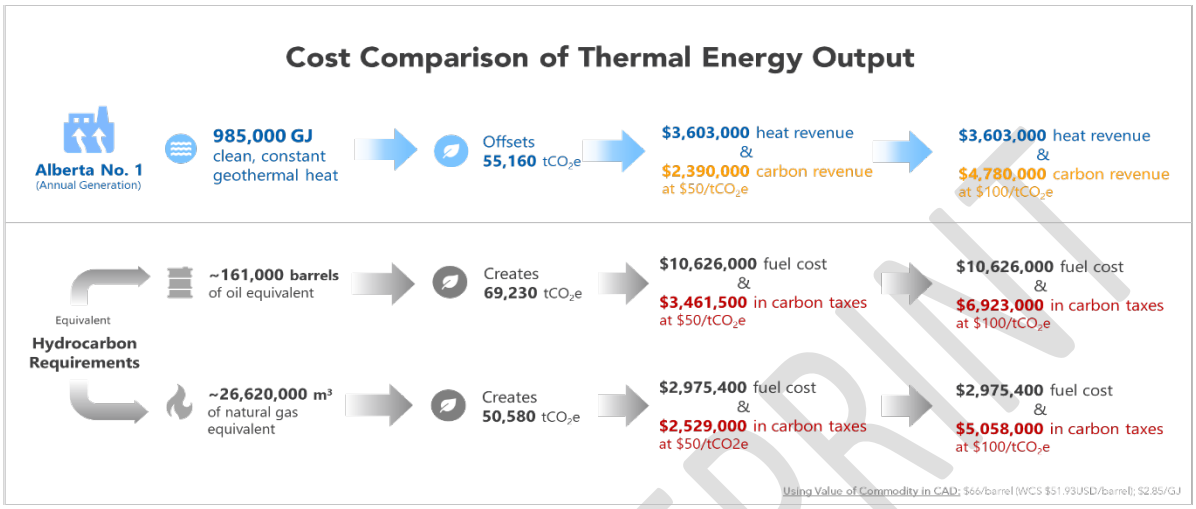

Figure 4: A cost comparison of thermal energy output comparing the Alberta No.1 project to hydrocarbons.

Figure 4 shows the yearly cost of producing the same amount of heat using oil and NG. It is now economics that are driving the third wave in Canada and surety of supply in Europe. Finally, by combining increasing fuel costs and carbon taxes, geothermal projects are showing the financial returns necessary to attract serious, patient investors. Significant government funding, largely through the Federal Ministry of Natural Resources (NRCan), has supported several projects as well as broader R&D efforts. However, there is still a struggle in the north to create viable projects due to a very sparse population, tiny communities, vast distances over challenging terrain and an extremely cold climate.

Decarbonizing Heat

In Canada more than 60% of residential energy consumption is used for space heating. Of this more than 45% is supplied by NG (Figure 5).

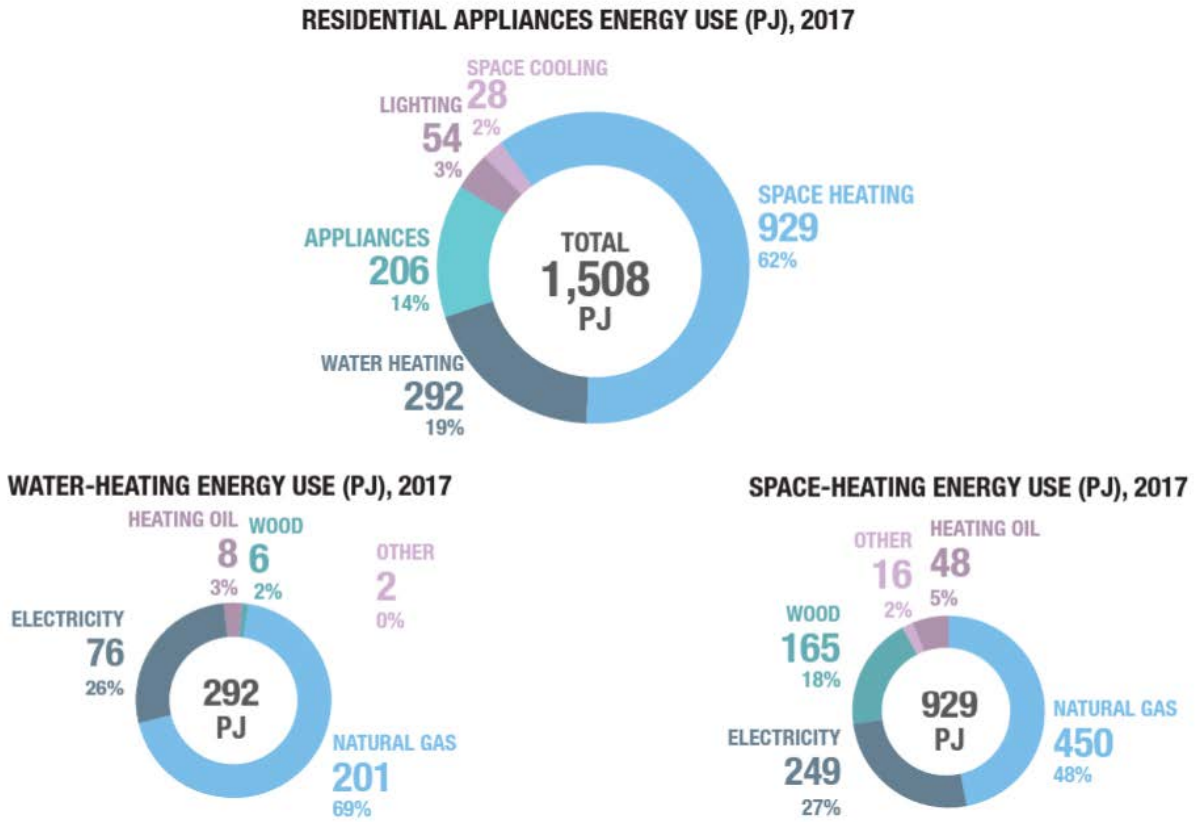

Figure 5: More than 55% of Canada's energy needs go towards space heating. (2022)

This amounts to 594 billion cubic feet of NG per year (2022), valued at $3.3 Billion in 2021 dollars. Even with the most efficient boilers and heat exchanger systems this results in GHG emissions of 61.5 mega tonnes from electricity and heat generation, which represents 10% of Canada's total GHG emissions (2022). It should be noted that even with this output, Canada still has a modest GHG emissions on a per capita basis (Figure 6).

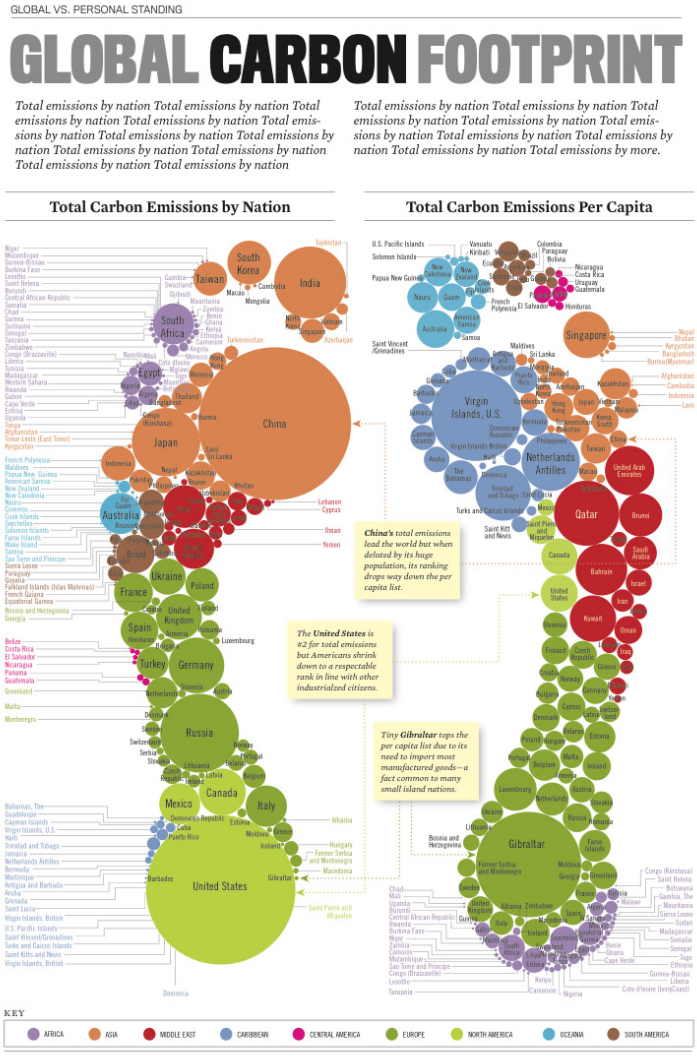

Figure 6: More than 55% of Canada's energy needs go towards space heating. (2022)

Considering Canada's cold climate, sparse population, and costly infrastructure due to a dispersed population component and great distances, Canada has done well at reducing its GHGs over time. Many provinces are blessed with abundant renewable hydro resources, much of it developed as megaprojects in the 1960s. The expansion of NG pipelines to individual homes, farms and commercial buildings reduced GHGs significantly through converting heating to NG from wood and coal sources. Creating a system of propane delivery to rural, off-grid areas also helped decarbonize communities using diesel or wood.

Decarbonizing the electrical grid in those provinces that are more reliant on hydrocarbon sources rather than hydroelectricity has also played a role. But more could be done to reduce

long-term costs of hydrocarbon-based heating in remote communities where the price of fuel is skyrocketing, and carbon taxes are being concurrently implemented.

Northern Canada

Canada's north requires innovative solutions to overcome the geographic and climate related hurdles of the area, coupled with a sparse population and hundreds of small communities (<1000 persons). Solutions need to look beyond the short-term needs of these communities and invest in infrastructure that provides appropriate stable (multi-decadal), baseload heating. These solutions are hybrid approaches that provide short-, medium- and long-term payback.

Waste Heat Recovery

The first, simplest, short-term solution to heat in northern communities that generate electricity with diesel generators is waste heat recovery. There are a number of technical considerations to these systems, but a water jacket placed around the engine exhaust system is able to recover much of the waste heat. This heat can then be distributed via a local heating loop to nearby buildings. The size of the loop, the distance to buildings and the type of heating systems already installed within the buildings are important considerations. Already constructed buildings with hydronic heating systems that run at temperatures in the 70 to 90° C range are best suited to add a waste heat recovery system, keeping the existing fuel oil (diesel) heating as a back-up. These systems must be carefully designed to match the waste heat recovery to the heating system, taking into account seasonal changes in the output of the generators as well as building heating needs. But for communities in Canada's north the generation output is well matched to the heating needs due to long hours without sunlight and the need for lighting and other electricity uses during the dark winter months.

Permafrost

One of the important considerations for northern communities is the presence of permafrost (Figure 7), especially where ground ice is present. Increasing the shallow subsurface temperature with buried pipes, well casings and well bores (as in the case of geoexchange and heat storage) can lead to unfavorable conditions such as melting and ground subsidence. Many northern communities built in areas with ground ice have overcome thawing problems by elevating buildings so that permafrost formation is not impeded. By allowing air flow under the building during winter months the ground ice is preserved. However, this means increased heat loss from the building must be designed for through improved insulation, air seepage barriers, and countercurrent flow ventilation that allows slow air exchange while recovering >80% of the heat.

Many northern communities have created systems of "utilidors" where sewage, water, telecommunications and sometimes electricity are delivered to individual residences and buildings through elevated corridors (Figure 8) that do not impact the permafrost. In communities where it is not practicable to build utilidors, water and sewage trucks deliver

potable water to residences and buildings on a regular basis, filling water tanks within the buildings. The same is true for sewage: holding tanks within the buildings are pumped out on a regular basis. This service contributes to the carbon footprint of northern communities.

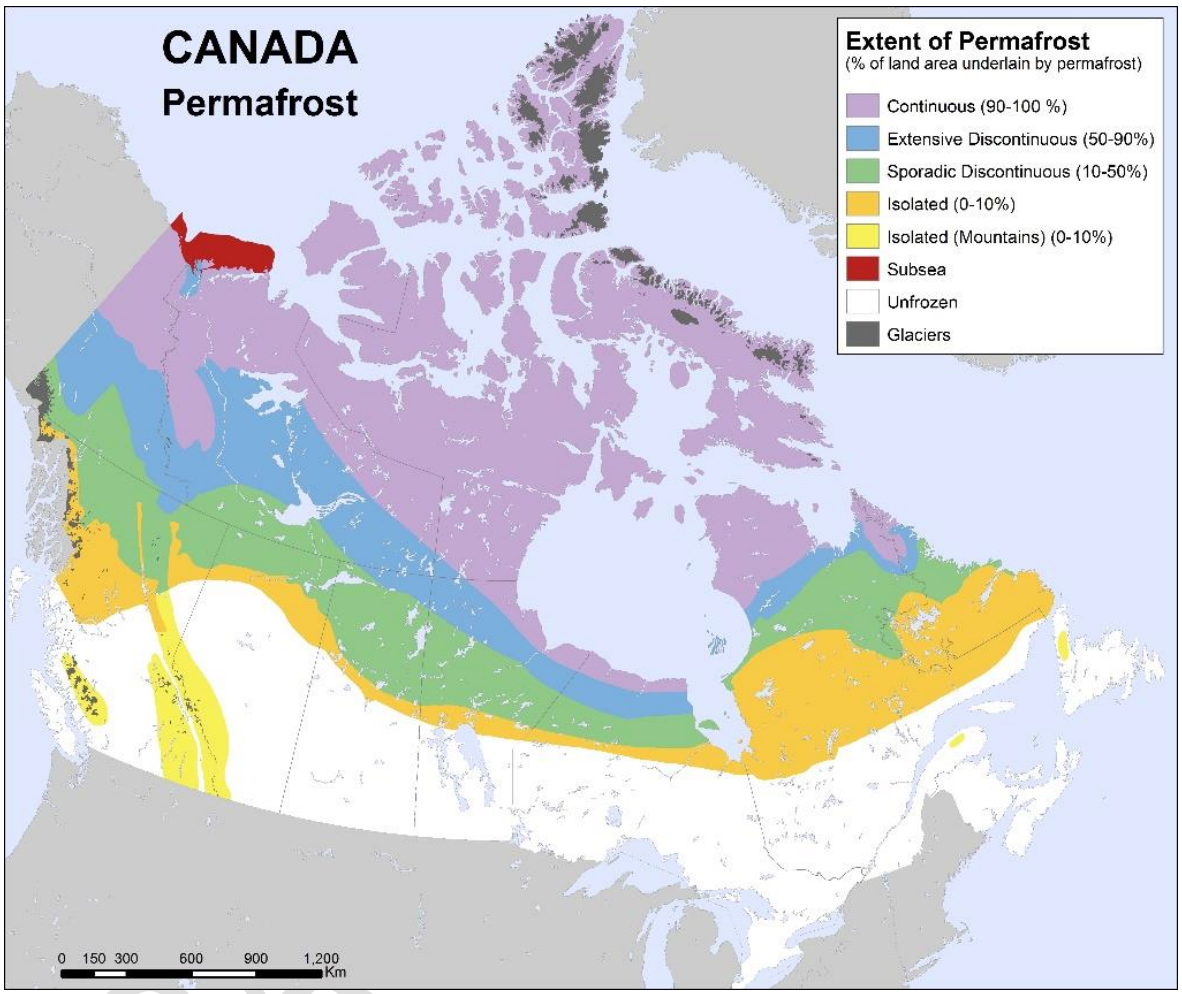

Figure 7: A permafrost map of Canada shows widespread areas where ground temperatures are below zero, in some cases to depths greater than 2 km (2020).

Figure 8: Utilidor in Inuvik, Northwest Territories.

Geoexchange

Geoexchange systems (Hickson *et al*. 2023) can be used to store waste heat in the shallow ground (10s to 100s of meters); however, they are not suitable for areas with ground ice, but would work in areas underlain by coarse gravels, dense sedimentary rock, or crystalline basement rock – "dry bedrock". Geoexchange systems using water such as in lakes not subject to deep freezing in the winter or ocean sources may be useful. This is because in northern Canada the winter temperatures are so low that even a thermal source a few degrees above zero is a potential energy source because of the large temperature difference (ΔT). The ΔT can be more than 30° C for prolonged periods during the winter months. For a heating system this means saving part of the cost of the fuel burned to raise the temperature of the ambient outside air to indoor temperatures. It would not be sufficient to provide the full heating needs of a community, but would offset the fuel burned, and over time would recover the expenditures in fuel costs and GHG avoided.

Conventional Geothermal

Conventional geothermal (Hickson *et al.* 2023) has many advantages in that if the fluid temperatures exceed 70° C (or 60° C in extreme northern climates) both electrical and thermal energy can be produced. However, large diameter wells are required to flow sufficient fluid to extract the energy from; these are costly, they need to be engineered, and mobilizing the equipment to drill wells in remote regions adds extra costs to the project's CAPEX. Modelling of well-managed conventional systems shows that the resource is extractable (with concurrent

injection) on a multi-decadal time frame with little or no temperature loss and low OPEX. These types of systems would be ideal, for example, where the fluids are at high enough temperature (>50-60° C) within two or three kilometers of the surface within a high porosity and permeable sedimentary sequence to support the energy extraction.

Conventional power and heat geothermal systems are likely to cost between $50 Million and $100 Million to build (including ORC and/or heat exchangers). Additionally, the surface infrastructure needs to be adapted to handle the direct-use heating aspect of the system. Such retrofits are likely to be costly and not practical for individual homes that might be spread out over a large area. If new infrastructure or industry is planned for a community, fitting the development to the new system, rather than retrofitting, would likely offer the most cost-effective way to proceed. However, it should be noted that investment of 10s of millions of dollars into small communities (<1000 people) is unlikely to be supported – even though the long-term financial gain is significant. Figure 9 shows the payoff for a low temperature (<65° C) district heating system (thermal energy only) where the CAPEX is estimated to be $40 million (scenario 1) and $30 million (scenario 2). This long term, base-load energy resource begins to pay back significant costs over operating the same system using NG in under 10 years, and even sooner when avoided carbon taxes are taken into account. For a municipality, these long-term avoided costs make projects sustainable to the taxpayer for the 70+ years that most municipal infrastructure is built to last.

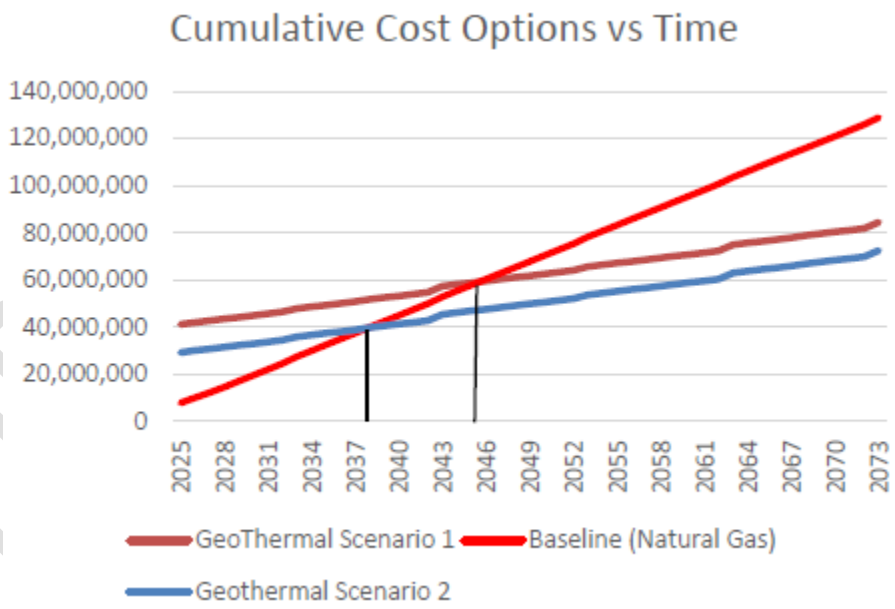

Figure 9: Two development scenarios are shown for a direct-use low temperature geothermal system. (Binns 2023)

Closed loop systems

Geoexchange systems are inherently closed loop, in that a secondary fluid is circulated through underground pipes to store and extract heat in the underground. Closed loop, deep geothermal systems (below the base of groundwater and usually deeper than one or two kilometers) are being investigated by several companies. Of these systems there are two types. One with multiple connected bore holes (multibore) and an above surface heat exchanger and/or ORC unit (e.g., Eavor Loop™). The other type is a monobore system with a single well bore and downhole heat exchanger (e.g., CeraphiWell™ and Novus, among others).

The closed loop monobore systems are unlikely to support power production, unless in very hot wells, and the multibore systems may see temperature drops below surface equipment specifications within a short period of time, continually requiring additional makeup wells. To date, neither technology has been commercially proven, but modelling shows that the multibore system, when placed in a convecting high temperature system, is sustainable over a multidecadal time frame (Yuan *et al*. 2021).

Monobore systems can have a significantly lower CAPEX than other types of geothermal systems. For example, modelling of a narrow vertical wellbore (4") drilled to a depth of one kilometer with a diamond drill rig such as used for mineral exploration, and often available in northern communities, will provide fluid to surface of 25° C on a multidecadal time frame *(Guo et al*. 2020, Guo *et al*. 2021). These systems can be installed for less than $2M; however, it then becomes an engineering exercise to adapt current building heating systems to handle this large-volume, low temperature heating fluid.

In the north, retrofitting existing buildings, unless they are large volume (such as sports complexes or industrial warehouses) is unlikely to be financially attractive. However, these low cost monobore systems may provide a practical solution for "right sizing" heating infrastructure for very small communities, providing them with a carbon free, baseload, multi-decadal heat source. An additional aspect of these systems is the potential to repurpose either suspended oil and gas wells or to recover hot fluids through stimulation of lower permeability strata. These systems are likely to show similar proportional cost savings to the one shown in Figure 9 with attendant GHG savings.

However, it should be noted that deep heat mining is not a renewable energy source if the heat is being extracted from a rock mass that is heated conductively – it takes 1000 years to replenish the heat to >95% for typical dimensions and temperature drops. Seeking systems with convectively heated rock sources will likely be the goal of commercially viable closed-loop systems with low OPEX.

Heat pumps:

Heat pump technology can extract the heat down to an exit water temperature of ~3-5° C, so 45-50° C water (such as provided by a low temperature geothermal system - either closed or

conventional) can provide a ΔT of ~40° C, giving ~175,000 J/kg (Joules per kilogram) of energy. Where there is excess electricity, such as a diesel generator that does not have maximum load draw (and/or the carbon footprint of the heat pump is supported by the GHG offsets of the completed system), a heat pump may provide a viable heating alternative.

A house in northern Canada may need 120-150 GJ/yr (Gigajoules/year), of which approximately 80% is heat need, and 20% is electrical energy need. If an average heating need of 100 GJ/yr of heat taken as the standard in Canada's north, in January at -35° C, the heat demand will be about 1 GJ per day.

If 175,000 J/kg can be extracted from warm water, this means the mass of water needed to carry the heat load is 6,000 kg of water, or ~6 m^3/day. Assuming a distribution system efficiency of 0.60 – this translates to ~10 m^3 of water per day. A standard 5/8th inch garden hose with the tap on full can provide 60 m^3 of water per day. This gives an idea of how to scale a system; a garden hose running full out fills a 5-gallon pail in 30 sec. If we can extract this amount of heat from 60 m^3 of water per day, the system is sufficient to heat six fully detached homes in January. If the homes are actually in a well-built apartment or are quadruplexes (only two walls exposed to the atmosphere), heat requirements are substantially less.

ORC (Organic Rankine Cycle) units operating in cold climates.

In the north during the winter (T_{amb} < -10 to -40° C), ORC engines can generate electrical power even if the water is only 60° C. Systems exist (c.f. example Climeon™, https://climeon.com) that can generate 100-200 kW of power from such low-grade heat, but they would have to be "retuned" for specific conditions. However, a problem with ORCs is that heat has to be stripped off the "working fluid" in the secondary ORC engine circuit to cool it for recompression and liquefaction. The conventional approach is merely to dump this heat into the atmosphere. Yet, if a better designed heat exchanger could be made (i.e., a better countercurrent air/air heat exchanger), the heat that is dumped to atmosphere could be largely exploited for its heat content through passing the warmish air (10-25° C) through an atmospheric heat pump system.

The colder the T_{amb} and the longer the cold season (i.e., farther North), the more efficient an ORC-type system becomes in extracting some electrical power from low T fluids. However, counteracting that, we would have to drill deeper to find rock of a particular T. In Finland, the ST1 Project in Espoo (2023) reached a T of 115° C at 6.1 km depth (approx.). In parts of Canada's far north, to access 60° C, we might have to drill 5 km.

Heat storage and hybrid systems

We waste a huge amount of low-grade heat in the north, as already mentioned under "waste heat recovery". There is the potential to store this heat underground seasonally in a geoexchange system, or deeper, in a closed-loop system. Deeper systems, well below permafrost, would likely be the best option in areas of shallow, ice-rich soils. Heat can also be

generated by solar collectors in the summer, and even wind turbines running electrical heaters might be a useful source of heat (Giordano *et al*. 2019). There is also the potential to integrate a heat storage system with a deep geothermal heat source to extend the useful life of the heat source. Understanding the energy demand curves of the thermal and electrical loads, as well as the heat-provision characteristics of thermal recharge sources, is important in engineering these hybrid systems.

Enhanced (engineered) geothermal systems

High enthalpy systems are the holy grail of geothermal developments. Dry stream systems (for example the Geysers, CA, USA), have very low OPEX and are relatively easy systems to operate (Zarrouk et al. 2014). This is likely why the first geothermal electrical generator was developed in Italy at Lardarello (Soltani *et al*. 2019). As energy demand increased around the world (Figure 2), despite the ups and down of the price of crude oil (Figure 1), where financially viable to do so, geothermal systems were developed from lower enthalpy sources. This led to the development of the geothermal versions of the ORC engine (Dambly *et al*. 1982). Gains in efficiencies were worked on by using different operating fluids for different temperature inputs. Different types of geothermal systems were explored and successfully utilized to produce electricity. However, high CAPEX and other financial considerations of the industry still favor locations where heat is available at depth of four kilometers or less.

To expand the geothermal realm beyond those specific regions with identifiable resources at relatively shallow depths (<4km) some countries began investigations of how to extract energy from “hot dry rock” (Rybach 2010). The field has evolved into the more commonly used term “enhanced geothermal system” and sometimes “engineered geothermal system” (EGS) but the fundamentals are the same: how to extract energy from rock that has no natural fluid to “scavenge the heat”. The closed loop systems (either with or without downhole heat exchangers), are potentially one solution, but are still faced with significant development costs to reach rock of temperatures sufficiently high to provide useful energy, deeper still for electrical generation. In the Canadian Shield, (covering as much as 60% of the country), the gradient is approximately 15° C per kilometer. This requires drilling to a depth of four to five kilometers or more to obtain enough heat for power generation. And the caveat must be repeated that deep heat mining is not a renewable energy source if the heat is being extracted from a rock mass that is heated conductively.

Overcoming these challenges will require multidisciplinary research teams to develop systems that are sustainable on a multidecadal life span; “right sized” for the heat loads required of communities and industrial activity; and with carbon footprints that justify the investment in the technology and its development. However, advances in EGS help conventional and lower temperature systems be more sustainable and have lower OPEX. Creating a sustainable heat system from hot dry rock is an engineering feat, but the lessons learned from such systems are applicable to enhancing existing systems and developing better ones.

EGS and geothermal systems in general will benefit from advances in drilling technology. Drilling costs must be reduced massively to promulgate both EGS and geothermal systems beyond niche applications. Drilling systems must be made much smaller, highly portable, and semi-automated. Two very different scales are needed. Drilling systems for >5 km deep wells to mine deep heat or tap into convecting hydrothermal systems, and systems for 0.25- to 1-kilometer-deep wells to install downhole heat exchangers and develop a seasonal heat repository.

Hydraulic stimulation of wellbore arrays in granite or other tight rock to achieve inter-well connectivity or enhance fluid flow for deep geothermal heat extraction must be developed. This is especially important in the large well bores needed for geothermal energy extraction. "Fracking" technology was developed for hydrocarbon extraction from small diameter wells bores in tight shales but is expensive and not as successful in large well bores. Deflagration has proven effective as has simple cold-water stimulation of the well bore.

These research efforts are best trialed in easy-to-reach locations where deep drilling is already underway and significant information about the subsurface is available. In a location with soon-to-be-drilled wells, the well design and engineering can be modified to drill deeper into the underlying bedrock and test drilling techniques and well bore stimulation.

Conclusions

Providing Canadians with long-term, sustainable, decarbonized thermal energy should be a goal of national, regional, and local governments. Just as the NG and electrical infrastructure was built out in the 1960s, so too must a heat infrastructure be developed. This infrastructure will look different, depending on the location and the specifics of the geography, population, built infrastructure, waste heat opportunities, and development plans. Systems must be "right sized" for communities to assist in reducing long term fuel costs and GHG emissions (decarbonization). Innovation, invention, and technology need to be brought to the forefront to help Canadians and the Canadian economy through the transition of reducing hydrocarbon use for heating; use of those hydrocarbons for other purposes including sale to offshore countries in need of decarbonizing their coal-fired electrical grids. Advanced drilling technologies, innovations in small-scale heat exchangers and power engines, well stimulation techniques, and understanding of the subsurface (especially in areas of permafrost) are all needed. These advances must be combined with technical assistance to individual communities and governments to assist them in understanding how to maximize long term fuel savings and decarbonizing their systems, while maintaining a robust, sustainable system on a generational time frame.

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