Direct Use of Geothermal Heat in Nova Scotia

Final Report

February 2022

dunsky
Energy + Climate

Study Team

In partnership with:

Note: Stephan Séjourné, project partner with Enki, is a professional geologist registered with the Association of Professional Geoscientists of Nova Scotia (APGNS License to Practice #144).

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List of Acronyms

APGNS – Association of Professional Geoscientists of Nova Scotia

AQ – Aquaculture System

DH – District Heating System

EGS – Enhanced Geothermal System

EIA – Energy Information Administration (USA)

Fm – Geological Formation

GH – Greenhouse System

GHG – Greenhouse Gas

GSHP – Ground Source Heat Pump

Mb - Geological Member

MD – Measured Depth

NRCan – Natural Resource Canada

NSDLF – Nova Scotia Department of Land and Forestry

NSDNRR – Nova Scotia Department of Natural Resources and Renewables

NSDEM – Nova Scotia Department of Energy and Mines

OERA - Offshore Energy Research Association

Sh – Seismic Horizon

Financial Glossary

CAPEX – Capital Expenditure: Expense incurred at the beginning of a project for purchasing equipment, building a facility, setting up a plant, etc.

DR – Discount Rate: The Rate that an organisation sets for itself to establish time-value of money (typically near 20% for commercial projects and lower for institutional or governmental projects providing public services).

NPV – Net Present Value: The difference between the present value of cash inflows (profits) and the present value of cash outflows (expenses) over a period of time, with future flows discounted according to the discount rate. A positive NPV represents a project that will give a return on investment eventually.

IRR – Internal Rate of Return: Rate that sets the NPV of a project to $0. If the internal rate of return for a project is greater than the discount rate, that project represents a financially worthwhile investment. Can be expressed in monthly or annual terms

OPEX – Operating expenses that are ongoing over the life of a project, including fuel and maintenance.

Executive Summary

Study Context

The **Offshore Energy Research Association (OERA)** and the Nova Scotia Departments of Natural Resources & Renewables, Agriculture, and Fisheries & Aquaculture are exploring the **potential for the direct use of deep geothermal heat in the province.**

Two geothermal studies were conducted in Nova Scotia. Phase 1, completed in 2020, provided insights on the geological character of geothermal resources and unknowns. Phase 2 focused on the economic competitiveness of mid-depth heat given the unknowns highlighted in Phase 1. This report presents the results and analysis conducted for the Phase 2 study.

Deep geothermal systems **extract hot water from aquifers deep underground,** providing high quality heat that can be directly used in heating applications.

In this Phase 2 study, **direct use of geothermal heat** is assessed in the context of **three "typical" industry** opportunities within Nova Scotia

This Phase 2 study seeks to determine if deep geothermal systems can be an alternative to **heating oil, propane, biomass, or natural gas** heating systems.

The ultimate goal of the *Direct Use of Geothermal Heat in Nova Scotia* study was to **evaluate the business case for deep geothermal systems in Nova Scotia** by assessing its potential cost effectiveness as a low-carbon heat source.

Study Objectives & Methodology

The study assessed the **technical and financial suitability** of deep geothermal systems for specific heating applications in **three geological regions of Nova Scotia**:
1) Cumberland Sub-Basin, 2) Stellarton Sub-Basin, and 3) Windsor-Kennetcook Sub-Basin.
The analysis followed three main steps, as outlined below.

1. Develop Facility Archetypes

Establish key parameters and hourly energy use profiles for three "typical" facilities where deep geothermal has potential:

- **Greenhouses**
- **Aquaculture**
- **District Heating**

2. Update Geological Profiles

Characterize three applicable geological regions based on results from the Phase 1 geological study to develop the necessary modeling inputs.

3. Modeling & Sensitivity Analysis

Conduct scenario modeling and sensitivity analysis to assess economic viability of deep geothermal relative to alternatives.

Executive Summary

Facility Archetypes & Energy Use Profiles

Greenhouse

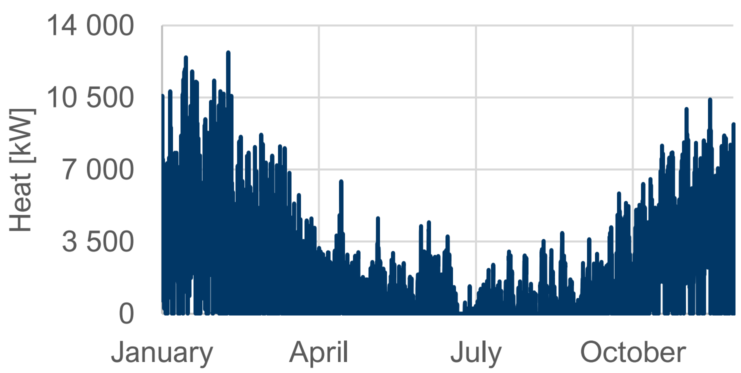
Facility	8 acres glass greenhouse
Crop	Year-long tomato production
Main Fuel	Residual biomass (wood chip)
Biomass Heating Load	49 420 GJ
Biomass System Size	3,500 kW + 10,000 kW propane auxiliary
Load factor	0.16
Current OPEX	$ 606,800

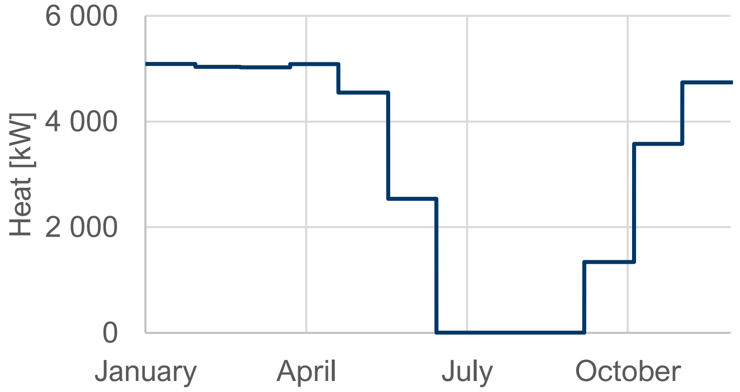
Aquaculture Facility

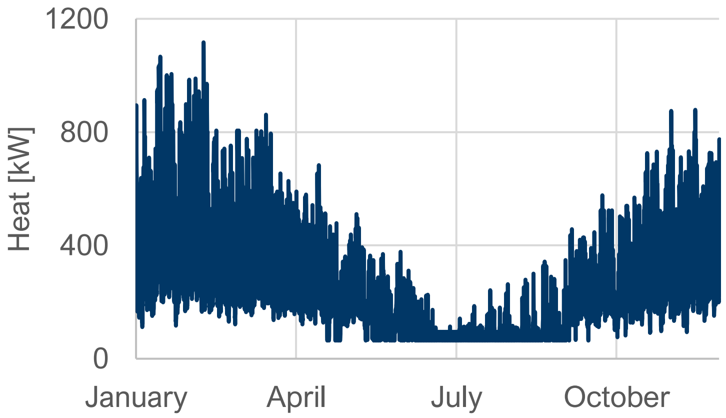
Facility	Land based, mid-sized indoor salmon hatchery
Product	Salmon Fry
Fuel	Oil boiler
Heating Load	107 750 GJ
Oil System Size	5,000 kW
Load factor	0.60
Current OPEX	$ 3,219,200

District Heating System

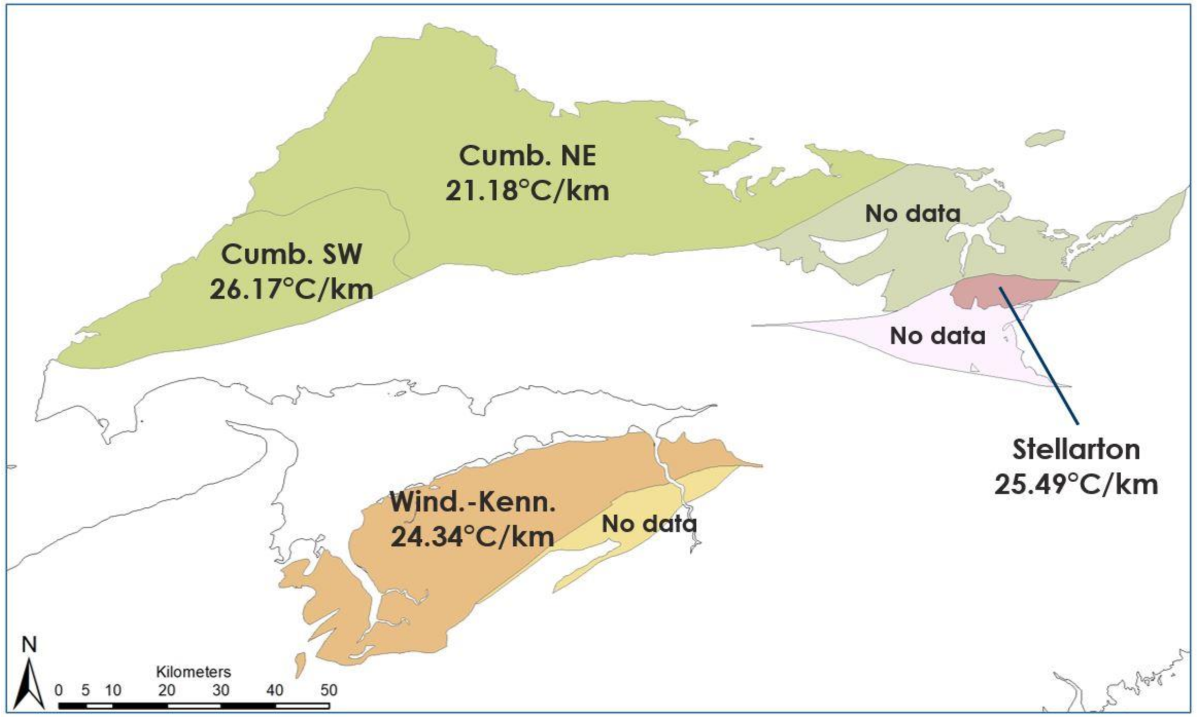
System	40 homes, 10 small businesses, and a community center
Services	Space and water heating
Fuel	Oil boiler
Heating Load	8 200 GJ
Oil System Size	1,117 kW
Load factor	0.23
Current OPEX	$ 260,675







Geological Regions Modeled



Study assumptions:

The study focused on three geological regions where sufficient data exists to assess the geothermal energy output:

- Cumberland Sub-Basin
- Stellarton Sub-Basin
- Windsor-Kennetcook Sub-Basin

These sub-basins were identified as promising regions from the Phase 1 study.

The study assessed the drilling and equipment costs and performance of deep geothermal resources, accounting for varying aquifer depth, porosity and heat quality. Each site was optimized to balance the impact of the number of wells vs pumping power needed to deliver heating required by the archetypal facilities.

Overview of Results - Financials

For the deep geothermal systems, **none of the archetypes were cost-effective under base case scenarios.**

Sensitivity analysis was conducted to determine if the deep geothermal systems could prove cost-effective under varied conditions.

When key variables were simultaneously adjusted for a “best case” sensitivity scenario, the aquaculture and district heating archetypes could become cost-effective. However, the "best case" scenario* presents a very optimistic scenario, that may be challenging to attain in reality (e.g., a 25% reduction in CAPEX, subsidies of up to 50% of CAPEX, 15% lower electricity costs, low-interest long-term financing, etc.)

		Deep Geothermal Base Case	Deep Geothermal Best Case*	GSHP Base Case
Greenhouse	NPV	- $29,467,000	-$15,627,000	- $4,832,000
	Payback	N/A	N/A	N/A
Aquaculture	NPV	- $5,019,000	$19,521,000	$50,784,500
	Payback	N/A	**2.75 years**	**< 1 year**
District Heating	NPV	- $57,538,000	$12,392,000	$5,154,000
	Payback	N/A	**6.2 years**	**4 years**

*The specific best-case conditions applied to each archetype can be found on pages 41, 45 and 49 of the report

Overview of Results – Possible Supporting Factors

	Favourable for Deep Geothermal	Findings from Nova Scotia Examples
Geology / Subsurface Conditions	• **High temperature basins:** offers more heating capacity from each well • **Shallow depth basins:** lowers drilling and well costs • Hot, shallow aquifers tend to be more desirable than deep porous aquifers	• Deep aquifers were either very deep, or not sufficiently porous • Shallow aquifers identified did not reach sufficient temperatures • The highest potential aquifers are found at depths that are only appropriate for large-scale projects
Facility Characteristics	• Stable **year-round heating demand** • **Larger facilities:** greater heating loads help justify CAPEX • Replaces **high-cost heating fuel** such as heating oil (i.e. not on gas network or fed with waste biomass)	• Greenhouse heating loads are too seasonal • Aquaculture has year-round heating needs that may be well suited to the right deep geothermal resource • District heating needs an anchor load to increase the year-round heating demand

Conditions Needed for Deep Geothermal

The study finds that if there is to be a case for deep geothermal in Nova Scotia, certain conditions would need to be met. With the knowledge we have now, the following **key factors need to align**:

- **Location, Location, Location**. Finding an appropriate aquifer is critical to establishing the business case for deep geothermal heating. Aquifer permeability, depth and temperature play a key role in the resource potential and heavily influence the project cost. Shallow, permeable aquifers tend to have lower costs by reducing well depth and pumping requirements. Where facility heating demands are relatively low, however (e.g. district heating system) permeability is less of a driver than the overall depth and temperature of the aquifer. High-temperature, shallow aquifers were identified in the study, (e.g., see Geology Appendix – Miscellaneous Information) but further geological investigation is required before they can be fully evaluated as deep geothermal resource.
- **Larger facilities with stable heating requirements are key**. Due to high fixed CAPEX costs, deep geothermal systems are only suitable in large facilities with a relatively constant heat load (i.e. load factors exceeding 0.5), which is the case for the aquaculture archetype. They may also be suitable in situations where the heat loads of various facilities can be aggregated – ideally with one or more larger "anchor loads" to raise the annual load factor.
- **Replacing high-cost fuels is also important:** The business case is stronger for deep geothermal when it replaces heating oil or other high-cost fuels. In the greenhouse example, the low cost of biomass (about five times lower than heating oil) eroded the business base for geothermal when compared to the current heating costs. However, even in cases where heating oil is the current fuel, GSHPs may still out compete deep geothermal as an alternative.
- **Financial tools can help**. Incentives and low-interest financing – in particular, those that reduce lender risk – could help to improve the business case where deep geothermal may be marginally financially viable.

The Bottom Line: For deep geothermal to be viable in Nova Scotia, a shallow high-temperature aquifer would need to be found, and then the appropriate energy end-uses would need to be identified in close proximity (e.g. large steady industrial load)

Possible Geological Niches for Deep Geothermal

Deep geothermal may be promising if locations with high temperatures at shallow depths can be found in Nova Scotia. These are highly localized in nature, and are typically found above three types of geological formations:

1) Faults that act as upward conduits for deep, hot hydrothermal waters
2) Salt domes with high thermal conductivity compared to the surrounding sedimentary rocks
3) Young, radioactive granitic bodies located near the base of the sedimentary cover that produce radiogenic heat.

These three features are present in the areas of interest, but a specific shallow high-temperature aquifer was not identified. Further studies would be needed to explore these features and determine their impact on the local geothermal gradient.

Ultimately, lower CAPEX and operating costs are required for deep geothermal to become a financially viable alternative. Specific opportunities, if identified through further study, could include:

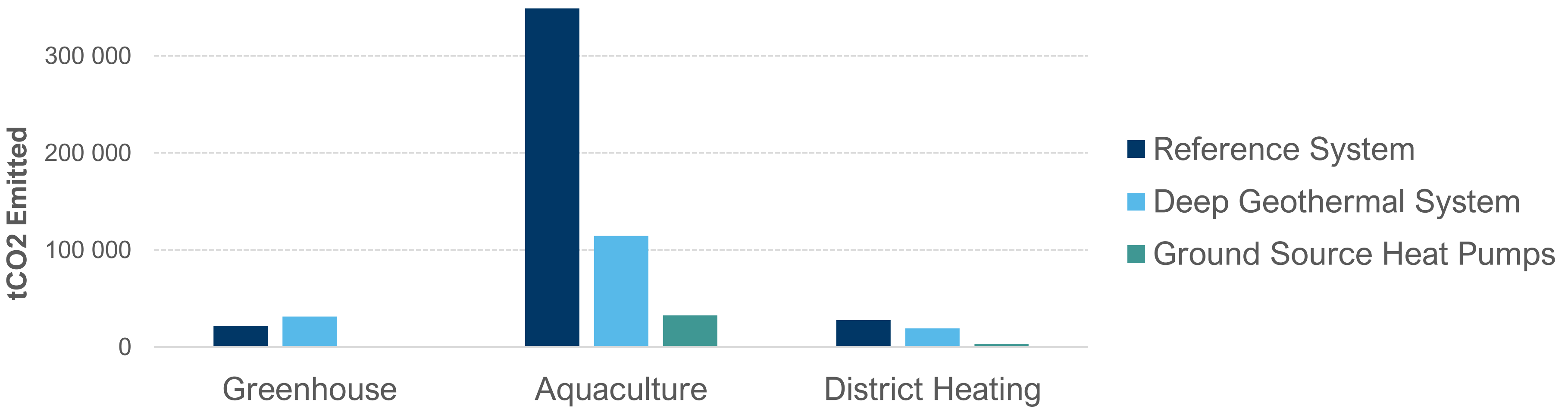
- For projects with low heating requirements, such as the reference district heating systems of 50 houses, hot shallow aquifers are more desirable than deeper more porous aquifers. However, the shallow aquifers identified in this study were not sufficiently hot. At lower depths, the aquifers were too cold to be used in direct heating. At greater depths, the CAPEX required to reach the aquifers was not worthwhile considering the small scales of the projects.
- Projects with high heating requirements sustained throughout the year, such as aquaculture projects in porous aquifers, can support the use of deeper aquifers. A smaller number of boreholes can be pumped at high flow rates in order to supply affordable energy. However, the most interesting aquifer, the Lime Kiln Brook aquifer, is so deep that only large scale projects should be considered in order to make full use of the boreholes able to reach it.

Competition with GSHP

Ground source heat pumps (GSHPs) appear to present a more favorable option than deep geothermal for all archetypes assessed. In all cases, GSHPs outperform deep geothermal systems on an financial and GHG basis, <u>even when the GSHP base case is compared to the best-case scenario for the deep geothermal system</u>. GSHPs tend to have lower CAPEX costs but higher OPEX costs (due to increased electricity consumption) than deep geothermal, so it may be possible that deep geothermal could outcompete GSHPs for facilities with very high and stable heating loads, located near a viable aquifer.

Further Benefits of GSHPs. GSHPs offer further benefits over deep geothermal, including their ability to provide cooling, posing less risk of well failure, and being a more established technology in the market. While this study focused on heating only applications, the addition of cooling load would help to increase the financial performance of GSHP, mitigate the risk of wells freezing, and increasing the GHGs reductions.

GHG Emissions Impacts from Energy Systems (2021-2061)



Recommendations

- **Recommendation #1 - Find high potential aquifers:** The assessed archetypes and aquifers did not yield a viable business case for deep geothermal in Nova Scotia, except for under extremely optimistic “best case” conditions. As a next step it is recommended to identify aquifers that offer higher potential resources, particularly with shallower higher-temperature aquifers than those examined in this study. Given the current low level of understanding on the subsurface geology of the studied areas and the conservative regional geothermal gradients considered in the evaluation, it is possible that such a resource could be identified through further investigation.

  Dedicated geological modeling, as outlined in Section 8 of the Phase 1 report, will be needed to document the geothermal properties in selected areas for specific potential projects, especially above 1) basement-rooted faults, 2) young radioactive granitic bodies at the base of the sedimentary cover or 3) salt domes, as these geological environments are particularly suitable for enhanced heat flow. Moreover, if potentially viable aquifers are identified, but they are found to be of low permeability, Enhanced Geothermal Systems (EGS) could be considered. Two recommendations to de-risk EGS practices are detailed in the Geology Appendix, citing how the available subsurface data can provide valuable information to assess the use of EGS.

Recommendations

- **Recommendation #2 - Identify appropriate heating loads that are in close proximity:** Once an appropriate aquifer (or set of aquifers) is identified, OERA and the government should aim to identify larger projects, such as industrial facilities with stable year-round loads that are, or could, be situated in close proximity. Engaging with these facilities at the earliest stages of the development process will further increase the chances of finding a fit for deep geothermal, particularly if it can be included in the initial construction or end-of-life heating system replacement process.

- **Recommendation #3 – Where a shallow high-temperature aquifer exists, aim to develop a pilot project:** Direct use of heat deep geothermal projects have not been constructed in Nova Scotia (in fact, there are few examples in Canada). We recommend looking for those opportunities that align with the key factors that will make deep geothermal a winning solution and develop a pilot project. That will provide valuable learnings, including who can provide the needed services; further understanding on the subsurface geology; on-the-ground performance metrics; and other insights that will help refine the business case for deep geothermal.

- **Recommendation #4 – Consider further assessment of GSHP:** While direct use of heat from deep geothermal was the focus of this assessment, due to the favorable economic and GHG results for GSHP we recommend a deeper dive into the opportunity for this technology in various use cases across the province (such as for district heating/cooling and aquaculture facilities). As part of a comprehensive feasibility assessment, further study is needed to understand how deep geothermal compares to other low-carbon solutions – both technologies and energy sources – such as air-to-water heat pumps, renewable natural gas, and hydrogen especially for replacing more costly energy sources such as heating oil.

1. Introduction

1.1 Context

1.2 Methodology

1.3 Geo-Economic Model

Study Context

The **Offshore Energy Research Association (OERA**) and the Nova Scotia Departments of Natural Resources & Renewables, Agriculture, and Fisheries & Aquaculture are exploring the **potential for the direct use of deep geothermal heat in the province**.

Deep geothermal systems **extract hot water from aquifers deep underground,** providing high quality heat that can be directly used in heating applications.

Deep geothermal systems may be able to provide an alternative option to heating systems currently supplied with **heating oil, propane, biomass, or natural gas.**

The *Direct Use of Geothermal Heat in Nova Scotia* study **evaluates the business case for deep geothermal systems in Nova Scotia** by assessing its potential cost effectiveness in providing low-carbon heat to large commercial facilities and district heating systems in the province.

Study Objectives & Methodology

The objective of this study is to determine the **technical and financial suitability** of deep geothermal systems for **specific types of customers** relative to the status quo and typical closed-loop ground-source heat pump systems in **three geological regions of Nova Scotia**.

Develop Archetypes → Create Energy Use Profiles → Update Geological Profiles → Modeling & Sensitivity Analysis

Develop Archetypes: Establish key parameters for facilities where deep geothermal has potential: greenhouses, aquaculture, and district heating.

Create Energy Use Profiles: Identify hourly energy use profiles for each archetype in order to model heating consumption and costs.

Update Geological Profiles: Characterize different geological regions based on results from a previous geological study and develop inputs for the geo-economic model.

Modeling & Sensitivity Analysis: Conduct scenario modeling and sensitivity analysis to assess economic viability of deep geothermal relative to alternatives.

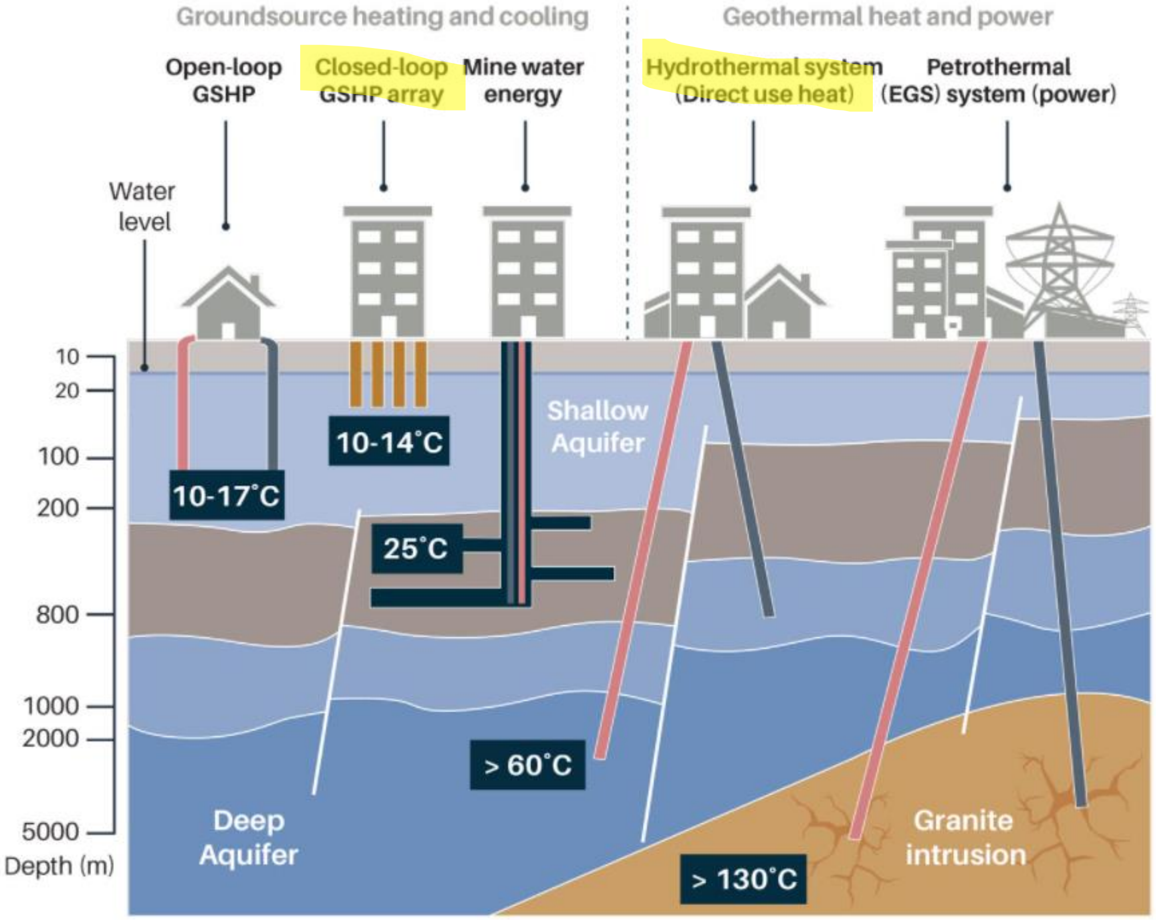
Overview of Energy System Types

Three energy system types are assessed as part of this study:

1. **Reference System** (i.e., status quo) – The reference system is the current heating system that is typically used – or most likely to be used in the near term – in Nova Scotia for each of the archetypes. For example, a oil-fired boiler.

2. **Direct Use Heat, Deep Geothermal System** – The deep geothermal system (a.k.a. doublets) consists of a production and an injection well, and provides direct-use heat from mid-depth sedimentary aquifers. Warm water is pumped to the surface from the production well and after the heat is extracted, the cooled water is returned to the reservoir through the injection well.

3. **Closed Loop Ground-Source Heat Pump** – A closed loop ground-source heat pump (GSHP) system accesses heat via exchange with the subsurface at moderate to shallow depths (typically 600 feet or less) that is then concentrated using a water–to-water or water-to-air heat pump, to provide space heating and cooling.



Source: British Geological Survey.

Scenario Modeling

Case Studies: The study scope included a total of 15 case study scenarios, including modeling the deep geothermal systems in three geological regions identified for the study: 1) Cumberland Sub-Basin, 2) Stellarton Sub-Basin, and 3) Windsor-Kennetcook Sub-Basin. In the end, more than 40 scenarios were modeled in order to explore the economics of different potential aquifers in each geological region.

Archetypes	System Type		
	Reference/Status Quo	Closed Loop Geothermal (w/Heat Pump)	Deep Geothermal in each Geological Region
Greenhouse	1	1	3
Aquaculture	1	1	3
District Heating System	1	1	3
	Total number of case study scenarios: 15		

Sensitivities: Sensitivity analysis was performed on key geological, facility (size and heating profile), and financial parameters. An optimal sub-basin/aquifer pair was chosen for each archetype and then 18-20 sensitivity scenarios were modeled. By analyzing sensitivity of different parameters, their relative importance to project profitability can be evaluated, informing later decisions such as optimal incentive levels or areas meriting further research.

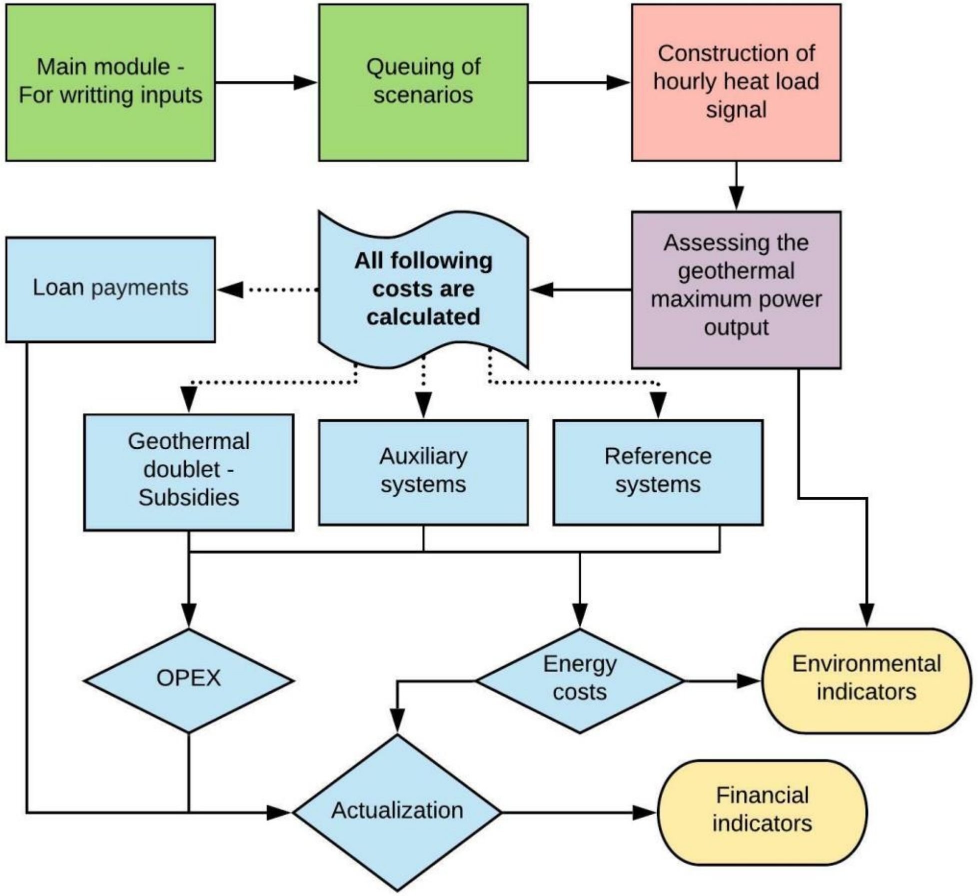
See Inputs and Results sections for additional information on the scenario and sensitivity parameters.

Geo-Economic Model Overview

The analysis was primarily conducted using SQGI's Geo-Economic Model. The model was used to translate geological, energy, and economic inputs into specific and useful financial and environmental indicators that allow us to assess the viability of deep geothermal projects for each case study.

Components of the model include:

- A main module where each variable and parameter is listed and can be changed for the sensitivity analysis;
- Annual CAPEX costs for the deep geothermal doublet, its auxiliary, and both reference systems (primary and auxiliary);
- Monthly OPEX costs of all recurring costs not involving energy (insurance, mechanical equipment, acidic treatment against scaling, etc.);
- Monthly energy costs based on tariffs applicable in Nova Scotia for fuel oil, biomass, propane and electricity;
- Monthly CO_2 emissions for the doublet, based on its electricity consumption, and the auxiliary and references systems;
- Actualization of all costs by taking into account inflation (overall inflation and on specific energy prices) and discount rate; and,
- Assembling of the financial indicators (NPV, IRR, payback period, simplified marginal costs of energy).



Geo-Economic Model Overview, *cont.*

The SQGI model was specifically updated for this study, including:

- Introducing the possibility of using two different reference heating sources simultaneously (i.e., a baseline system with a back-up auxiliary system)
- New module that interpolates electricity consumption of the well pump based on the aquifer's characteristics
- New module that estimates the cost of the heat exchanger based on temperatures and flow rates achieved
- New module that calculates the cost of the above ground portion of a district heating system based on the number of homes or buildings linked to the system
- A loan duration that differs from the simulation length
- Energy costs and tariffs for the Nova Scotia context (electricity, heating oil, natural gas, propane, biomass)
- Drilling costs specific for Nova Scotia that include mobilization from other parts of Canada
- A tax on carbon emissions that is applied to all fuel sources, including electricity

2. Inputs

2.1 Archetypes

2.2 Geological Inputs

2.3 System & Financial Inputs

Overview of End-Use Archetypes

Approach:

- For this study we identified three end-use archetypes that are candidates for the direct use of geothermal heat. These include a greenhouse, a land-based aquaculture facility, and a district heating system.
- Each archetype was constructed using key facility and reference energy system characteristics (see below), which also act as inputs to the geo-economic model.
- To ensure our archetype inputs are accurate and representative of the Nova Scotia context, we reached out to government and local industry experts to validate the assumptions. These experts are listed in appendix D.
- It is important to note that we are considering archetypes (that is, generic project types) as opposed to specific projects in the province, and as such the characterizations reflect averages based on industry practices and on-the-ground experience.

Facility & Energy System Characterization:

- Facility size – area and/or production capacity
- Annual, hourly (8760) load profiles
- Maximum heating load requirement
- Baseline equipment for heating and cooling – primary and auxiliary (if applicable) – including operational parameters
- CAPEX and OPEX costs for baseline equipment
- Applicable energy rates (including carbon pricing)

Greenhouse

Aquaculture Facility

District Heating System

The three archetypes are detailed in the following slides.

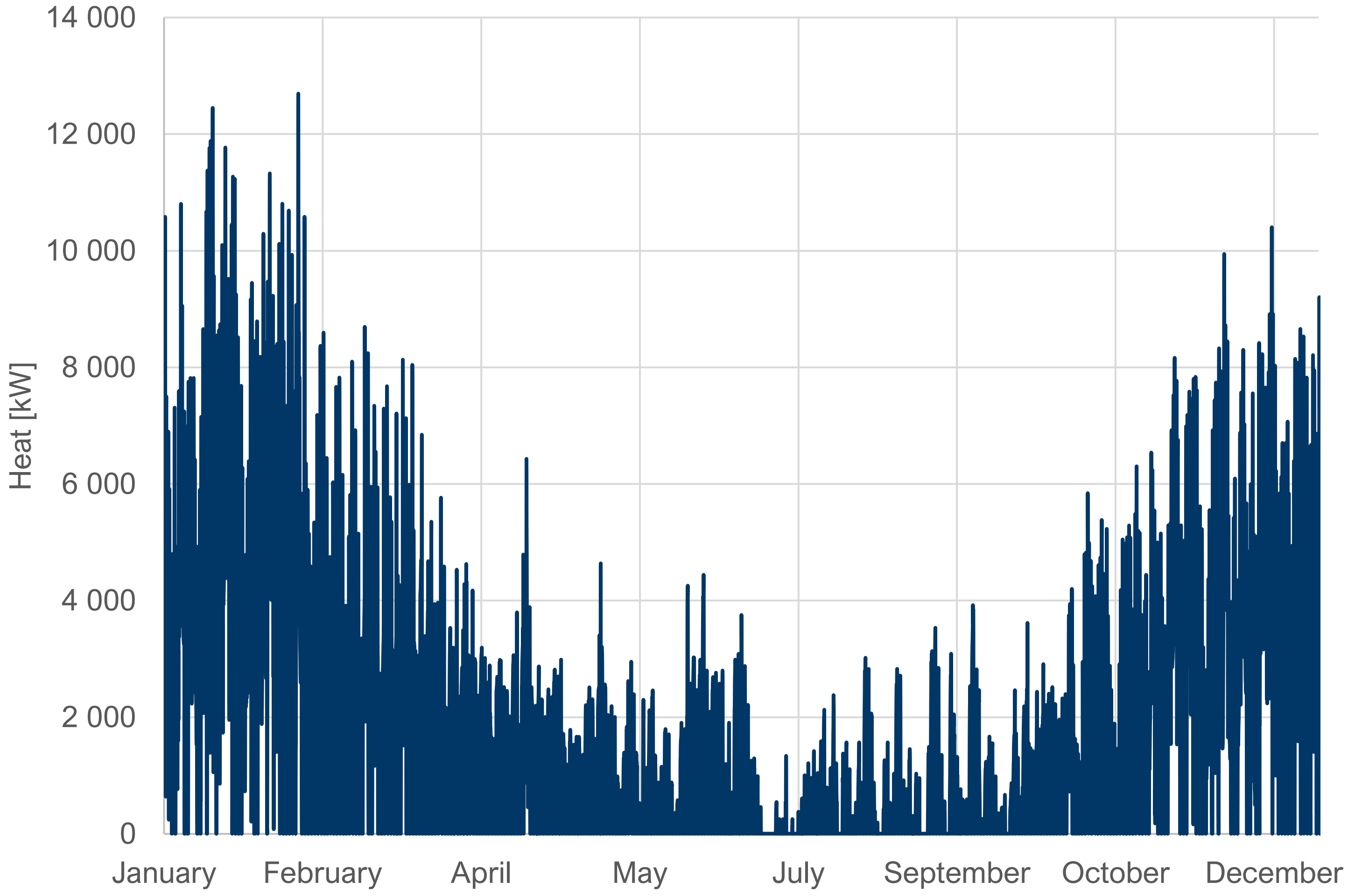
Greenhouse

The greenhouse archetype reflects a **mid-sized Venlo glass structure** (based on specs for existing and proposed facilities in Nova Scotia) for growing tomatoes year-round.

Greenhouse Facility Parameters		
Structure	Venlo (glass)	Most common for larger facilities
Surface Area	8 acres	Approximately equivalent to the largest facilities in Nova Scotia
Crop	Tomato	A common greenhouse crop
Production Cycle	Annual	Large facilities operate year-long to recover investments
Thermal Screen	Double layer (roof)	Common in Venlo greenhouses to reduce heat loss at night
Artificial Lighting	None	Less common Nova Scotia considering electricity costs
Heating Load	1.5 GJ/m^2	Based on heat losses and temperature setpoints

Reference Energy System		
Fuel & System	Residual forest biomass (wood chips)	Natural gas is not readily available. Biomass is less expensive and common in Nova Scotia greenhouses. Boiler efficiency of 75%.
System Sizing	3,500 kW	Based on energy requirement and design standards
Biomass price	$75/tonne	Based on $100 per oven dried tonne; 35% water content
Auxiliary Fuel	Propane, $0.89/L	Lower cost than fuel oil and more accessible than natural gas. Based on NRCan 2020 average data. Projected 3% inflation
Aux. System Size	10,000 kW	Capacity to cover peak needs and provide system redundancy
Electricity Tariff	Medium industrial	Peak load greater than 224 kW and less than 1,800 kW
CAPEX	$ 2,362,500	Cost of an automated hot water biomass boiler and a “MegaDome” structure (used as a boiler room and wood chip storage); 675 $/kW, from industry experience
OPEX	$ 606,806	Based on annual biomass and electricity cost, and boiler maintenance costs (~ 1% of CAPEX for greenhouses)

Greenhouse Energy Use Profile



- This chart represents total hourly heat requirement to maintain an 8-acre greenhouse at optimal temperature for crop growth, as modeled by Dunsky.
- Significantly more heat is required in winter months.
- Summer period heating mainly to overcome overnight heat loss and to control humidity levels, a standard practice in the industry.

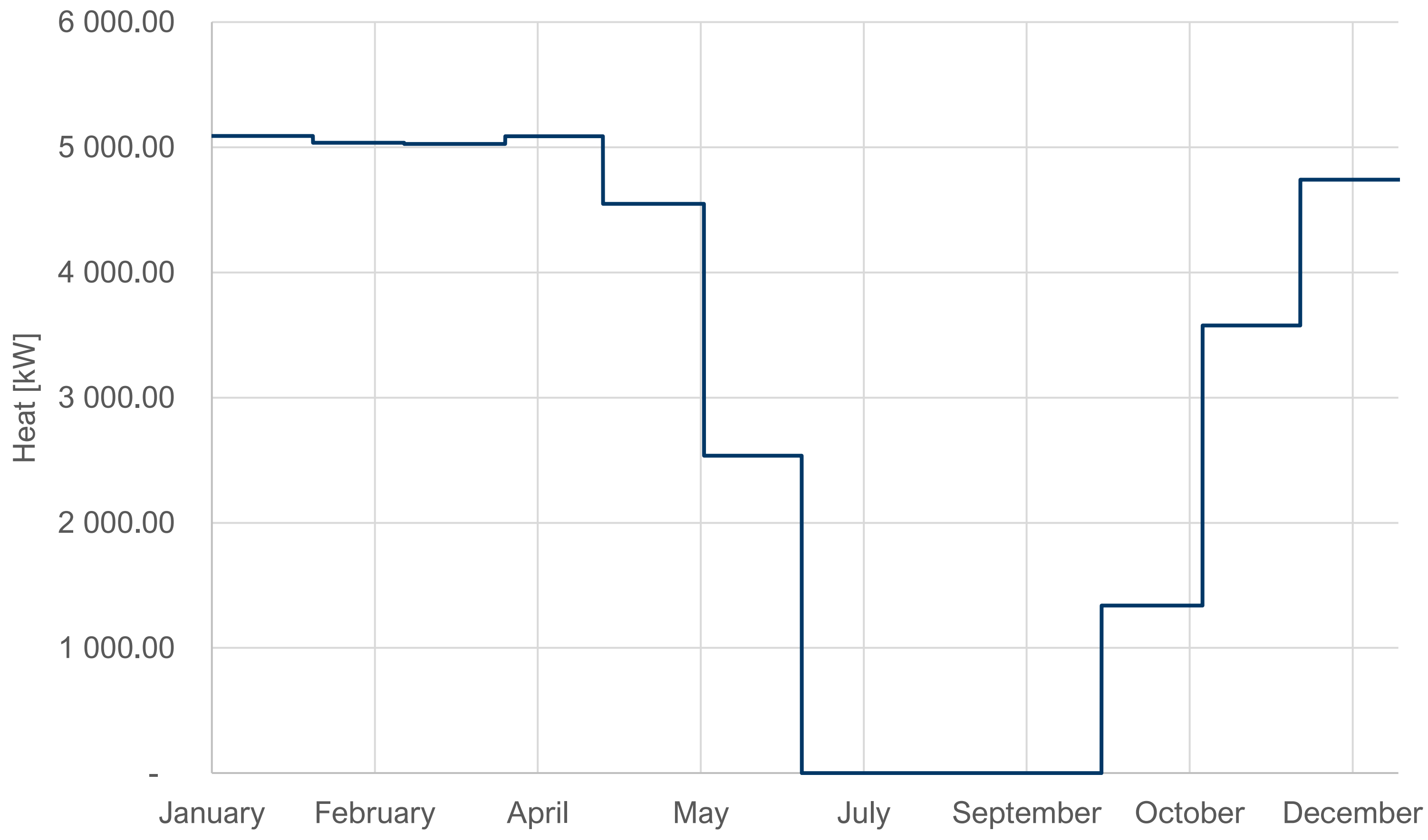
Aquaculture

dunsky

The aquaculture facility archetype reflects a **land based, mid-sized indoor salmon hatchery** (based on specs for existing and proposed facilities in Nova Scotia). The facility heats surface-drawn water to maintain water temperature of tanks at 14°C year-round to improve growth rates.

Aquaculture Facility Parameters		
Product	Salmon fry	Hatchery includes growth from egg to fry to supply grow-out operations on-site
Volume	300 000 L	Mid-sized hatchery based on review of existing and proposed facilities in Nova Scotia
Flow rate	208 L/s	2.5 Volume changes per hour based on *Handbook for Common Calculations in Finfish Aquaculture*
Target temperature	14 C	Based on *A Review Of Factors Influencing Maturation Of Atlantic Salmon*. Hatcheries in Nova Scotia are not always heated but doing so improves growth rate.
Production Cycle	Annual	Year-round heating of facility permits consistent supply
Heating load	107 750 GJ	Based on water temperature, target growth temperature, water flow rate and effluent recovery efficiency
Reference Energy System		
System & Fuel	Oil Boiler	Based on review of similar operations; 85% medium efficiency hot water boiler system
System Sizing	5,000 kW	Based on energy requirements and design standards
Oil price	$1.13/L	Most recent NRCan data. Projected 3% inflation
Auxiliary Fuel	None	Heating is a non-critical load for the facility
Electricity Tariff	Large industrial	Peak load greater than 1 800 kW due to overall facility pumping requirements
CAPEX	$ 1,232,000	Taken from EIA 2017 equipment study, indexed to inflation
Annual OPEX	$ 3,219,200	Based on annual water heating and boiler maintenance costs

Aquaculture Energy Use Profile



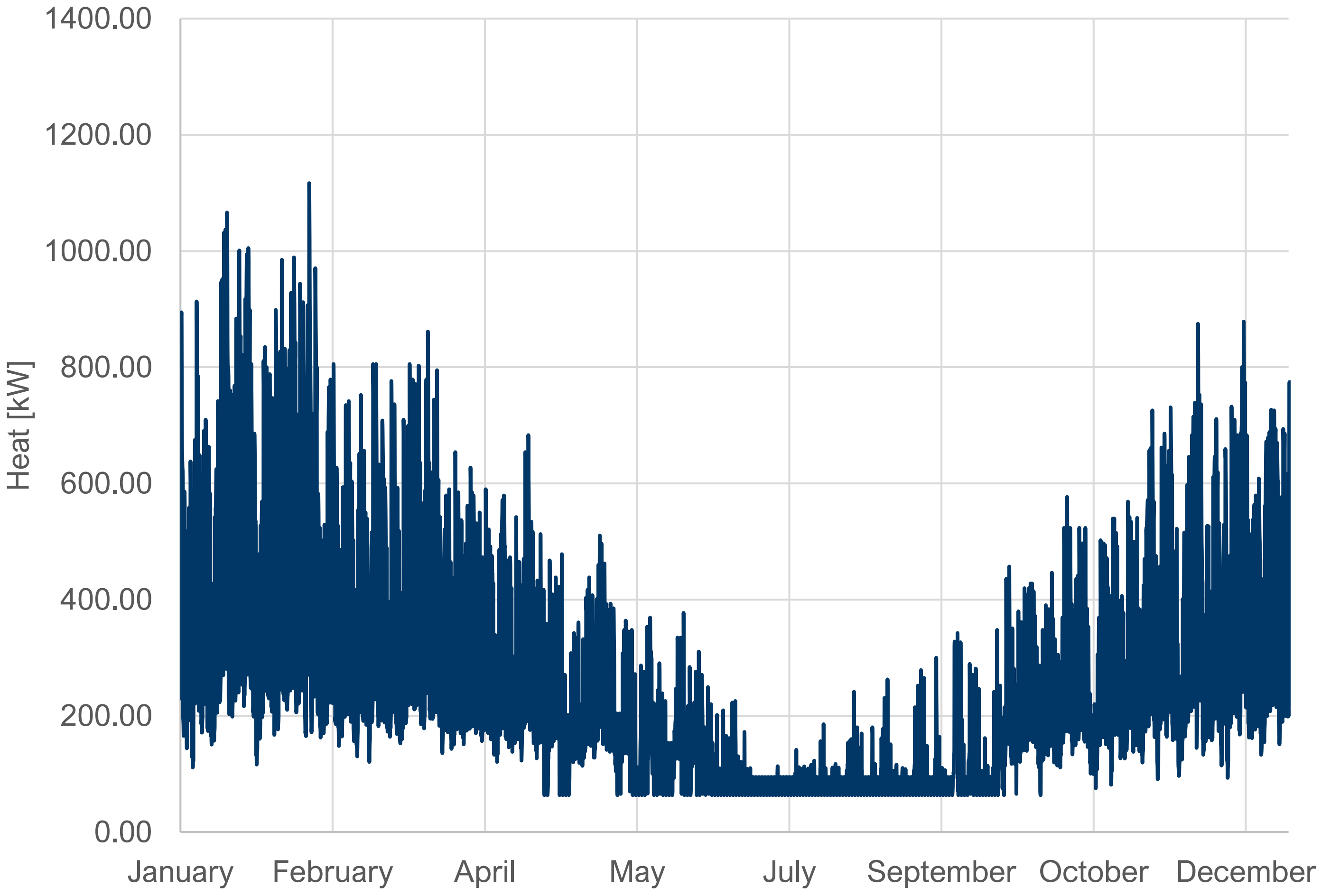
- This chart represents the total hourly heat required to heat incoming water to the optimal growth rate temperature of 14°C year-round, as modeled by Dunsky.
- Average summer (June-August) water temperature is already above optimal temperature, so no heating is required.
- Heat load is based on average monthly water surface temperature of the sea, measured at Parrsboro, NS:

District Heating System

The district heating archetype reflects **mixed-use development** including 40 semi-detached homes, 10 small businesses, and a community center with a gymnasium, pool, and meeting space.

District Heating System Parameters		
40 Homes	$140m^2$ semi-detached	Energy use based on *2014 NRCan Survey of Home Energy Use*
10 Shops	$93m^2$ individual shops	Energy use based on *2018 NRCan Building Energy Use Surveys*
Community centre	$1200m^2$ Gymnasium + 25x20m Pool heated to 27C	Energy use based on *2018 NRCan Building Energy Use Surveys* and *EnergyStar Swimming Pool Technical Reference (2018)*
Reference Energy System		
Type	Individual heating systems	Most common construction
System & Fuel	Oil Boiler	85% medium efficiency hot water boiler system; Common fuel type in new construction in Nova Scotia based on *2018 NRCan Building Energy Use Surveys*
System Sizing	1,117 kW	Based on energy requirements and design standards
Oil price	$1.13/L	Most recent NRCan data. Projected 3% inflation
Auxiliary Fuel	Electric Boiler	No back-up system for homes and businesses; electric boiler for the community center
Electricity Tariff	Residential & Commercial	Residential tariff rate for homes; commercial tariff rates for businesses and community center
CAPEX	$ 346,925	Taken from EIA 2017 equipment study, indexed to inflation.
Annual OPEX	$ 260,675	Based on annual heating load and system maintenance costs

District Heating System Energy Use Profile



- This chart represents the total hourly heat required to heat 40 homes, 10 shops, and the community center, as modeled by Dunsky.
- The most important heating clients are space heating, driving winter peaks when outdoor air is coldest.
- Pool heating requirements make up the baseline “floor” seen May through September.
- The presence of a large, year-round “anchor” heating load (the community centre & pool) ensures a minimal energy demand throughout the year. This improves the usage factor, favoring a heat pump over a fuel-based solution.

Geological Profiles & Inputs

Approach:

- For this study we selected several potential aquifers within each sub-basin. Potential aquifers that were too deep (e.g., the southwestern part of the Cumberland sub-basin, beyond 3 000 m) or too cold (less than 35°C) were discarded early in the project. Key geological parameters were then gathered or calculated for each potential aquifer: depth, temperature and rock quality (see below).
- Depths were derived from seismic data for the Cumberland and Windsor-Kennetcook sub-basins, thus allowing us to assess the variability of this parameter across the whole sub-basin (see example next slide). In the case of the Stellarton sub-basin, the lack of seismic data precluded this approach and a single, type vertical profile was generated for the entire area.
- Temperatures were calculated at depths corresponding to the middle of each potential aquifer, using the geothermal gradients estimated in the Phase 1 report (*Assessment of Geothermal Resources in Onshore Nova Scotia*). Results were corrected to account for the local impact of the mean annual surface temperature and for the paleoclimatic effect.
- The quality of the rock, that is, its ability to freely produce heated water, is the most difficult parameter to evaluate based on the data currently available in Nova Scotia. For this reason, the aquifers considered here are invariably referred to as “potential aquifers”, in keeping with the Phase 1 report. The input data stems mostly from scattered historical petroleum exploration datasets. The location of these wells was not optimized for documenting the true potential for geothermal energy in the province, although they occasionally gave out promising observations (see Geology Appendix – Miscellaneous information). The overall scarcity of porosity and permeability data was an important constraint for this work.

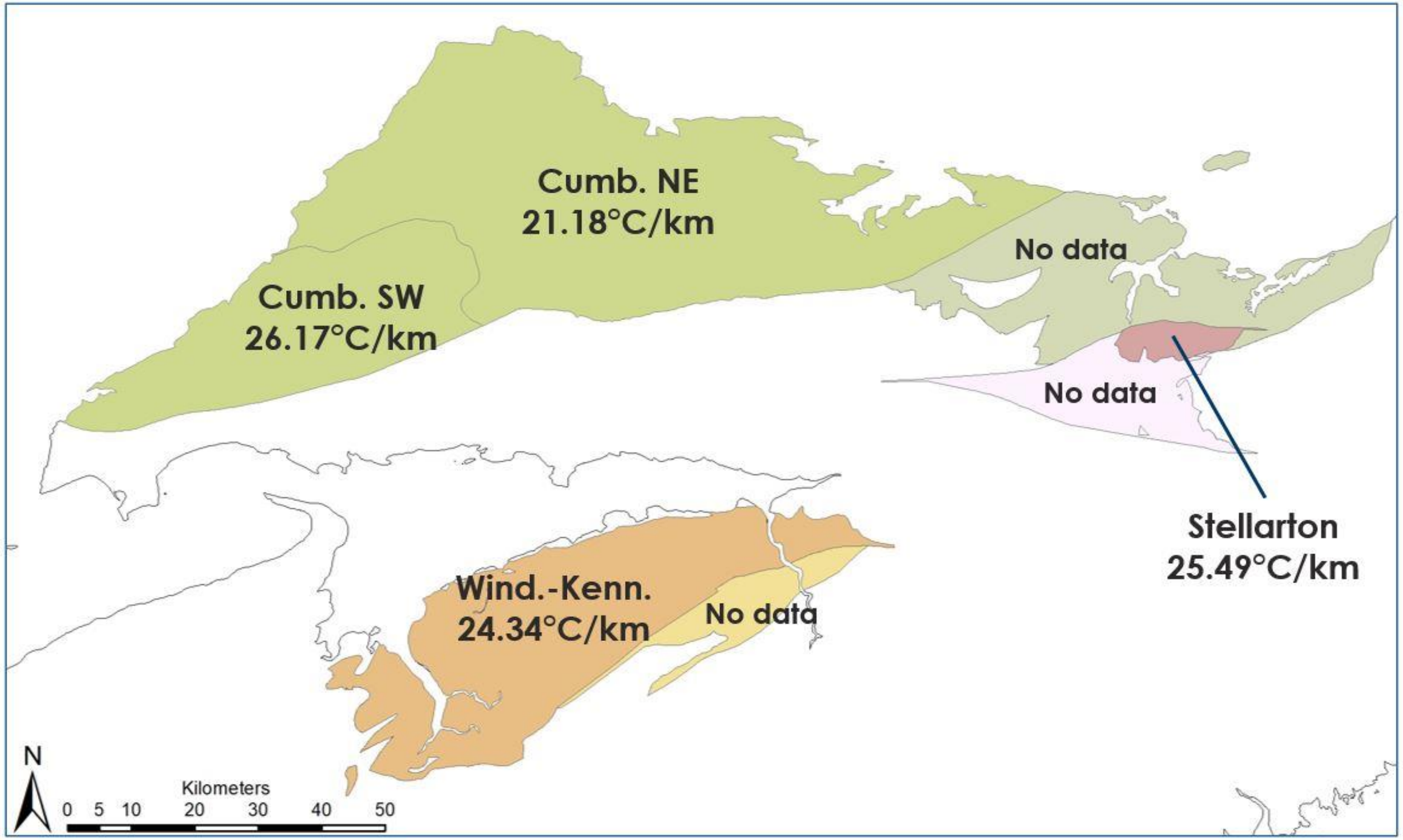
Depth and Thickness

Temperature at Mid-Depth

Lithology, Porosity, Permeability

The methodology used to develop these key parameters is presented in Appendix A along with the results.

Geological Regions



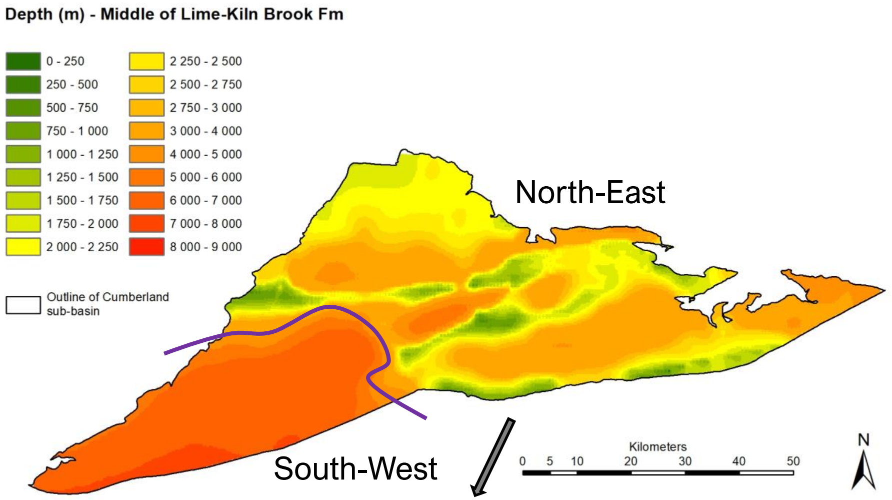
Assumptions:

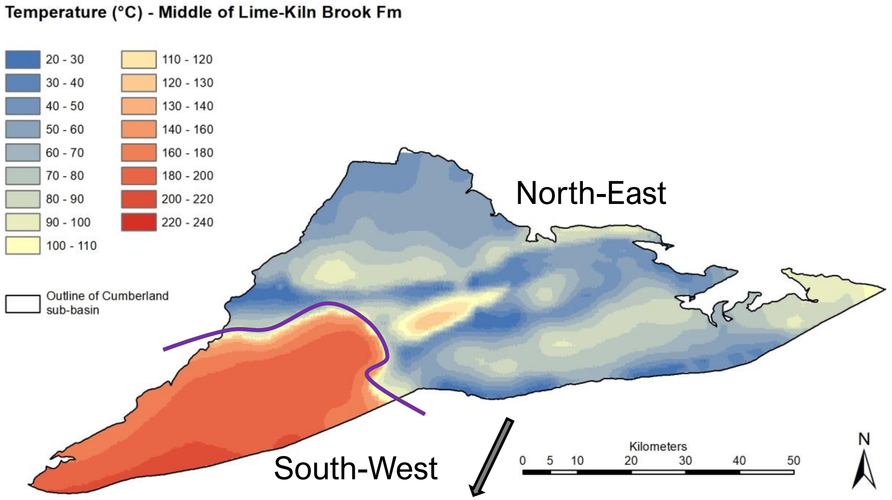
- **Model is limited to areas with sufficient data.**
- **Areas left outside of the model (no data):**
  - Cumberland SE
  - Rawdon Block (W.-K.)
  - Hopewell Block (Stellarton)
- **Cumberland and Windsor:**
  - Potential aquifers defined based on petroleum exploration plays
- **Stellarton:**
  - Geographic (surface temperature) and depth (paleo-geothermal gradient) variations accounted for
  - Simplified geology (little subsurface data)

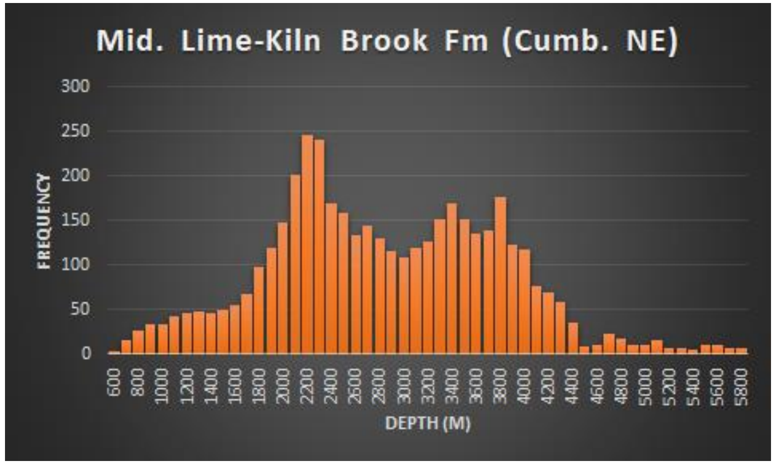
Geological Profiles & Inputs - Example

Example of depth and temperature variation – Lime-Kiln Brook Formation, Cumberland sub-basin:

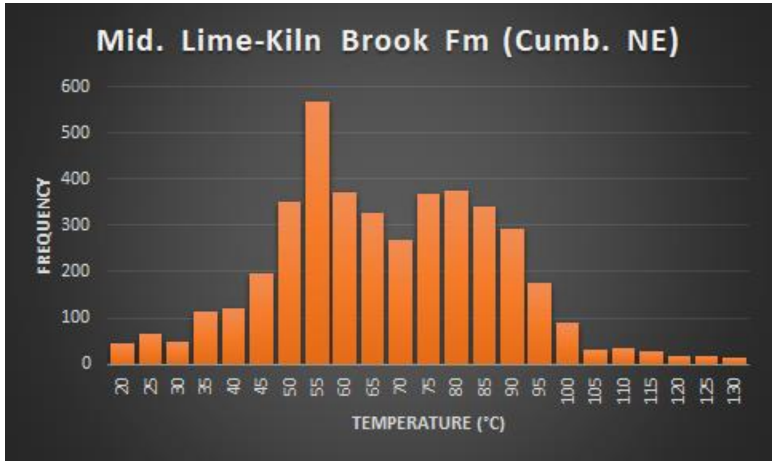
(Refer to appendix A for further detail)







Distribution plots of the depth (left graph) and temperature (right graph) expected in the northeastern part of the Cumberland sub-basin for the Lime-Kiln Brook Formation. Each data point corresponds to a geographic cell on the map.



Geothermal System & Financial Inputs

- In addition to the archetypes and geological inputs outlined in the previous pages, as part of the geo-economic model customization process, SQGI and Enki developed energy and financial inputs for the deep geothermal (and Enhanced Geothermal Systems or EGS) systems, including CAPEX and OPEX parameters. Dunsky developed similar inputs for the ground source heat pump (GSHP) system comparison, which was modeled outside of the geo-economic model.
- Default financial parameters were also developed by the project team, in consultation with OERA and government representatives. These are summarized in the table below. It is noted which are subject to sensitivity analysis, which will be discussed in more detail in the following section of the report.

	Assumption	Included in Sensitivity Analysis
Cash-Down / Equity	0%	✓
Loan Duration	N/A	✓
Borrowing Rate	N/A	✓
Discount Rate	Greenhouse & Aquaculture: 20% District Energy System: 7%	✓
Inflation	5% (2021-2023); 2% (2024+)	
Financial Incentives	None	✓

3. Results

3.1 Overview

3.2 Greenhouse

3.3 Aquaculture Facility

3.4 District Heating System

3.5 Other Impacts

Overview of Results

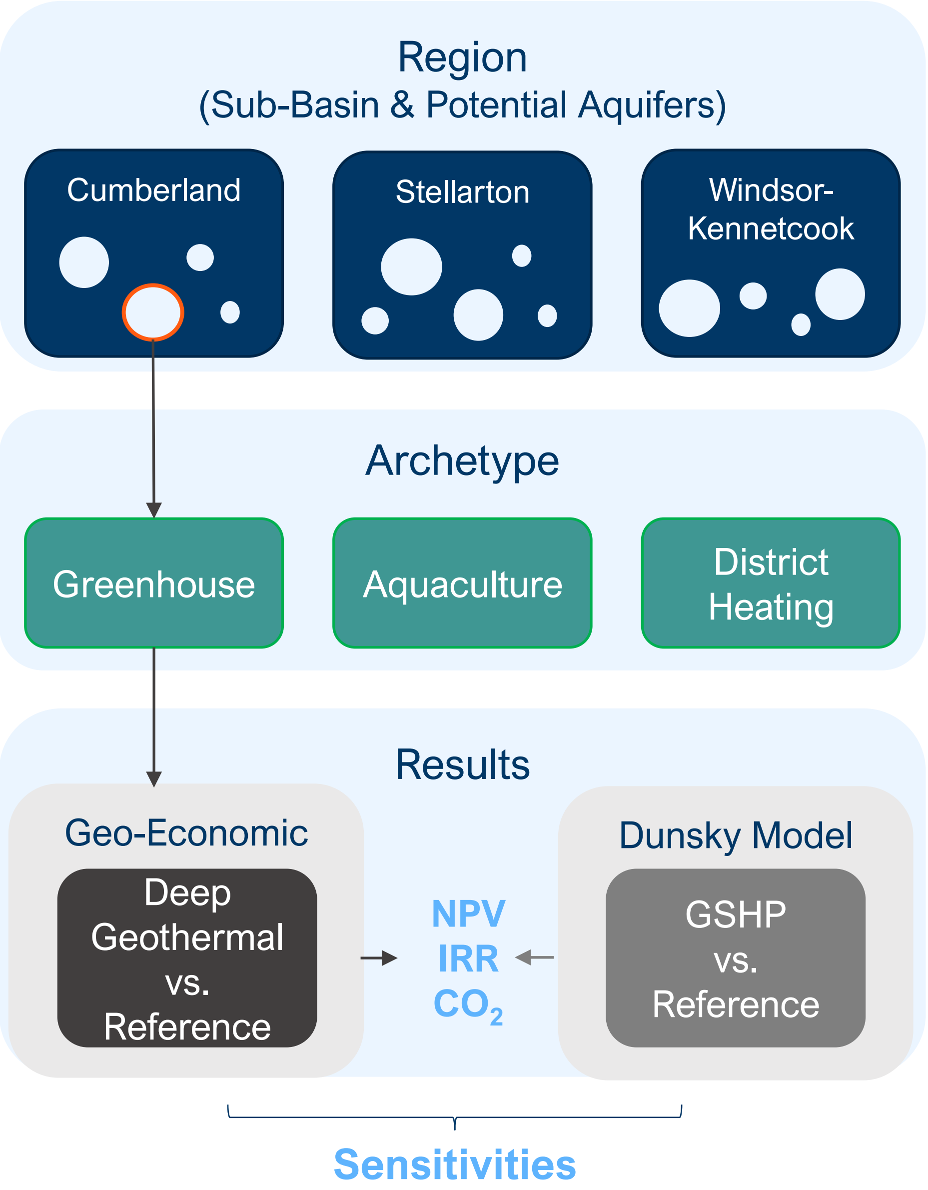
This section of the report includes:

- The results of the geo-economic modeling – which compares the deep geothermal system to the reference system for each archetype.
- The results of the deep geothermal sensitivity analyses and a "best case" scenario optimization.
- A comparison of the cost-effectiveness of the deep geothermal system versus a closed-loop heat pump – which is modeled by Dunsky outside of SQGI's geo-economic model.

Outputs:

- For reporting purposes, we do not present the results for all 40+ sub-basin/potential aquifer combinations analyzed. Instead, for each archetype we focus on the "optimal" scenario – i.e., situating the deep geothermal system in the sub-basin/potential aquifer that generates the most benefits across three functions: NPV, Internal Rate of Return, and CO_2 emission reductions (in tons).* Additional data for the other geothermal scenarios is included in the appendices.

Illustration of Outputs



*i.e., the Pareto-optimal solution. Since there are multiple competing objective functions being simultaneously optimized in the model to generate the largest possible NPV or IRR or CO_2 reductions, our optimal solution is the one which might not have the largest NPV, but maximizes benefits across the three functions. The CO_2 reduction is not equal in importance to the maximization of IRR and NPV, but was used to differentiate solutions which yielded similar financial performances. Also, the dollar value of CO_2 emissions is included in the IRR and NPV, therefore the CO_2 reductions refer to emissions in tons rather than dollars.

Deep Geothermal vs. Reference System

Greenhouse

For the greenhouse, the **Cumberland Sub-Basin, Lime-Kiln Brook potential aquifer** was chosen as the optimal location of those included in the assessment.

- Depth: 2,713 m
- Temperature: 64 °C
- **Number of boreholes: 2**
- Flow rate: 30 L per second
- **Doublet capacity: 3,696 kW**
    - % of peak biomass system heat load requirements = 105.6%
    - % of biomass system energy requirement = 100.0%

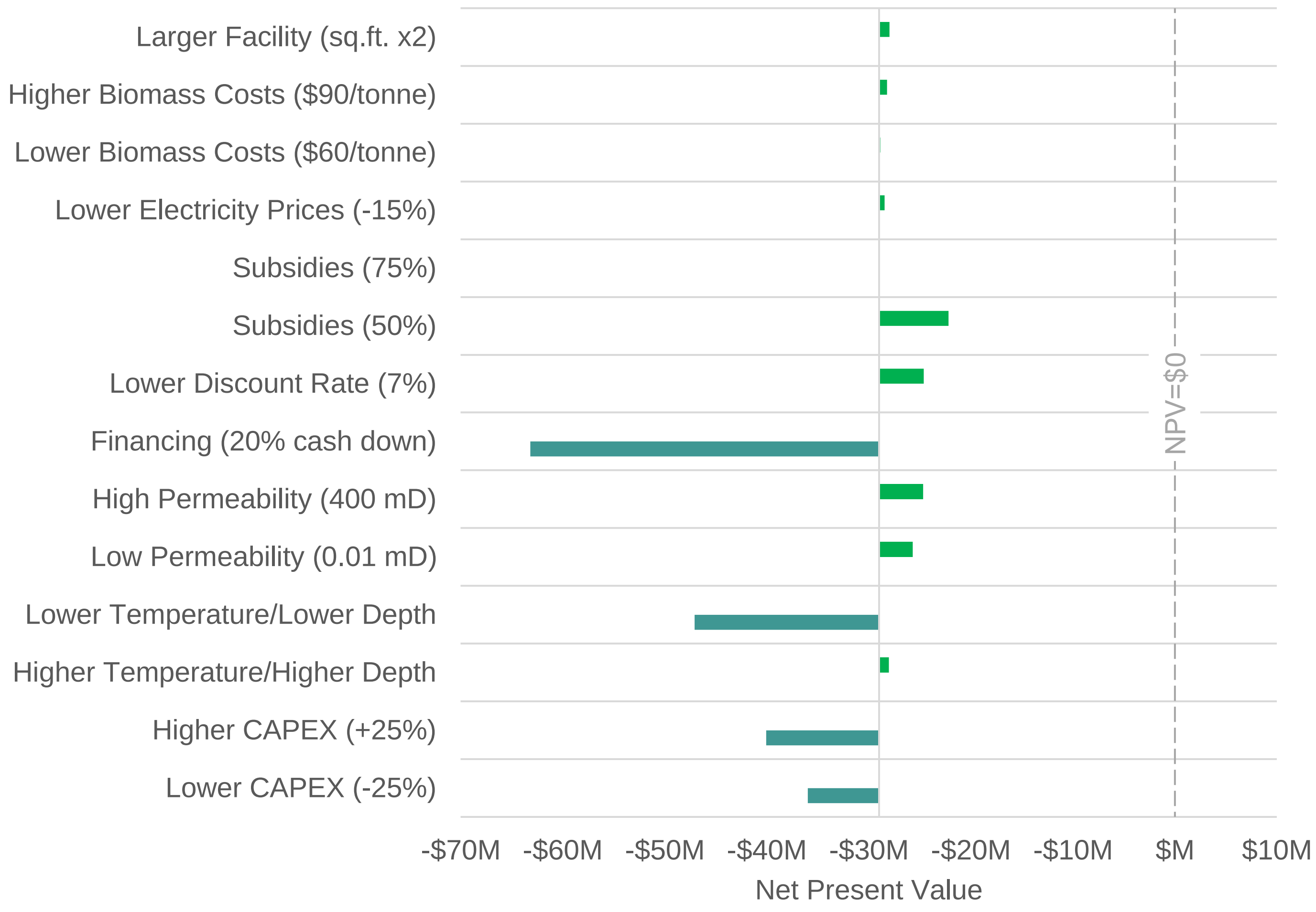
Results (2021-2061):

- NPV = - $29,467,000
- Payback period = N/A
- Monthly IRR = N/A
- CO_2 emissions saved = - 9 949 tCO_2 (46% increase)
- Average cost of energy = $10.64/GJ

Insights:

- **None of the greenhouse scenarios assessed are profitable relative to the reference system** under the default deep geothermal system parameters.
- This is **primarily due to the low cost of biomass** used in the industry in Nova Scotia (and elsewhere). If the reference fuel in the industry was more costly, such as a fossil fuel, the geothermal system would be more cost-effective.
- The increase in CO_2 emissions over the study period is due to the electricity consumption of the geothermal system's well pumps. The associated emissions are higher than biomass and electricity emission from the reference system. To note, the Nova Scotia electricity grid emission intensity will be significantly lower in 2030, and thus projects that come on-line later will emit fewer GHG compared to a project today. Also, the auxiliary system provides the peak heating needs in the winter months both in the reference and deep geothermal systems, resulting in equivalent GHG emissions from the auxiliary system in both cases.

Relative Impact of Key Variables on NPV



A sensitivity analysis was conducted on the optimal greenhouse scenario by independently varying facility size, energy costs, financial parameters, geological inputs, and geothermal system costs. The horizontal bars represent the impact of changing isolated variables on the overall NPV.

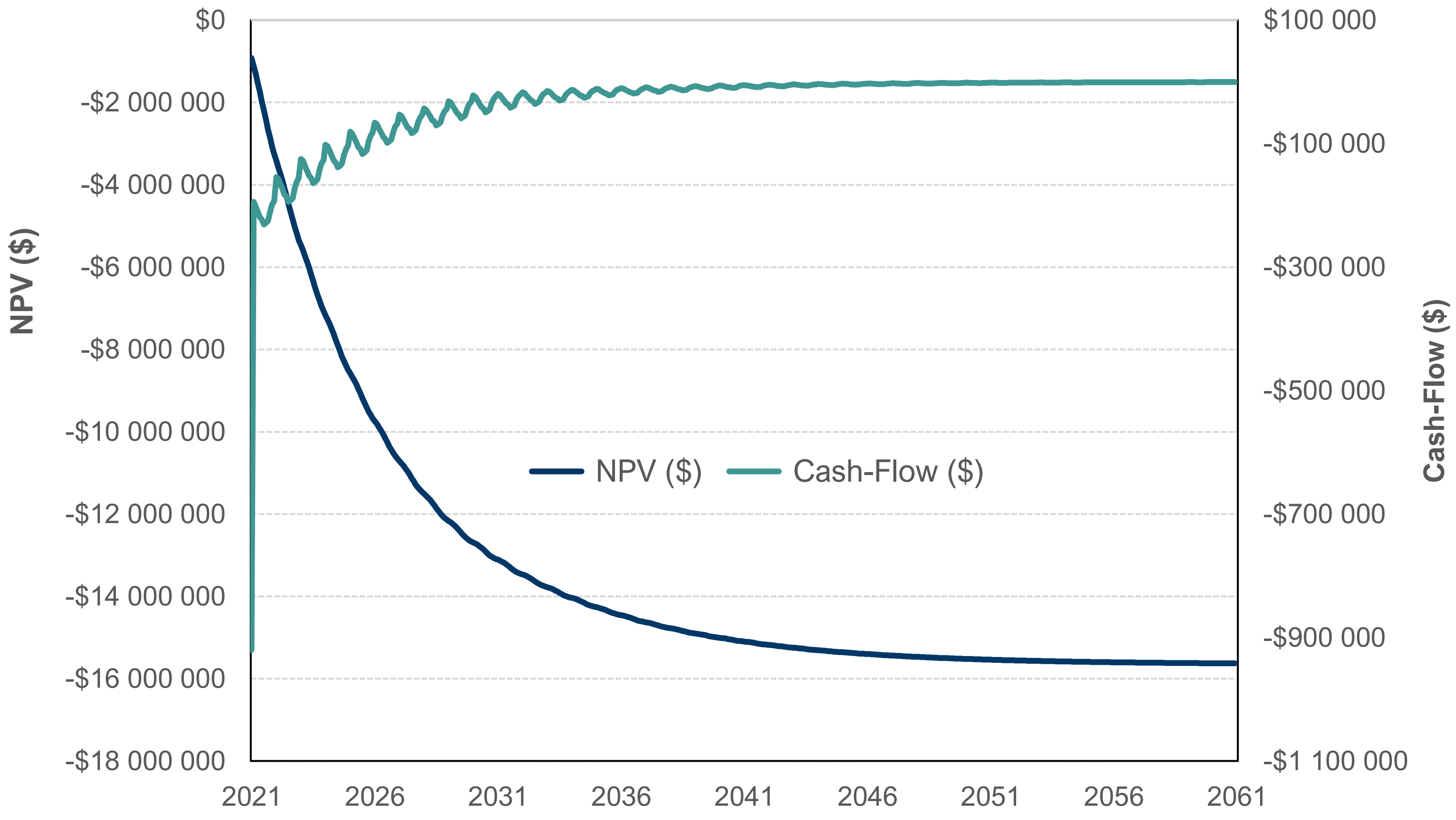
- **Again, none of the individual sensitivity scenarios were profitable when compared to the reference system** (i.e., no NPV above $0, all returned a negative NPV), due to the low cost of biomass (about five times lower per unit of energy than the cost of heating oil).
- Even under a "best case" scenario where key variables are simultaneously adjusted, the greenhouse archetype is not cost-effective:
  - *See following page*
- We note that measures affecting OPEX have little effect: increasing biomass costs from $75/tonne to $90/tonne has a negligible impact on NPV, as do lower electricity prices, since OPEX still remains low compared to heating oil. A biomass cost above $90/tonne is not likely in the coming years.
- Measures affecting initial investment: Government subsidies, lower CAPEX costs and geological characteristics have a greater relative impact, although none generate a positive business case for deep geothermal.

"Best Case" Sensitivity Scenario Results

The following variables were simultaneously considered for the "best case" sensitivity scenario:

- CAPEX reduced by 25%
- Financing with 20% cash down (30 years loan at a 5% borrowing rate),
- 50% of CAPEX subsidized
- 15% lower electricity costs
- Greenhouse area doubled from 8 to 16 acres

Note all other variables were held constant at default values.



The Cash-Flow line tracks the monthly revenues or lack thereof generated by the geothermal system with regard to the reference system while the NPV line tracks the ongoing NPV of the project during the 40-year simulation period.

Note: Under this scenario, a larger auxiliary system using propane is needed as back-up to meet the higher heating load in the larger greenhouse. There may be a way to make a larger greenhouse profitable by redesigning the doublet with a higher flow rate and lower auxiliary need, which would have an impact on the marginal cost of energy. However, in all scenarios the economics for this type of project are challenging because of the important seasonal variation in heating demand. A much larger greenhouse, up to 80-100 acres, would still require significant CAPEX for a greater number of deep wells and the seasonal variation in heat load would still remain (i.e., the geothermal system would not be optimized year round).

Comparison with Ground Source Heat Pump

- Due to the relatively inexpensive equipment requirements and low average fuel costs associated with a biomass system, none of the alternative scenarios (or sensitivities) assessed are profitable relative to the reference system.
- The Deep Geothermal Base Case extracts heat from a very deep, warm and permeable aquifer. This productive aquifer allows for a lower average cost of energy than the biomass system. However, the large CAPEX required to drill results in a negative NPV and is therefore a cost-ineffective alternative.
- The Deep Geothermal Best Case is a compromise, settling for a shallow but less permeable aquifer. This results in lower CAPEX requirements, but high average energy costs due to increased pumping requirements to overcome low permeability. This improves NPV relative to the deep geothermal base case but is still not a cost-effective alternative.
- The Ground Source Heat Pump's relatively low CAPEX and average cost of energy similar to the biomass system result in a better NPV than either of the deep geothermal systems. However, this solution is still not competitive with the biomass reference system.

Comparison between Deep Geothermal (base and best-case scenarios) and GSHPs Scenarios (2021-2061)

	Deep Geothermal Base Case	Deep Geothermal Best Case	Ground Source Heat Pump Base Case	Reference System
Net Present Value	- $29,467,000	-$15,627,000	- $4,832,000	--
Payback Period	N/A	N/A	N/A	--
Monthly IRR	N/A	N/A	N/A	--
CAPEX	$9,717,300	$728,797*	$5,584,000	$2,362,500
Average Cost of Energy	$10.64/GJ	$20.81/GJ	$10.94/GJ	$12.47/GJ

Notes: *CAPEX for the deep geothermal best-case scenario include subsidies and represent only the cash-down payment.
Results for the deep geothermal and GSHP are relative to the reference case.
Additional data with respect to the GSHP base case and sensitivities is available in the appendices.

Deep Geothermal vs. Reference System

Aquaculture

For the aquaculture facility, the **Cumberland Sub-Basin, Lime-Kiln Brook potential aquifer** was chosen as the optimal location of those included in the assessment.

- Depth: 2,713 m
- Temperature: 64 °C
- **Number of boreholes: 2**
- Flow rate: 35 L per second
- **Doublet capacity: 4,313 kW**
    - % of peak heat load requirements = 85.4%
    - % of system energy requirement = 91.3%

Results (2021-2061):

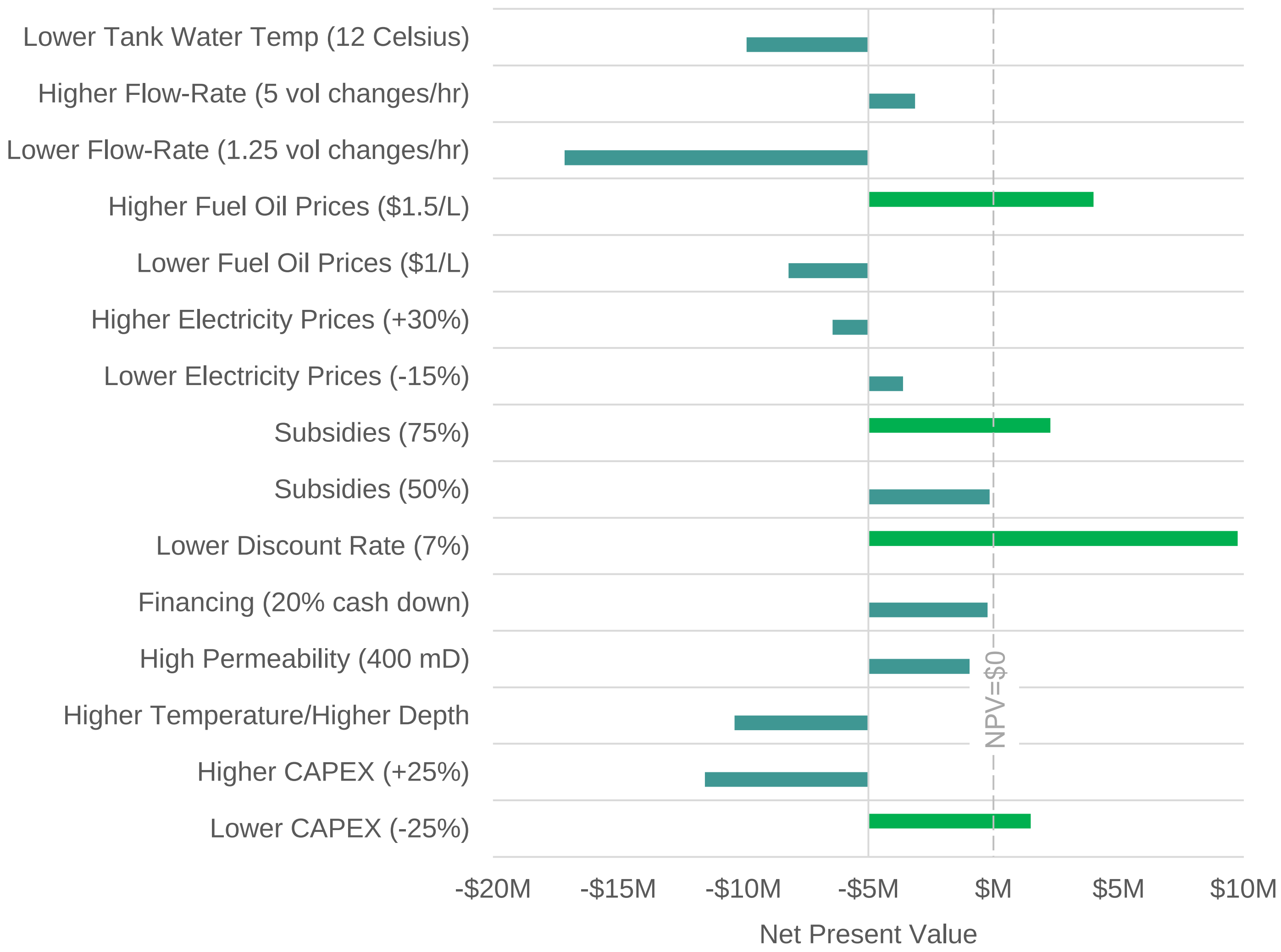
- NPV = - $5,019,000
- Payback period = N/A
- Monthly IRR = N/A
- CO_2 emissions saved = 234,400 tCO_2 (67% decrease)
- Average cost of energy = $17.15/GJ

Insights:

- **Under the base case conditions none of the system configurations are profitable.**
- The sensitivity analysis reveals conditions under which the system could be profitable for an aquaculture use case. In fact, the results from the optimal location indicate that **the project is within a reasonable range of economic viability.**
- The relatively high CO_2 savings are due to a) the comparison to heating oil in the reference system, and b) the relatively high aquifer flow rate that lowers pumping requirements and therefore electricity demand.

Sensitivity Analysis

Relative Impact of Key Variables on NPV



A sensitivity analysis was conducted on the optimal aquaculture scenario by independently varying water tank temperature, energy costs, financial parameters, geological inputs, and geothermal system costs.

- The **profitability of the aquaculture facility depends on key parameters**, notably the discount rate, permeability of the potential aquifer, fuel oil prices, availability of subsidies, and CAPEX costs. **By adjusting each of these parameters individually, positive NPVs are achieved (shown by green lines surpassing, to the right, the vertical line at $0 NPV).**
- It is important to note that drilling costs in the model are conservative (based on preliminary quotes from companies located in Quebec and western Canada, like Akita Drillings, who did not give their approval to have their quotes appear in the report). If for example there were multiple projects occurring in the province at the same time, then it is reasonable to assume drilling costs would be lower and likely in-line with those seen in Quebec (~ 25% lower than what is currently the default in the model). This scenario, reflected in the lower CAPEX sensitivity analysis (Lower CAPEX –25%), achieves a positive NPV.
- The results of each of these individual sensitivities (with NPV, payback period, IRR, and CO_2) are included in the appendix B. In addition, a "best case" scenario where key variables are simultaneously adjusted for the aquaculture archetype is presented on the following page.

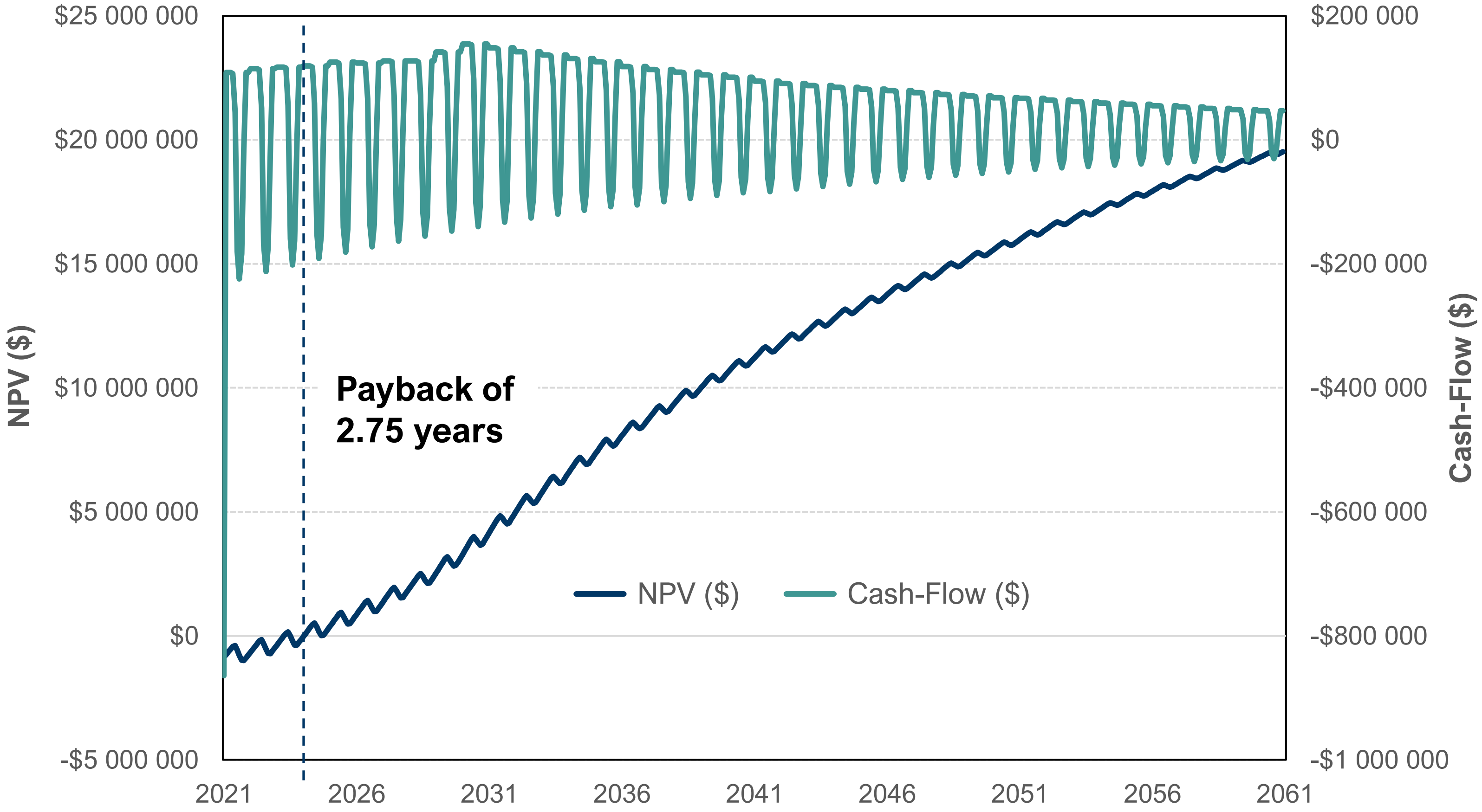
"Best Case" Sensitivity Scenario Results

The following variables were simultaneously considered for the "best case" sensitivity scenario:

- CAPEX reduced by 25%
- Financing with 20% cash down (30 year loan at 5%)
- Lower discount rate of 7%
- Subsidies set at 50% of CAPEX
- 15% lower electricity costs

All other variables (e.g., tank temperature) are held constant at default values.

Note: The system generates positive cash-flows during winter when the geothermal heat is less expensive than the reference system. The negative cash-flows are generated in the summer peak when the system it not in operation but still requires payments.



The Cash-Flow line tracks the monthly revenues or lack thereof generated by the geothermal system with regard to the reference system while the NPV line tracks the ongoing NPV of the project during the 40-year simulation period.

Under this sensitivity, the NPV is $19.5 million, the payback period is 2.75 years, and monthly IRR is approximately 4% over the 2021-2061 study timeframe (60.1% Annual IRR).

Comparison with Ground Source Heat Pump

- Highly stable annual heating load and relatively low temperature requirements – which is the case for this aquaculture archetype – are ideal conditions for a ground source heat pump.
- The size of the aquaculture facility is key as the NPV increases with flow rate (based on tank volume changes) and higher temperature requirements. In other words, smaller aquaculture facilities will be less economic.
- A heat pump could also be operated in cooling mode (by installing reversing valves) to permit cooling of the fish tanks in the months when water temperature is above optimal (roughly July to September). This could prevent fish overheating, which may result in slowed growth and even loss of fish, so cooling could improve productivity and resilience of the system.

Comparison between Deep Geothermal (base and best-case scenarios) and GSHPs Scenarios (2021-2061)

	Deep Geothermal Base Case	Deep Geothermal Best Case	Ground Source Heat Pump Base Case	Reference System
Net Present Value	- $5,019,000	$19,521,000	$50,784,500	--
Payback Period	N/A	2.75 years	< 1 year	--
Monthly IRR	N/A	4%	16%	--
CAPEX	$9,729,000	$972,890*	$8,120,000	$1,105,000
Average Cost of Energy	$17.15/GJ	$15.34/GJ	$8.63/GJ	$34.07/GJ

Notes: *CAPEX for the deep geothermal best-case scenario include subsidies and represent only the cash-down payment.
Results for the deep well geothermal and GSHP are relative to the reference case.
Additional data with respect to the GSHP base case and sensitivities is available in the appendices.

Deep Geothermal vs. Reference System

District Heating

For the district heating system, the **Stellarton Sub-Basin, Westville potential aquifer** was chosen as the optimal location of those included in the assessment.

- Depth: 2,024 m
- Temperature: 57 °C
- **Number of boreholes: 2**
- Flow rate: **10** L per second
- **Doublet capacity: 1,109 kW**
    - % of peak heat load requirements = 99.3%
    - % of system energy requirement = 100.0%

Results (2021-2061):

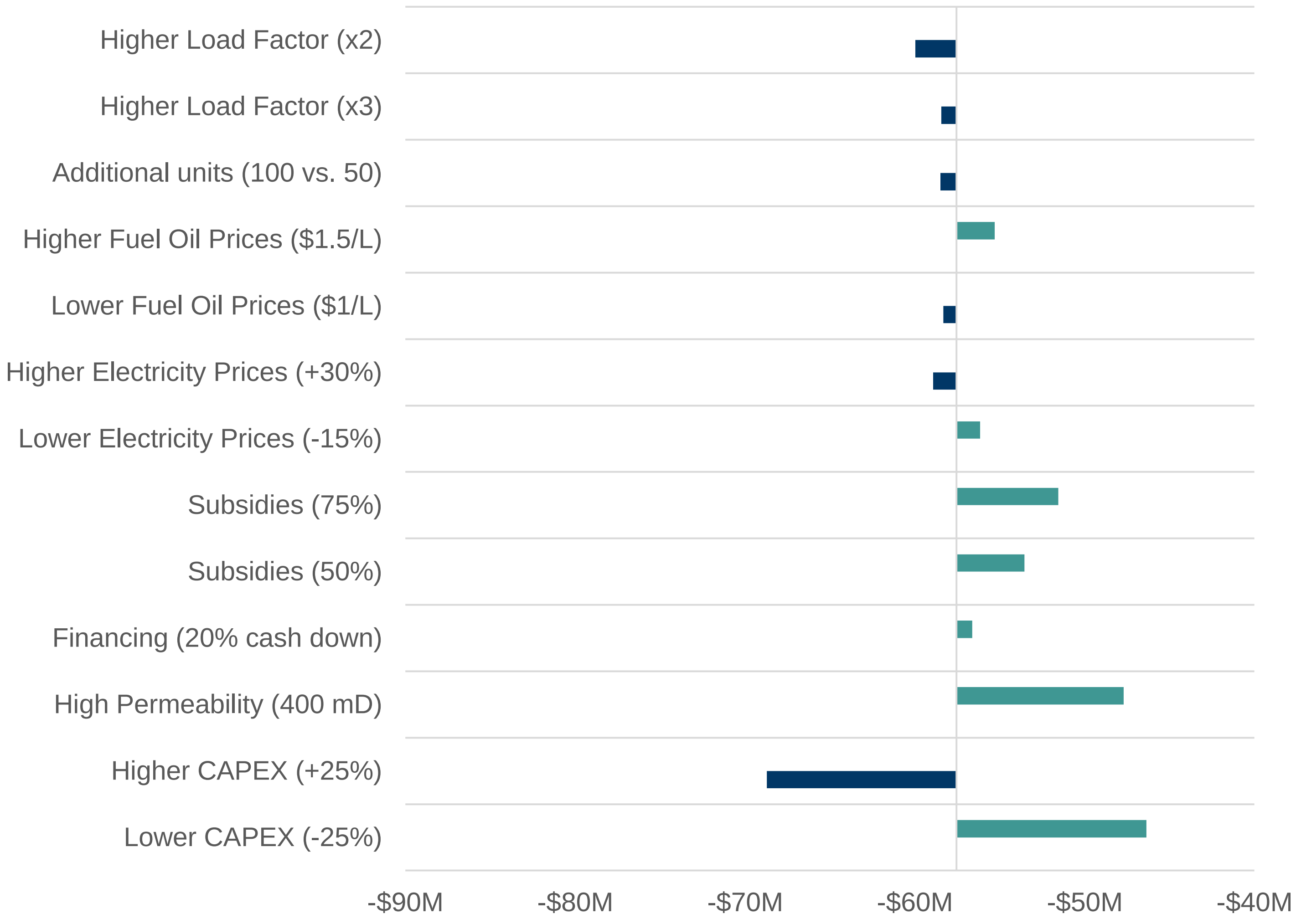
- NPV = - $57,538,000
- Payback period = N/A
- Monthly IRR = N/A
- CO_2 emissions saved = 8,685 tCO_2 (31% decrease)
- Average cost of energy = $42.10/GJ

Insights:

- **Similar to the other archetypes, none of the district heating scenarios assessed are profitable relative to the reference system** under the default deep geothermal system parameters.
- The poor permeability of the Westville potential aquifer (0.2 mD) and aquifer to non-aquifer ratio (21%) drives electricity demand for the well pump and increases OPEX costs. However, the higher CAPEX cost associated with drilling in the other, deeper potential aquifers results in even lower NPV values, which is why it was selected as the “optimal” location under the default parameters.
- The relatively low CO_2 savings is primarily a reflection of the poor permeability and resulting increase in demand for electricity.
- 57°C is the temperature of the water extracted from the ground, not necessarily the temperature being supplied to the district heating system.

Sensitivity Analysis

Relative Impact of Key Variables on NPV



A sensitivity analysis was conducted on the optimal district heating scenario by independently varying the number of housing and business units, the overall heating load profile of the units and community center, energy costs, financial parameters, geological inputs, and geothermal system costs.

- At first glance, the results indicate that it will be challenging to develop a cost-effective district heating project using deep geothermal heat in Nova Scotia.
- However, if the project is moved from the Westville potential aquifer (which was the best option in terms of NPV in the reference case) to the Lime Kiln Brook potential aquifer, and key variables simultaneously optimized, then the results of the "best case" scenario indicate that **it may be possible to develop a cost-effective district heating** project in the province (see results and explanation on next page). This would require sizing for a specific project and was not performed as part of this study.
- We do note here a few of the sensitivities with potentially counterintuitive results: the higher load factor and going from 50 to 100 units. The reason that these scenarios further reduce profitability is because the size of the geothermal system is held constant in the individual sensitivity analysis (shown here), and at its current size/flow rate the deep-well system just barely meets the heating needs of the archetype. An increase in energy and/or demand from a larger project thus requires the addition of an auxiliary system - increasing CAPEX and OPEX costs.

“Best Case” Sensitivity Scenario Results

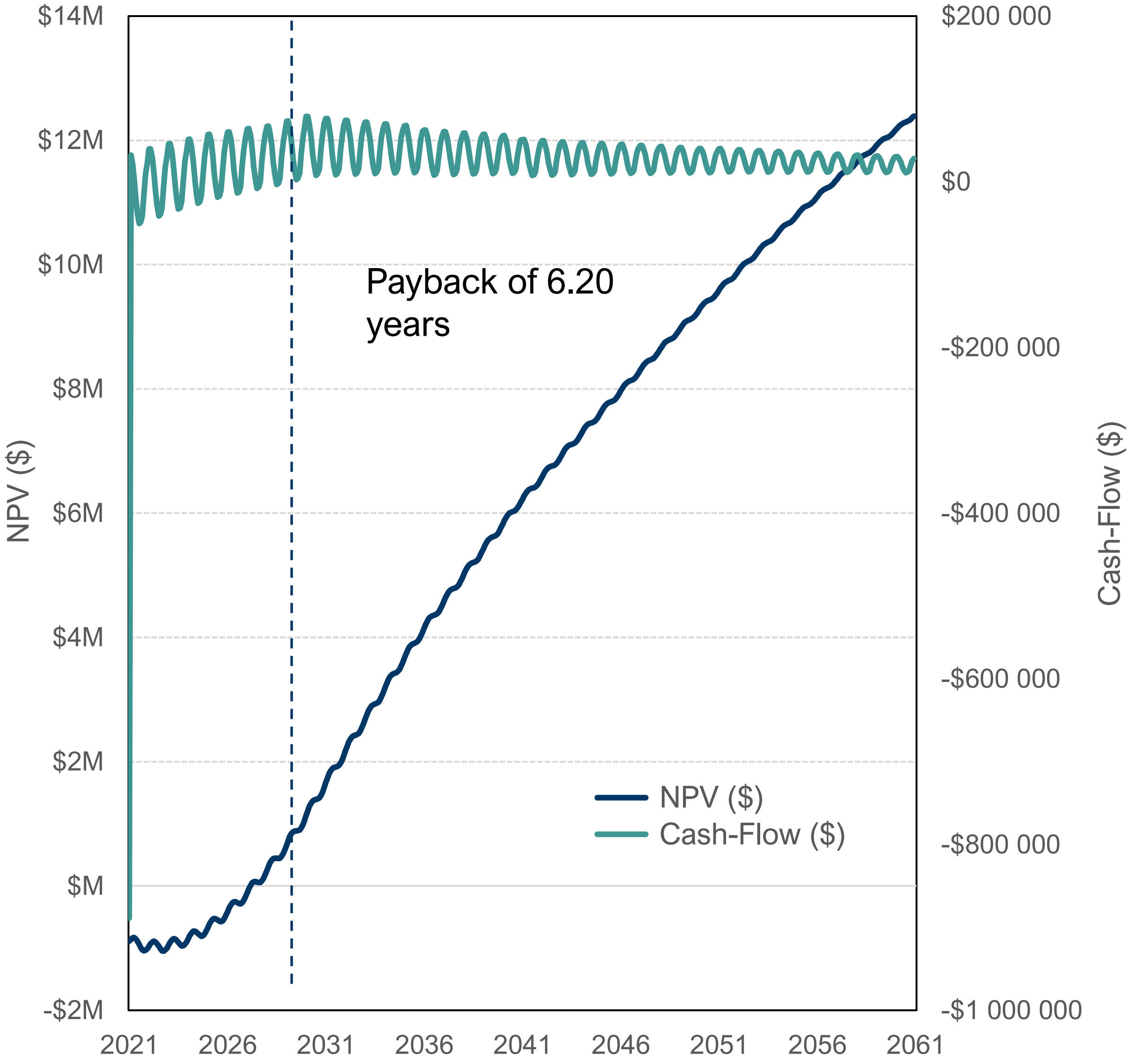
The following variables were simultaneously considered for the “best case” sensitivity scenario:

- CAPEX reduced by 25%
- Financing with 20% cash down
- Subsidies set at 50% of CAPEX
- Doubling of the load factor
- 15% lower electricity costs
- Increase in the number of residential and commercial units from 50 to 200
- The project was moved to the deeper Lime Kiln Brook aquifer and the size of the geothermal system increased, allowing for a flow rate of 40 L/s as opposed to 10 L/s in the reference case.

Under these conditions, the NPV is $12.4 million, the payback period is 6.20 years, monthly IRR is approximately 2.3% and total CO_2 reductions are 189,600 tonnes over the 40-year timeframe.

A system’s load factor (avg/max load) measures how stable demand is over a year. A highly variable demand (low load factor) favours a system with inexpensive capacity so peaks can be covered, even if average fuel cost is high. A stable system (high load factor) increases the importance of low average fuel costs as is the case for this geothermal system. By increasing stability in this best case, a positive NPV is reached.

Industrial loads often represent stable and year-long loads that can be coupled with more seasonal space heating loads.



The Cash-Flow line tracks the monthly revenues or lack thereof generated by the geothermal system with regard to the reference system while the NPV line tracks the ongoing NPV of the project during the 40-year simulation period.

Comparison with Ground Source Heat Pump

- Though more expensive to build than the GHSP, the best case deep geothermal scenario provides very inexpensive energy based on its increased capacity and optimized well placement.
- However, as noted above we have only assessed heating applications. Should the use case include cooling options (especially for the commercial facility) then the business case for GSHP would be further improved.
- The construction costs per unit of a district heating system (central plant & piping network) are reduced as more units are connected, favoring large GSHP systems. Furthermore, larger systems have more stable loads, meaning the heat pump is used more consistently with less recourse to auxiliary heating, reducing the marginal cost of energy.

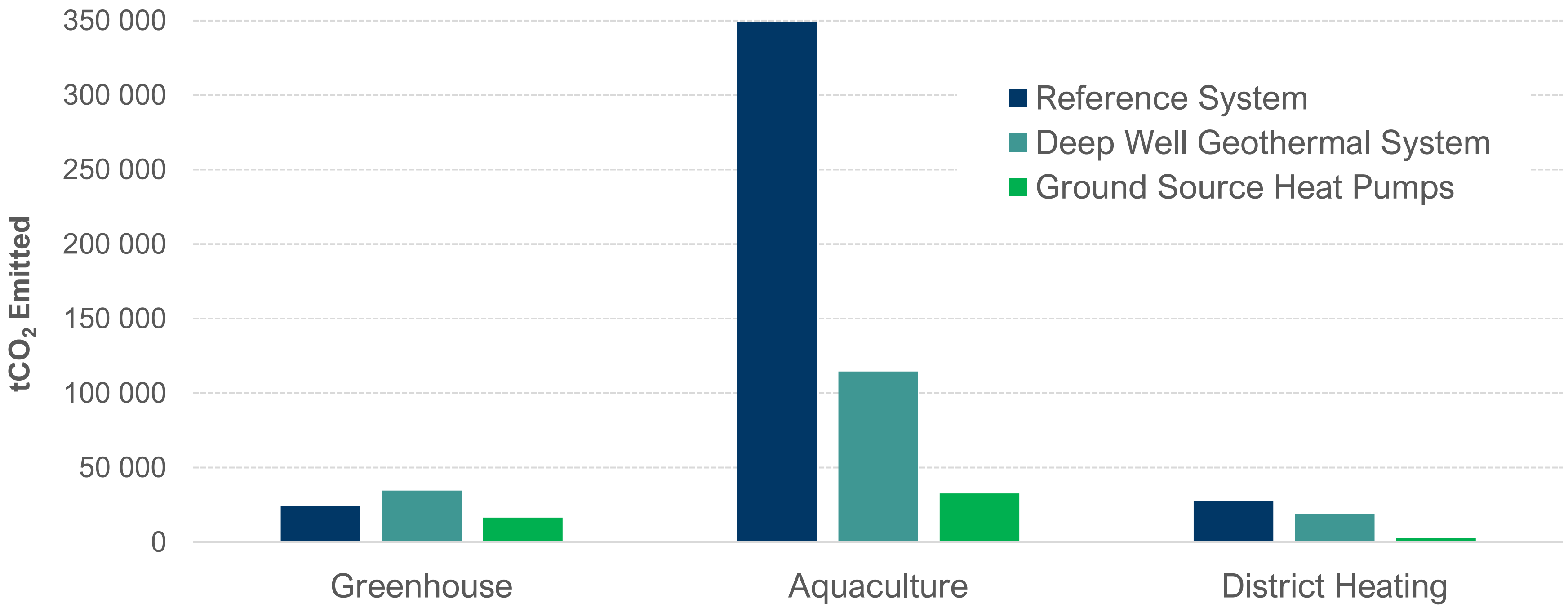
Comparison between Deep Geothermal (base and best-case scenarios) and GSHPs Scenarios (2021-2061)

	Deep Geothermal Base Case	Deep Geothermal Best Case	Ground Source Heat Pump Base Case	Reference System
Net Present Value	- $57,538,000	$12,392,000	$5,154,000	--
Payback Period	N/A	6 years	4 years	--
Monthly IRR	N/A	2%	4%	--
CAPEX	$7,899,000	$920,400*	$1,755,000	$ 375,000
Average Cost of Energy	$42.10/GJ	$4.08/GJ	$11.23/GJ	$34.07/GJ

Notes: *CAPEX for the deep geothermal best-case scenario include subsidies and represent only the cash-down payment.
Results for the deep geothermal and GSHP are relative to the reference case.
Additional data with respect to the GSHP base case and sensitivities is available in the appendices.

Summary of Greenhouse Gas Emissions Impacts

The following summarizes the CO_2 emissions from each system type by archetype. Emissions increase under the greenhouse scenario (between the reference and deep geothermal scenarios) but are significantly reduced under the aquaculture and district heating cases.



Aquaculture's high emissions are due to the very large scale of the project (compared to the greenhouse and district heating) and the high emissions factor of heating oil.

Emissions factors by fuel type are available in the appendix C.

4. Findings & Recommendations

4.1 Key Findings

4.2 Recommendations

Summary of Key Findings

- **Limited and targeted opportunities for deep geothermal in Nova Scotia.** With the knowledge we have now, deep geothermal has limited potential applications in Nova Scotia. As we see from this assessment, key factors need to align for there to be a solid business case in the province, in particular:
  - **Fuel cost is a major driver for cost-effectiveness**. Under the current energy (and carbon) pricing context, only those use cases where deep geothermal replaces heating oil or other high-cost fuels should be considered as potential candidates. As we saw with the greenhouse, the low cost of biomass (about five times lower than heating oil) currently used in the industry simply eroded the business case for geothermal.
  - **Larger facilities with stable year-round heating requirements are key**. Due to high CAPEX and fixed costs, deep geothermal systems are only suitable in large facilities with relatively constant heat loads, which is the case for the aquaculture archetype. They may also be suitable in situations where the heat loads of various facilities can be aggregated – ideally with one or more larger "anchor loads" – helping to flatten the load curve and distribute the initial costs (e.g., large district energy systems with large, relatively constant heat load needs throughout the year).

Summary of Key Findings, *cont.*

- **Financial tools can help**. Incentives and innovative financing programs – in particular, those that reduce initial investments – could play a significant role in making deep geothermal systems financially viable.
- **Location matters**. Although more permeable aquifers are not required, they help to lower CAPEX costs because higher flow rates can be reached to match high heating demands without generating high electricity costs (from pumping requirements). When heating demands are relatively low, however – such as the case of the district heating system, permeability is less of a driver than the overall depth and temperature of the aquifer. Higher temperatures at shallower depths can be expected locally where specific geological conditions are met. These conditions are present within the studied areas (e.g., see Geology Appendix – Miscellaneous Information) but will require further geological investigation before they can be fully evaluated.

- **Ground source heat pumps are the more favorable option.** In all cases, GSHPs outperform deep geothermal systems on an economic and GHG basis, even when the GSHP base case is compared to the best-case scenario for the deep geothermal system. This is in part due to the high cost of deep drilling and the poor permeability of the geology. Heat pump technology also has the added advantages of being known, already present in the province, and much easier to locate, among others.
    - **Opportunity to optimize GSHP output**. While this study focused on heating only applications, this is not the optimal performance option for GSHPs. The addition of cooling load would help to mitigate the risk of wells freezing, further improve the business case for GSHPs, and reduce GHGs by reducing the electricity required for cooling.

Recommendations

- **Recommendation #1 - Find high potential aquifers:** The assessed archetypes and aquifers did not yield a viable business case for deep geothermal in Nova Scotia, except for under extremely optimistic “best case” conditions. As a next step it is recommended to identify aquifers that offer higher potential resources, particularly with shallower higher-temperature aquifers than those examined in this study. Given the current low level of understanding on the subsurface geology of the studied areas and the conservative regional geothermal gradients considered in the evaluation, it is possible that such a resource could be identified through further investigation.

  Dedicated geological modeling, as outlined in Section 8 of the Phase 1 report, will be needed to document the geothermal properties in selected areas for specific potential projects, especially above 1) basement-rooted faults, 2) young radioactive granitic bodies at the base of the sedimentary cover or 3) salt domes, as these geological environments are particularly suitable for enhanced heat flow. Moreover, if potentially viable aquifers are identified, but they are found to be of low permeability, Enhanced Geothermal Systems (EGS) could be considered. Two recommendations to de-risk EGS practices are detailed in the Geology Appendix, citing how the available subsurface data can provide valuable information to assess the use of EGS.

Recommendations

- **Recommendation #2 - Identify appropriate heating loads that are in close proximity:** Once an appropriate aquifer (or set of aquifers) is identified, OERA and the government should aim to identify larger projects, such as industrial facilities with stable year-round loads that are, or could, be situated in close proximity. Engaging with these facilities at the earliest stages of the development process will further increase the chances of finding a fit for deep geothermal, particularly if it can be included in the initial construction or end-of-life heating system replacement process.

- **Recommendation #3 – Where a shallow high-temperature aquifer exists, aim to develop a pilot project:** Direct use of heat deep geothermal projects have not been constructed in Nova Scotia (in fact, there are few examples in Canada). We recommend looking for those opportunities that align with the key factors that will make deep geothermal a winning solution and develop a pilot project. That will provide valuable learnings, including who can provide the needed services; further understanding on the subsurface geology; on-the-ground performance metrics; and other insights that will help refine the business case for deep geothermal.

- **Recommendation #4 – Consider further assessment of GSHP:** While direct use of heat from deep geothermal was the focus of this assessment, due to the favorable economic and GHG results for GSHP we recommend a deeper dive into the opportunity for this technology in various use cases across the province (such as for district heating/cooling and aquaculture facilities). As part of a comprehensive feasibility assessment, further study is needed to understand how deep geothermal compares to other low-carbon solutions – both technologies and energy sources – such as air-to-water heat pumps, renewable natural gas, and hydrogen especially for replacing more costly energy sources such as heating oil.

Appendices

Appendix A: Geology

Overview

This appendix provides further documentation on the following:

- The methodology used to gather, select and evaluate the geological parameters
- The stratigraphic position of the potential aquifers for each sub-basin
- The values obtained for the key geological parameters for each sub-basin
- High-level considerations on the use of Enhanced Geothermal Systems in Nova Scotia
- Additional, relevant miscellaneous information gathered in the course of the study

The geological aspects of the geo-economic modeling have been gathered and analysed by Stephan Séjourné, P. Geo. (APGNS License to Practice # 144).

Methodology

Geological input and assumptions for the potential aquifers in each sub-basin include the following:

- Selection of the potential aquifers
- Depth and thickness
- Temperature and temperature uncertainty at mid-depth
- Lithology, porosity and permeability

Most potential aquifers for the Cumberland and Windsor-Kennetcook sub-basins correspond to known petroleum exploration targets, in keeping with the outcomes of the Phase 1 Report (*). Some adjustments have been made subsequently based on the porosity and permeability data. The potential aquifers for the Stellarton sub-basin have been selected based on the lithology. For each sub-basin, potential aquifers that were too deep (e.g., the southwestern part of the Cumberland sub-basin) or too shallow (Ragged Reef Formation, Macumber Formation and Thorburn Member) were discarded early in the project

The methodology used to gather the other parameters is further described below.

(*) Comeau, F.-A., Séjourné, S., Raymond, J., 2020. Assessment of geothermal resources in onshore Nova Scotia. Offshore Energy Research Association of Nova Scotia, research funded by the Nova Scotia Department of Agriculture and Nova Scotia Department of Energy and Mines, 216 p., available under this link.

Depths and thickness of potential aquifers

Cumberland and Windsor-Kennetcook

The tops and/or bases of potential aquifers are derived from the seismic horizons provided by the Nova Scotia Department of Energy and Mines (NSDEM). These seismic horizons, available in-depth sub-sea, are converted in vertical depth from surface using the digital elevation model available from the Nova Scotia Department of Lands and Forestry (NSDLF). Both the NSDEM and NSDLF are now merged into the Department of Natural Resources and Renewables (NSDNRR).

The process is straightforward for the Windsor-Kennetcook sub-basin, where seismic horizons are available for both the top and the base of each potential aquifer. In the case of the Cumberland sub-basin, where only one seismic horizon is available to mark the top or the base of a potential aquifer, the missing base or top is derived from the available seismic horizon and the thickness of the stratigraphic unit as estimated from petroleum well data.

Stellarton

Due to the lack of seismic horizons available for this sub-basin, the tops and bases of potential aquifers are inferred from a type stratigraphic section, complemented by miscellaneous references and the examination of one seismic line for the basal units.

Methodology, *cont.*

Temperature and temperature uncertainty at mid-depth of potential aquifers

The surficial extents of the Cumberland and Windsor-Kennetcook sub-basins are gridded in a series of datapoints. In the case of the Stellarton sub-basin, only one datapoint corresponding to the type stratigraphic section is considered because of the current low amount of subsurface data.

Each datapoint is then populated with depth values of the top, middle and base of each potential aquifers at the corresponding location, along with the mean annual surface temperature (from Phase 1 Report). The dataset is completed by the temperatures and temperature uncertainties at these depths. Calculation of these temperatures and temperature uncertainties stems from, and refines, the methodology detailed in the Phase 1 Report, including corrections for the paleoclimatic effect.

The resulting dataset consists in a series of surface locations to which correspond depths and temperatures of each potential aquifer. An ancillary dataset is also prepared with incremental depths of 100 m down to 4,000 m and the corresponding temperatures, that can be used for the evaluation of locations where potential aquifers are deemed impractical (e.g., district heating where potential aquifers are too deep, or Enhanced Geothermal Systems).

Lithology, porosity and permeability of potential aquifers

Lithology

The stratigraphic units considered as potential aquifers are defined at the stratigraphic level of a formation or a member. They are not characterised by a single, homogeneous lithology. Intervals acting as aquifers or aquitards can be present within a given potential aquifer, thus impacting the overall efficiency of the geothermal properties. To account for this variability, the available geological descriptions and geological logs of petroleum wells are reviewed and synthesised and for each potential aquifer, the percentage of aquitard versus aquifer lithologies is documented.

Porosity and permeability

The porosity and permeability of the potential aquifers are the most difficult characteristics to obtain with the datasets currently available.

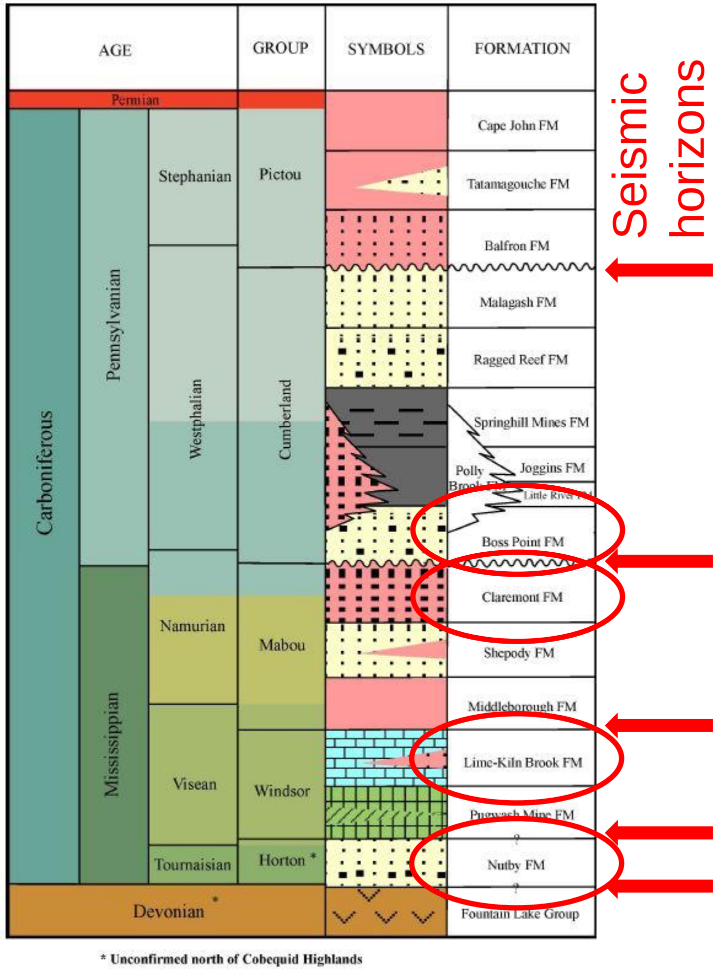
Values for the Windsor-Kennetcook sub-basin are derived from core laboratory analyses of petroleum well cores. No such data are available for the Cumberland sub-basin, where the porosity and permeability values are inferred from the Windsor-Kennetcook sub-basin and, in the case of the Nuttby Formation, complemented by data from the Moncton sub-basin in New-Brunswick. Values for the Stellarton sub-basin are also inferred from those of the Windsor-Kennetcook sub-basin, and complemented with literature data where appropriate.

Potential Aquifers

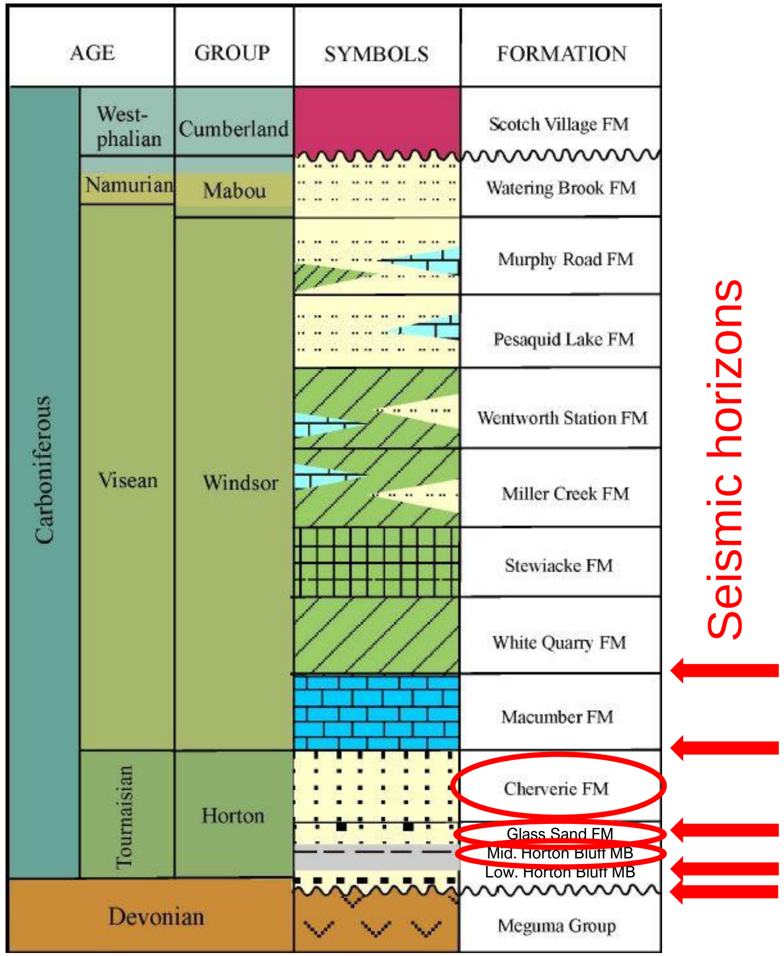
The stratigraphic position of the potential aquifers identified in the three sub-basins is shown in the type sections below.

The Ragged Reef Formation, Macumber Formation and Thorburn Member are also potential aquifers, but they are deemed too shallow (often exposed at surface) and are not considered in the evaluation.

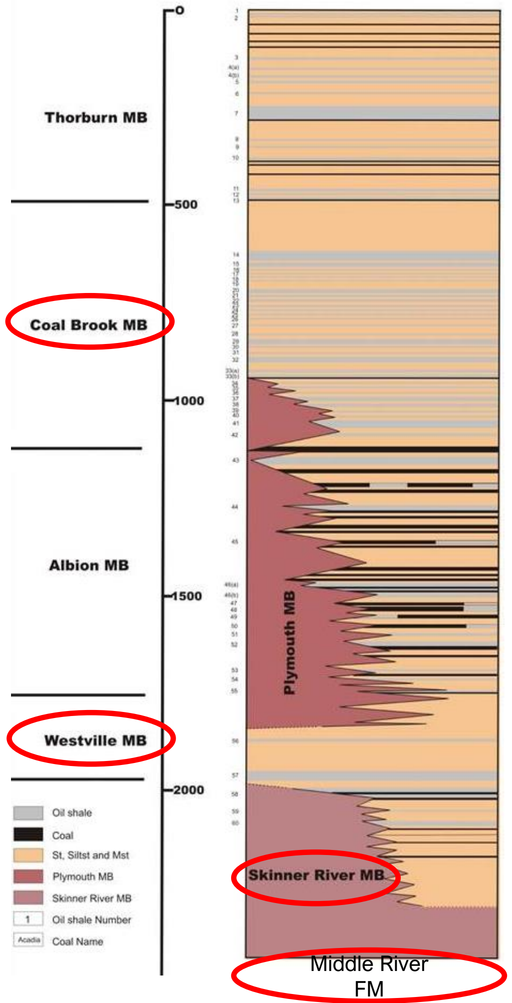
CUMBERLAND



WINDSOR-KENNETCOOK



STELLARTON



Sources: Cumberland and Windsor-Kennetcook: adapted from Hayes et al. (2017) and NSDOE; Stellarton: adapted from Smith et al. (1989), courtesy of NSDEM

Cumberland

Data sources and assumptions

Aquifer	Source for Depth-Thickness Values	Source for Porosity-Permeability Values	Input for Top	Input for Base	Input for Thickness
Ragged Reef Fm	- Seismic surfaces provided by NSDEM - Hayes, B.J.R., Dorey, K., Longson, C.K., 2017. Assessment of Oil and Gas Potential, Windsor and Cumberland Basins, Onshore Nova Scotia. For Nova Scotia Department of Energy by Petrel Robertson Consulting Limited, Open File Report 2017-03	Not evaluated (too shallow)	At or near surface	Surface MINUS Well geology thickness range	Well geology thickness range (N=4, minimum values)
Boss Point Fm		- Inferences from Windsor-Kennetcook Sub-Basin and surface data - For Nuttby Fm: Inferences from Moncton Sub-Basin - Cen, X., 2017, Preliminary petrophysics database, onshore Nova Scotia. Nova Scotia Department of Energy Open File Report 2017-10 - Bibby, C., Shimeld, J.W., 2000. Compilation of reservoir data for sandstones of the Devonian-Permian Maritimes Basin, Eastern Canada. Geological Survey of Canada, Open File Report 3895, 102 p.	S.h. Base Cumberland PLUS Well geology thickness range (N=2)	S.h. Base Cumberland	Well geology thickness range (N=2)
Claremont Fm			S.h. Base Cumberland	S.h. Base Cumberland MINUS Well geology thickness range	Well geology thickness range (N=2, minimum values)
Lime Kiln Brook Fm			S.h. Base Mabou	S.h. Base Mabou MINUS Well geology thickness	Well geology thickness (N=1)
Nuttby Fm			S.h. Base Windsor	S.h. Top Basement	S.h. Top Basement MINUS S.h. Base Windsor (N=4785)

(Fm: Formation; S.h.: Seismic horizon; N: Number of datapoints)

Lithology, porosity and permeability

Aquifer	Thickness (m)			Porosity Aquifer			Permeability Aquifer			Lithology	
	P10	P50	P90	Min (%)	Med (%)	Max (%)	Min (mD)	Med (mD)	Max (mD)	Aquifer	Non-Aquifer
Boss Point Fm	N/A	325	N/A	0.5	6.0	10.0	0.01	0.25	12.00	60% Sandstone / Conglomerate	40% Mudstone
Claremont Fm	N/A	433	N/A	3.0	7.0	20.0	0.01	0.60	20.00	60% Sandstone / Conglomerate	40% Siltstone
Lime-Kiln Brook Fm	N/A	25	N/A	2.0	7.0	25.0	0.01	12.00	40.00	40% Limestone - 20% Sandstone	15% Shale - 15% Siltstone - 10% Evaporate
Nuttby Fm	N/A	803	N/A	2.0	6.0	12.0	0.01	0.50	30.00	30% Sandstone / Conglomerate (inferred)	35% Siltstone - 35% Shale / Mudstone (inferred)

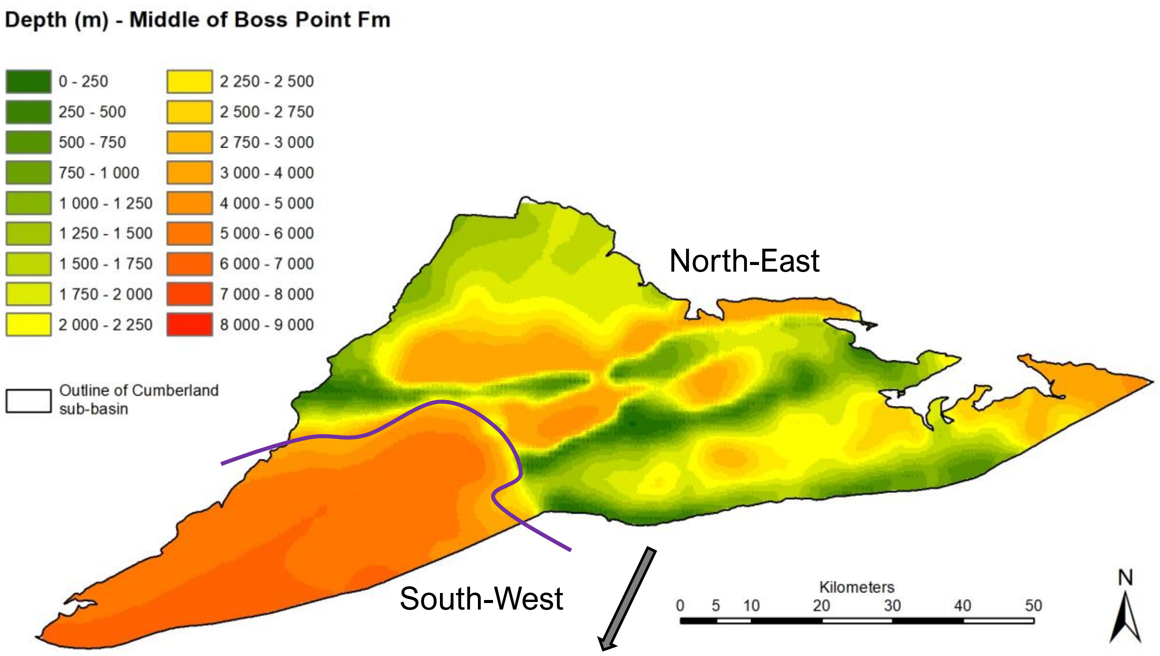
Depth at mid-point and corresponding temperature for Cumberland North-East

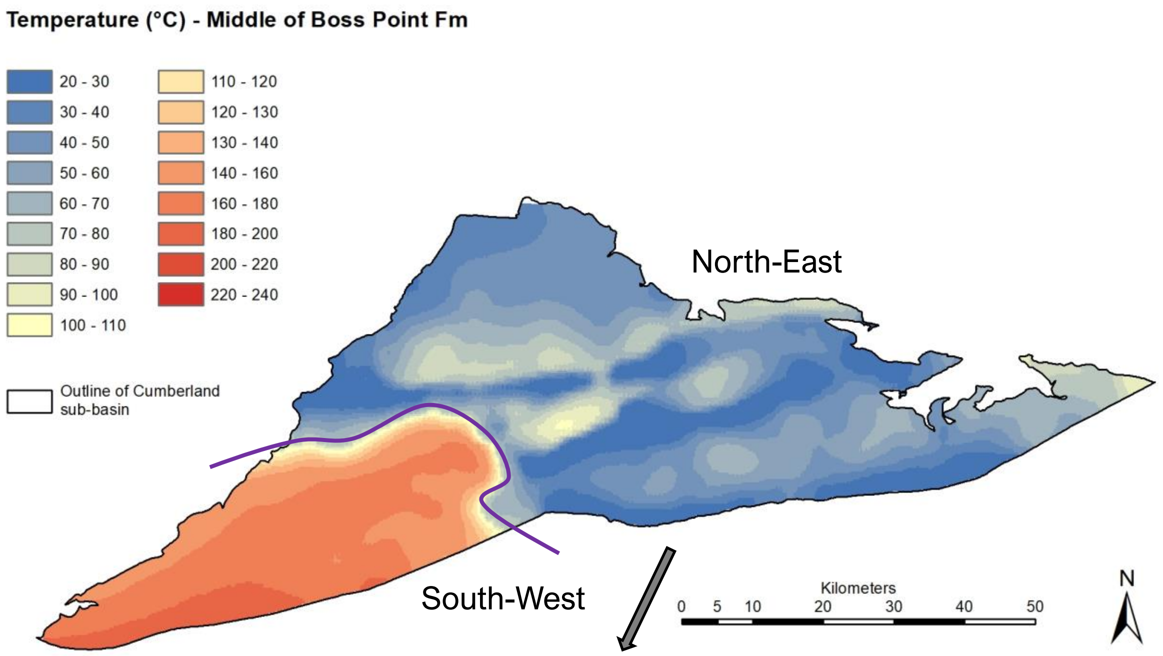
(the southwestern part, too deep, is not considered in the geo-economic model)

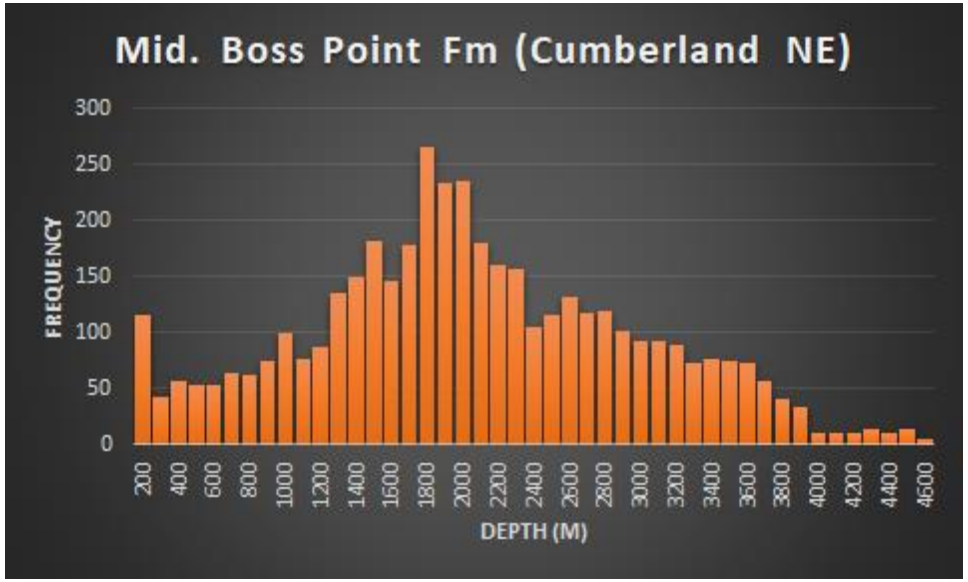
Aquifer	Mean Annual Surf. Temp. (°C)	Depth (m) at P10	Temp. (°C) at P10	Error (°C) at P10	Depth (m) at P50	Temp. (°C) at P50	Error (°C) at P50	Depth (m) at P90	Temp. (°C) at P90	Error (°C) at P90
Boss Point Fm	6.31	772.07	19.59	0.07	1921.5	47.00	2.08	3302.5	74.90	3.57
Claremont Fm		1151.07	30.7	1.24	2300.5	55.03	2.48	3681.5	83.29	3.98
Lime-Kiln Brook Fm		1645.70	41.2	1.78	2713.1	63.77	2.93	3971.1	89.70	4.29
Nuttby Fm		4125.72	93.1	4.46	5091.8	114.31	5.50	5777.6	129.29	6.24

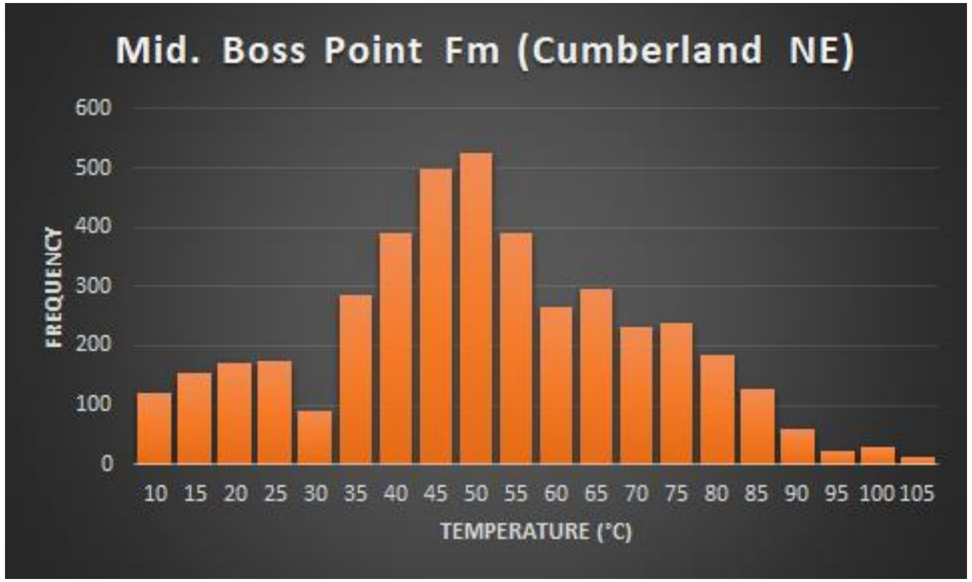
Depths and temperature variations for the Boss Point Formation:

Cumberland





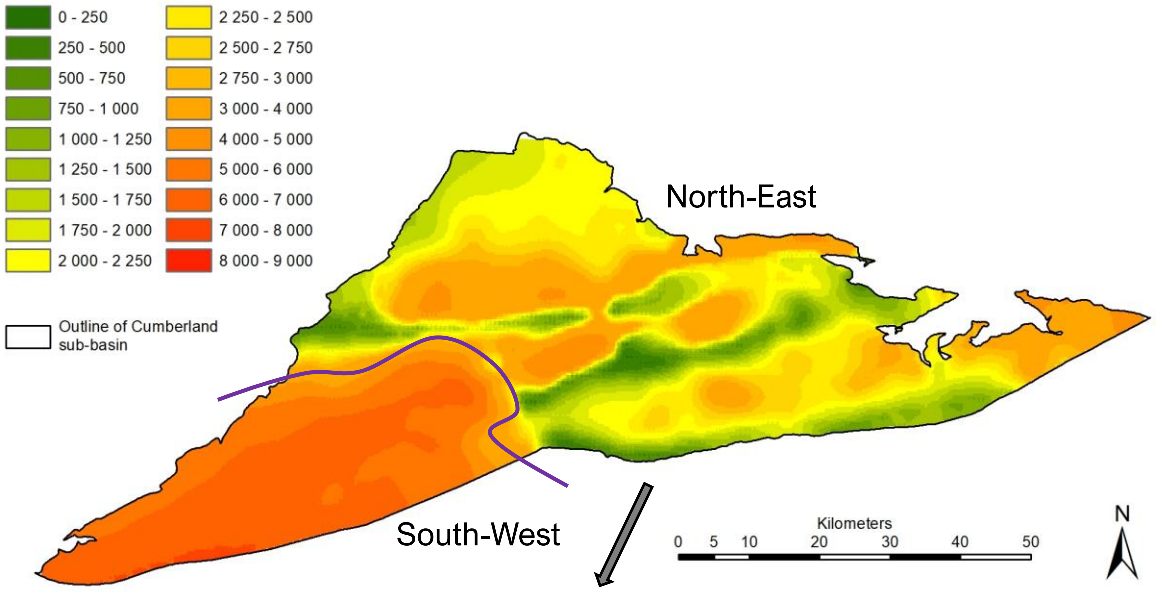




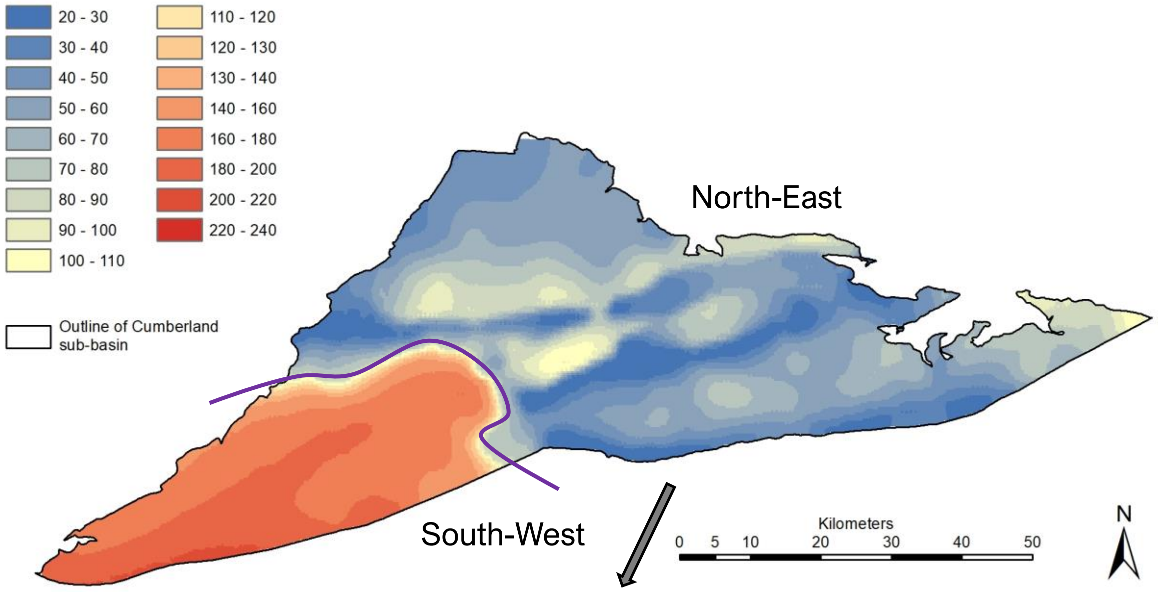
Depths and temperature variations for the Claremont Formation:

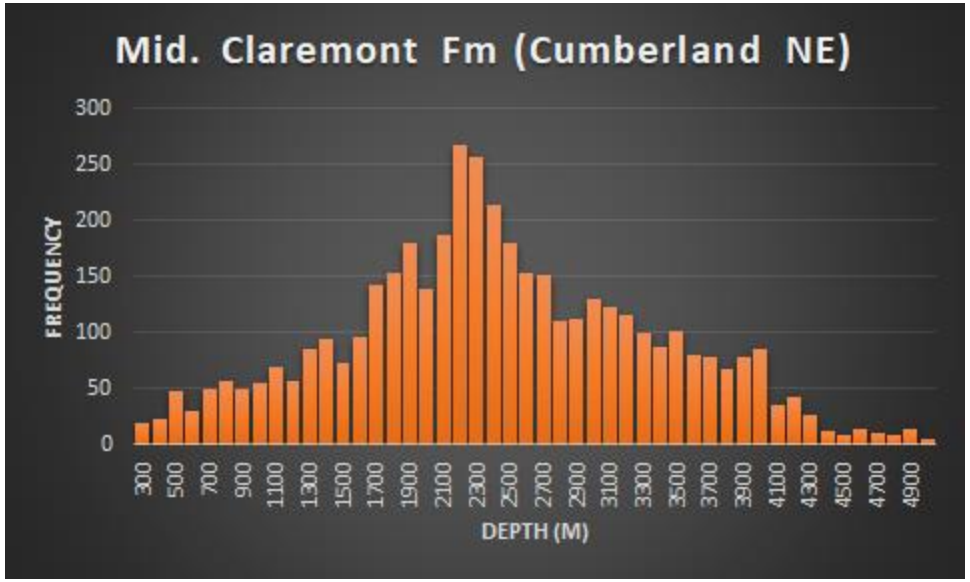
Cumberland

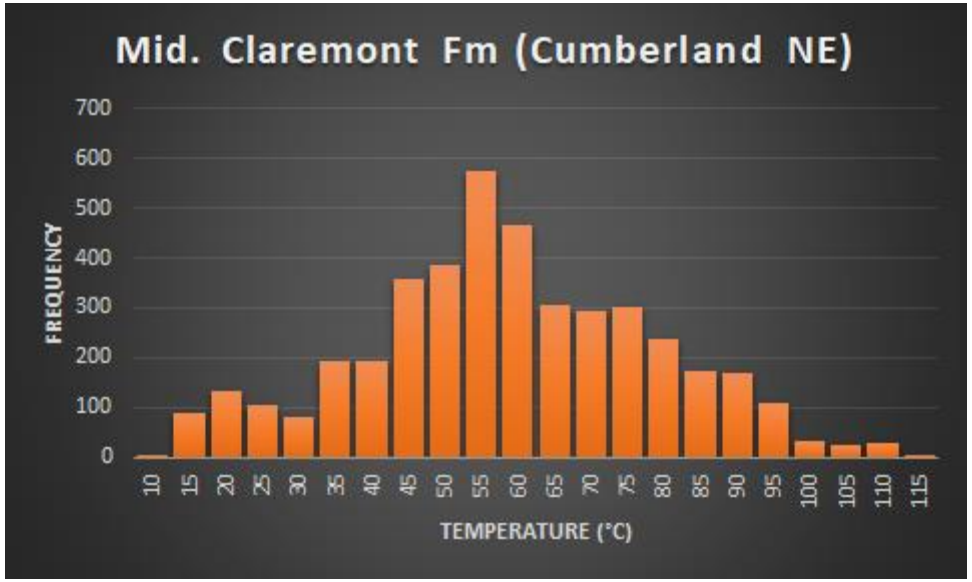
Depth (m) - Middle of Claremont Fm



Temperature (°C) - Middle of Claremont Fm

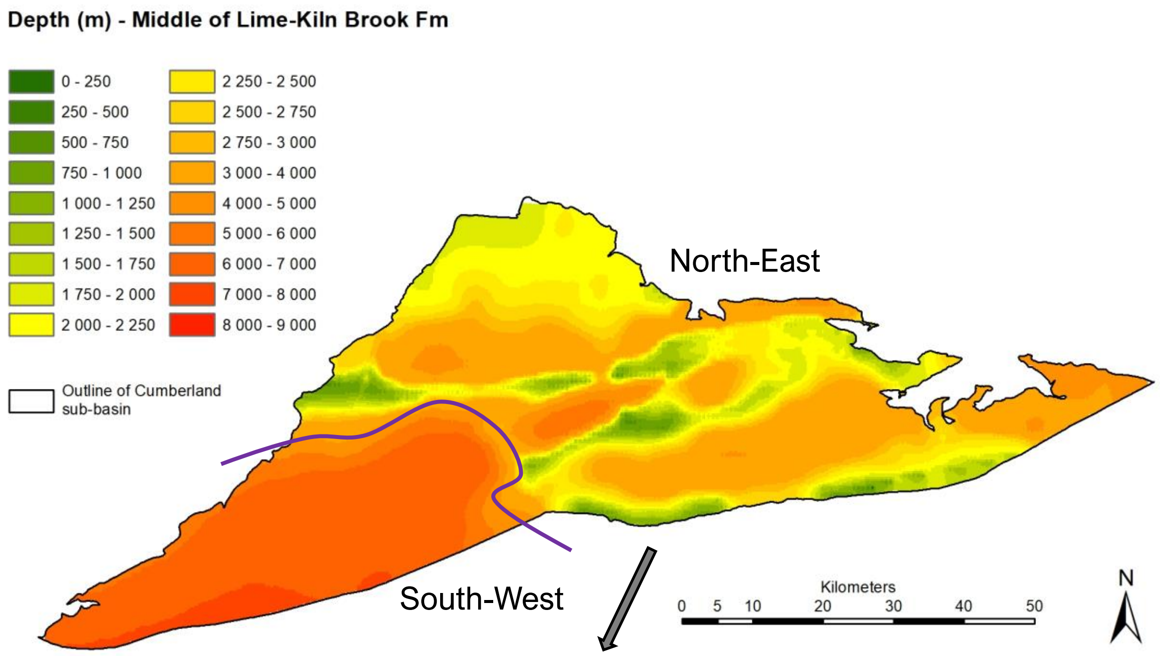


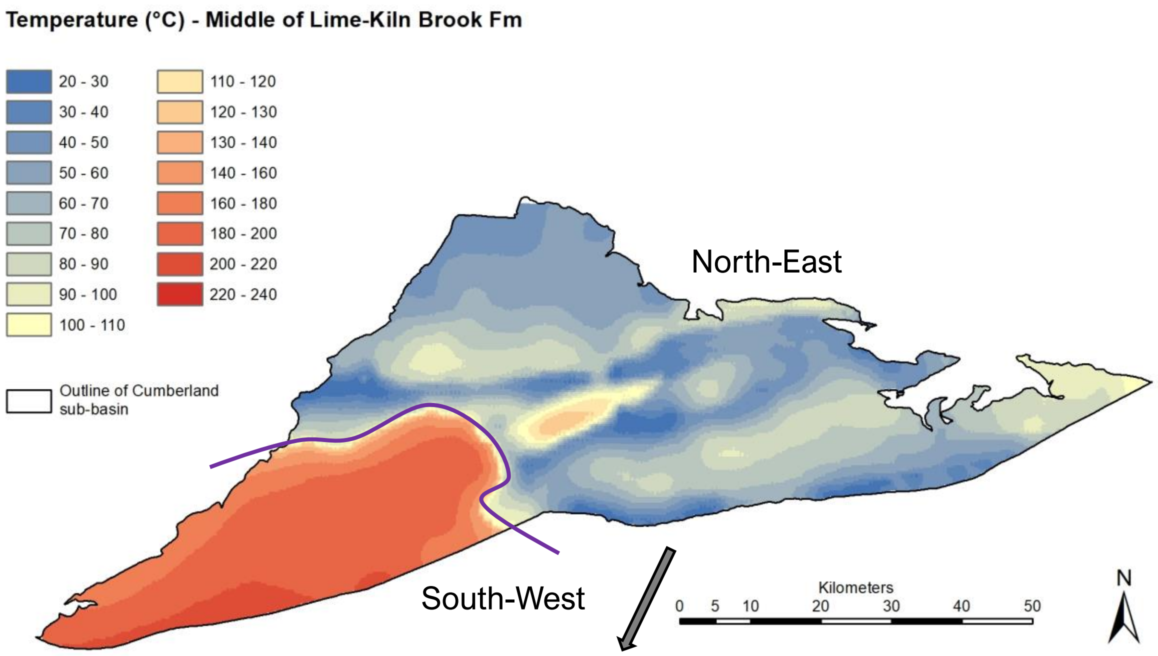


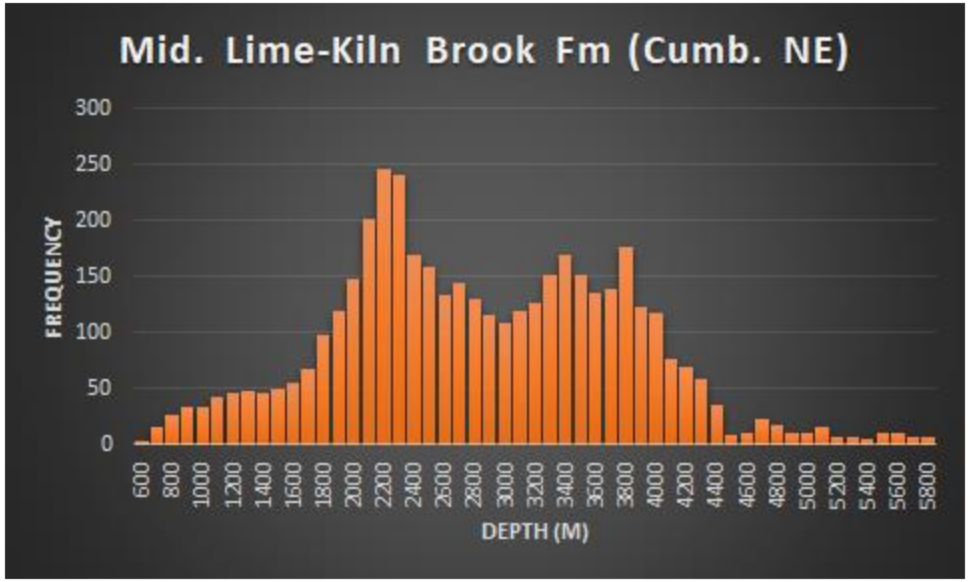


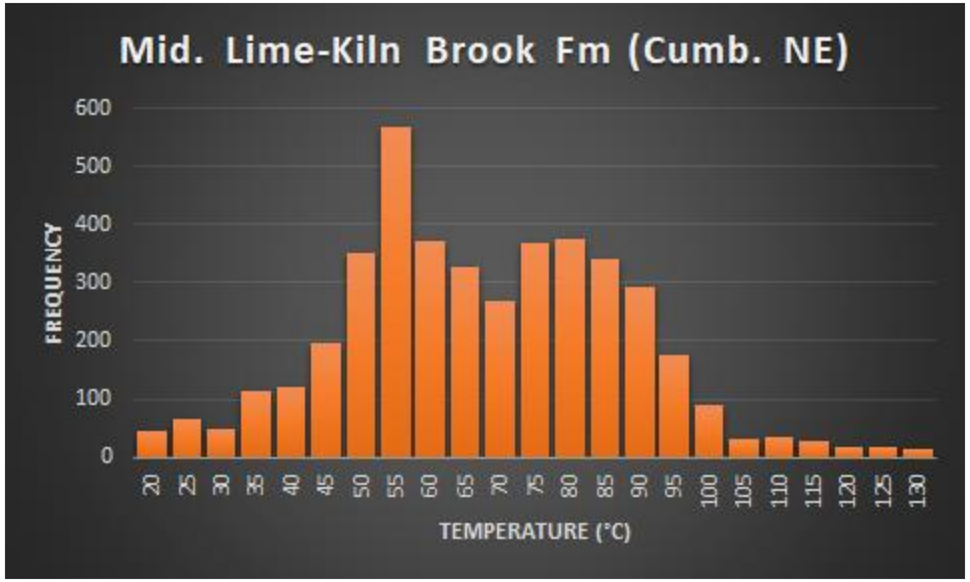
Depths and temperature variations for the Lime-Kiln Brook Formation:

Cumberland



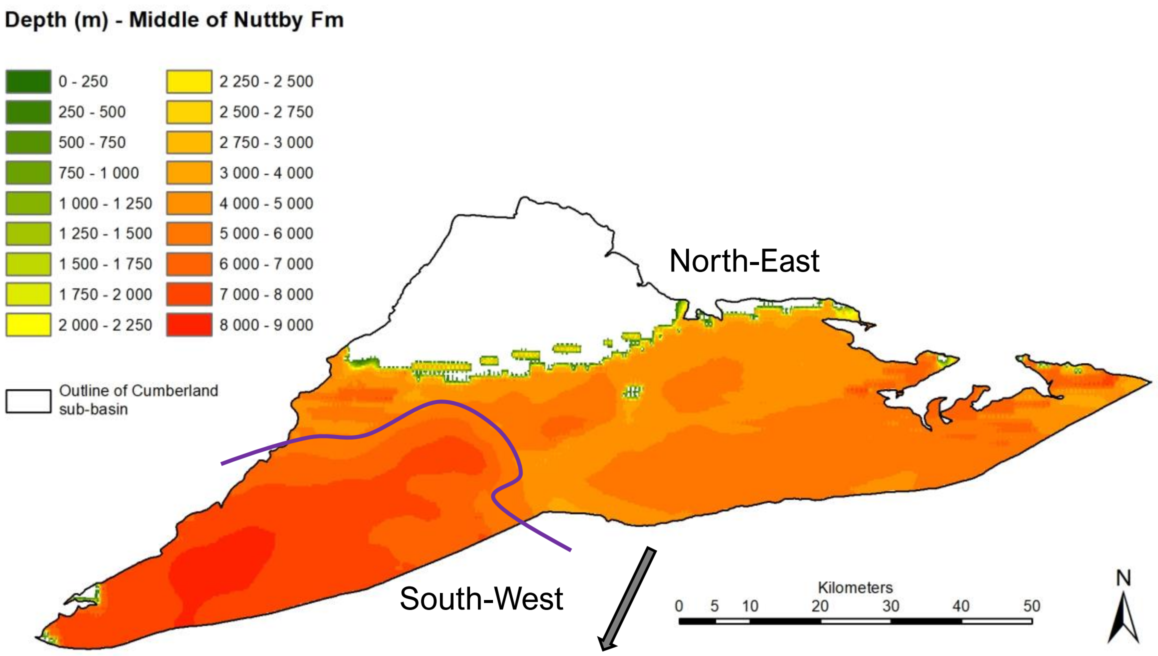


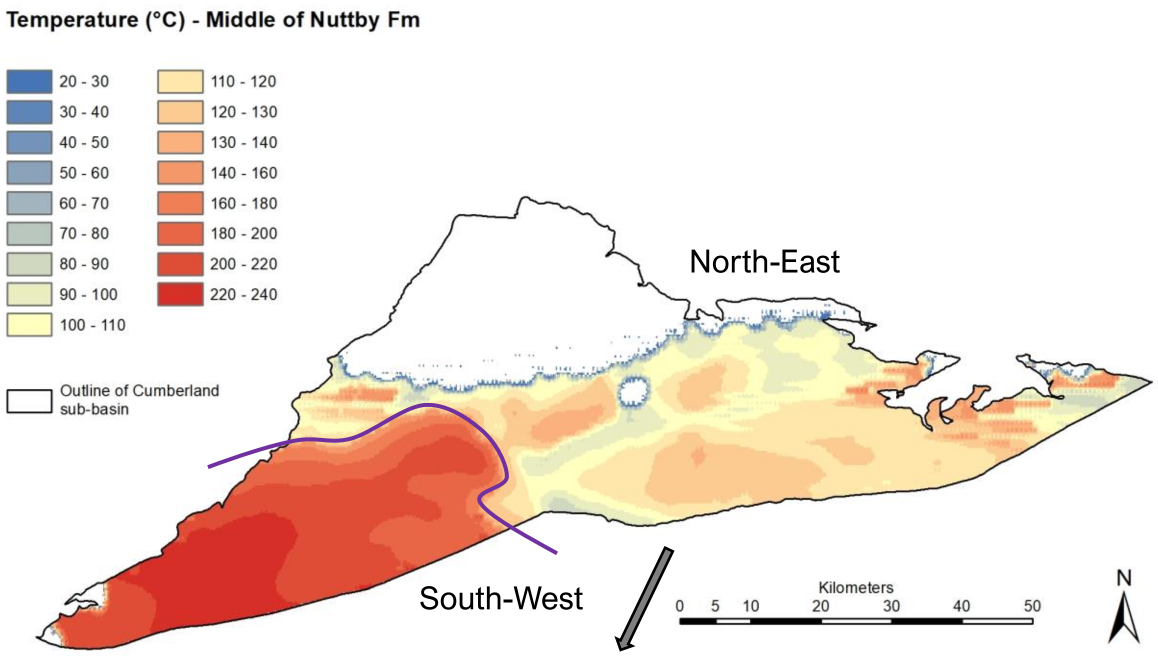


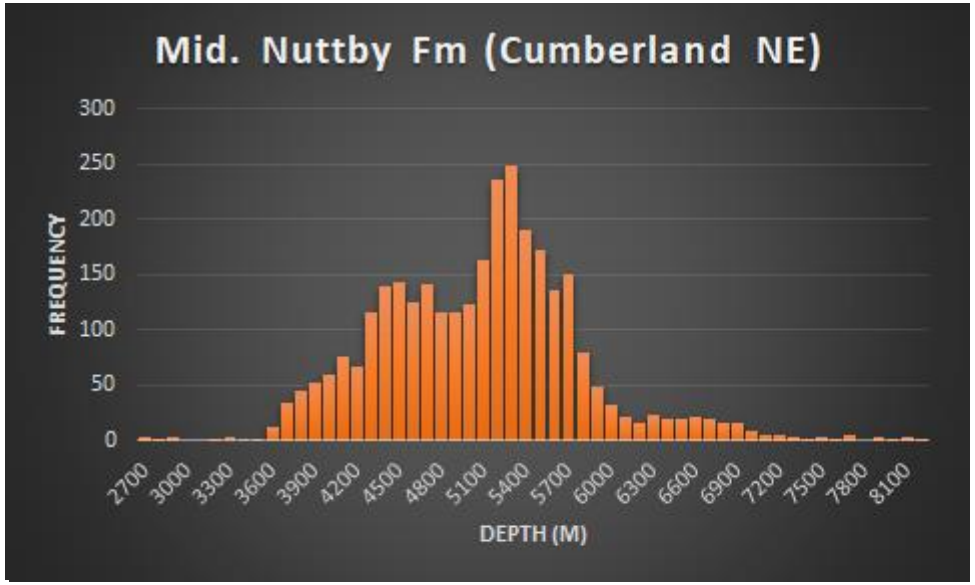


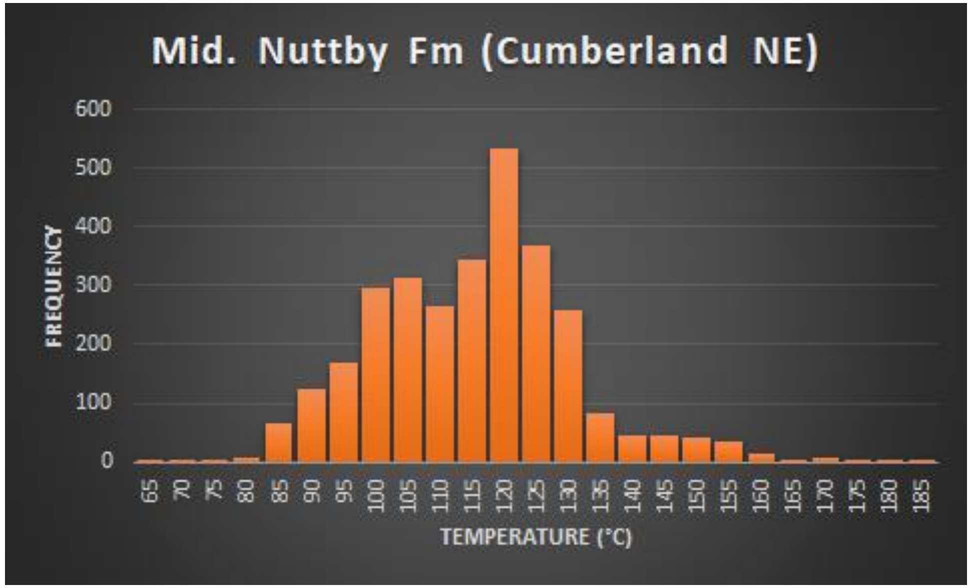
Depths and temperature variations for the Nuttby Formation:

Cumberland









Data sources and assumptions

Windsor-Kennetcook

Aquifer	Source for Depth-Thickness Values	Source for Porosity-Permeability Values	Input for Top	Input for Base	Input for Thickness
Macumber Fm	- Seismic surfaces provided by NSDEM - Cen, X., 2017, Seismic interpretation in the Windsor Basin. Nova Scotia Department of Energy Open File Report 2017-06 - Hayes, B.J.R., Dorey, K., Longson, C.K., 2017. Assessment of Oil and Gas Potential, Windsor and Cumberland Basins, Onshore Nova Scotia. For Nova Scotia Department of Energy by Petrel Robertson Consulting Limited, Open File Report 2017-03	Not evaluated (too shallow)	S.h. Top Macumber	S.h. Top Cheverie	S.h. Top Cheverie MINUS S.h. Top Macumber (N=1472) AND Well geology thickness range (N=5)
Cheverie Fm		- Petroleum wells P-87, P-111, P-112, P-121 - Cen, X., 2017, Preliminary petrophysics database, onshore Nova Scotia. Nova Scotia Department of Energy Open File Report 2017-10 - Bibby, C., Shimeld, J.W., 2000. Compilation of reservoir data for sandstones of the Devonian-Permian Maritimes Basin, Eastern Canada. Geological Survey of Canada, Open File Report 3895, 102 p.	S.h. Top Cheverie	S.h. Top Glass Sand	S.h. Top Glass Sand MINUS S.h. Top Cheverie (N=1973) AND Well geology thickness range (N=4)
Glass Sand Mb			S.h. Top Glass Sand	S.h. Top Middle Horton Bluff AND Well geology thickness range	S.h. Top Middle Horton Bluff MINUS S.h. Top Glass Sand (N=1971) AND Well geology thickness range (N=6)
Middle Horton Bluff Mb			S.h. Top Middle Horton Bluff	S.h. Top Lower Horton Bluff	S.h. Top Lower Horton Bluff MINUS S.h. Top Middle Horton Bluff (N=2253) AND Well geology range (N=4)

(Fm: Formation; Mb: Member; S.h.: Seismic horizon; N: Number of datapoints)

Lithology, porosity and permeability

Aquifer	Thickness (m)			Porosity Aquifer			Permeability Aquifer			Lithology	
	P10	P50	P90	Min (%)	Med (%)	Max (%)	Min (mD)	Med (mD)	Max (mD)	Aquifer	Non-Aquifer
Cheverie Fm	65	264	584	0.3	12.5	19.7	0.01	0.10	11.00	20% Sandstone / Conglomerate	20% Siltstone - 60% Shale
Glass Sand Mb	6	9	16	0.5	8.8	16.8	0.01	0.20	25.60	80% Sandstone	10% Siltstone - 10% Shale
Mid. Horton Bluff Mb	71	675	1838	2.5	6.6	11.7	0.01	0.30	7.05	40% Sandstone	20% Siltstone - 40% Shale

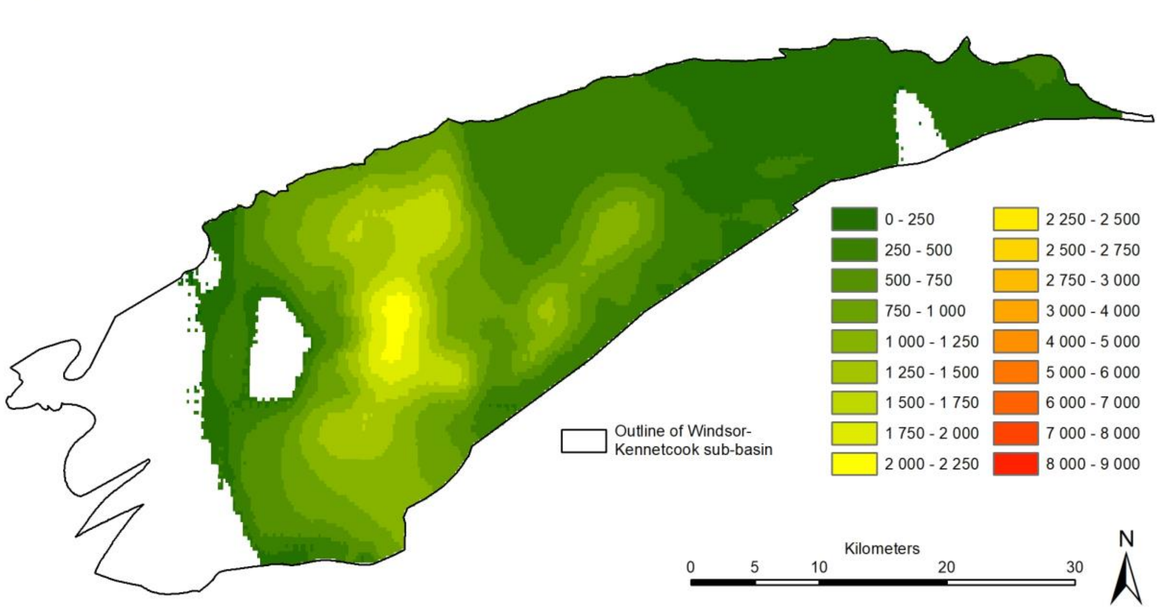
Depth at mid-point and corresponding temperature

Aquifer	Mean Annual Surf. Temp. (°C)	Depth (m) at P10	Temp. (°C) at P10	Error (°C) at P10	Depth (m) at P50	Temp. (°C) at P50	Error (°C) at P50	Depth (m) at P90	Temp. (°C) at P90	Error (°C) at P90
Cheverie Fm	6.61	101.03	8.99	0.00	494.0	18.30	0.00	1384.3	40.0	1.31
Glass Sand Mb		180.00	22.7	0.00	681.7	22.70	0.00	1573.1	42.29	1.49
Mid. Horton Bluff Mb		500.49	32.3	0.00	1056.8	32.33	1.00	1927.2	51.59	1.83

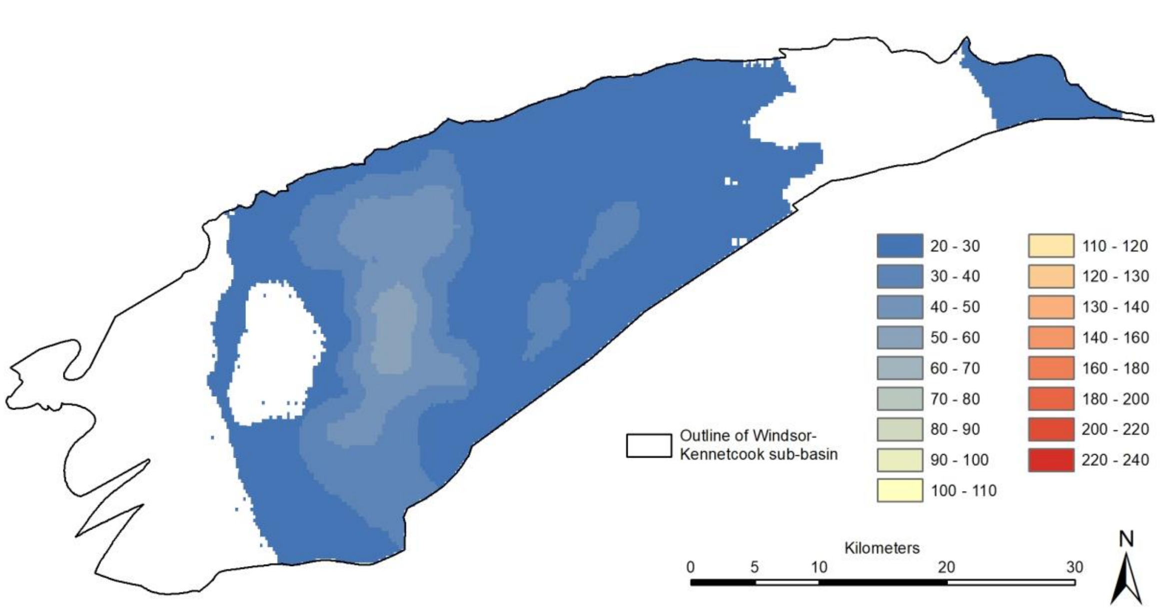
Depths and temperature variations for the Cheverie Formation:

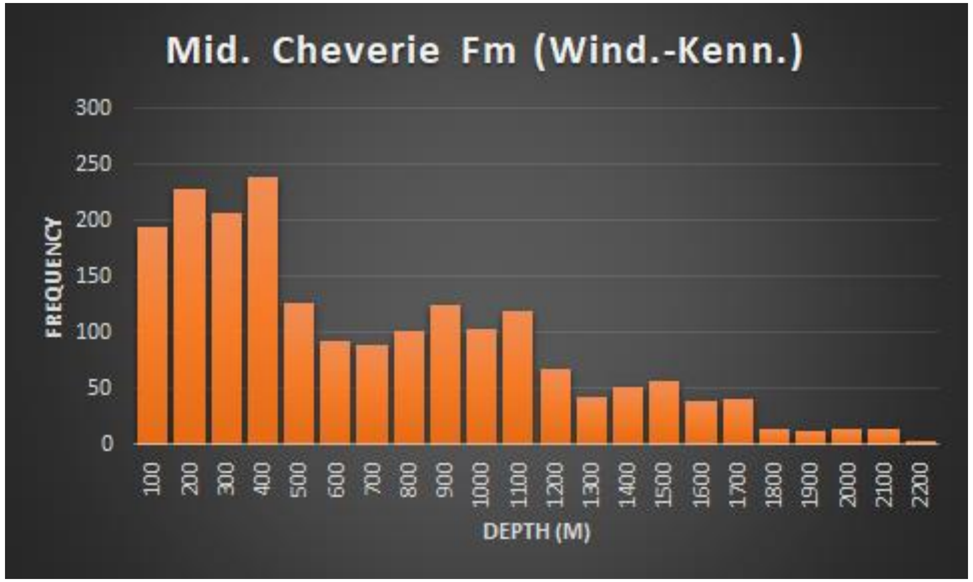
Windsor-Kennetcook

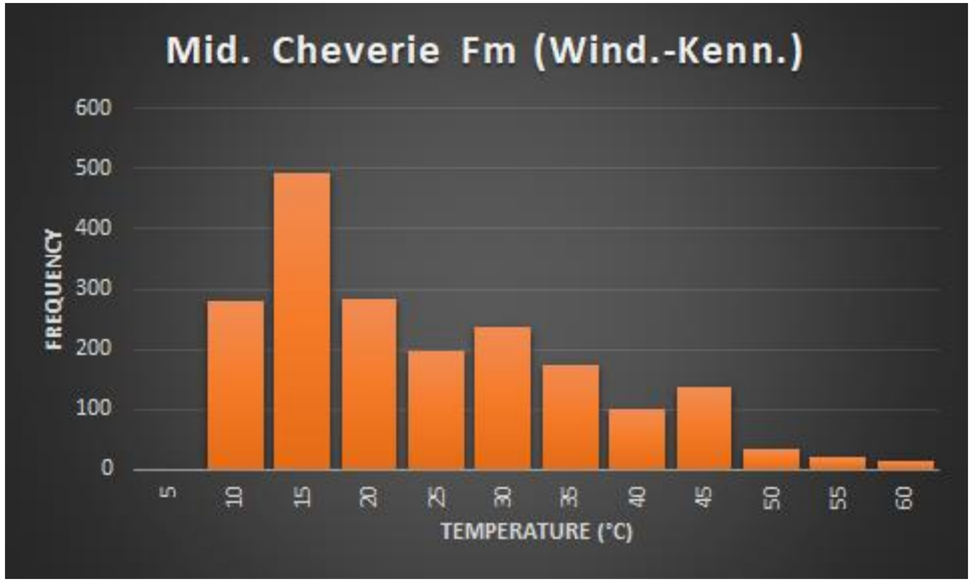
Depth (m) - Middle of Cheverie Fm



Temperature (°C) - Middle of Cheverie Fm

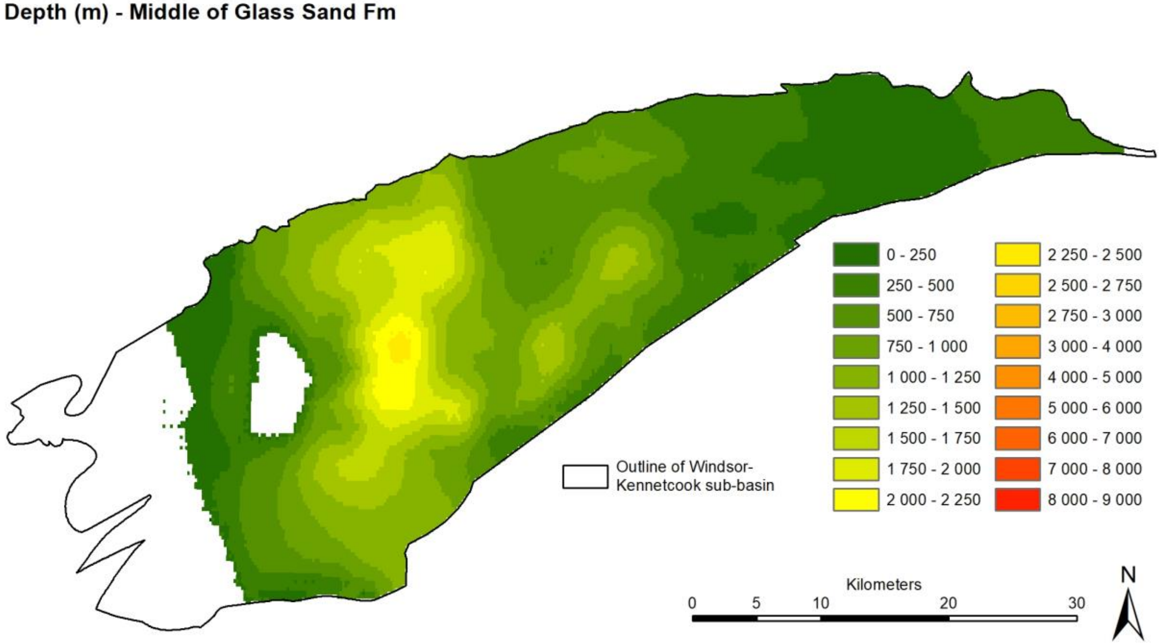


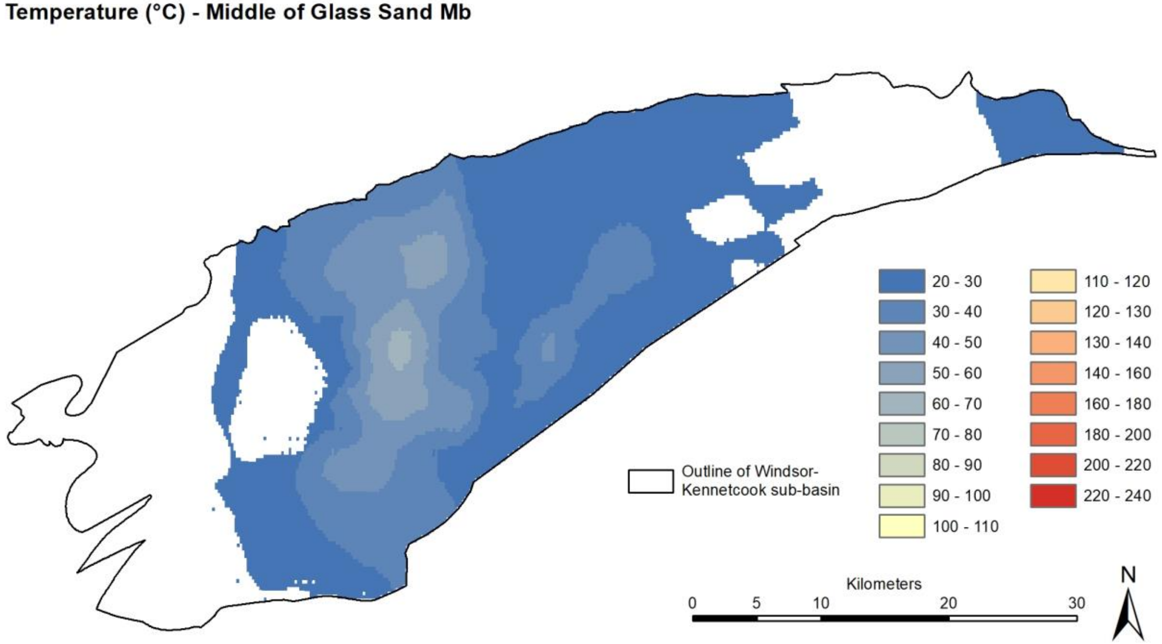


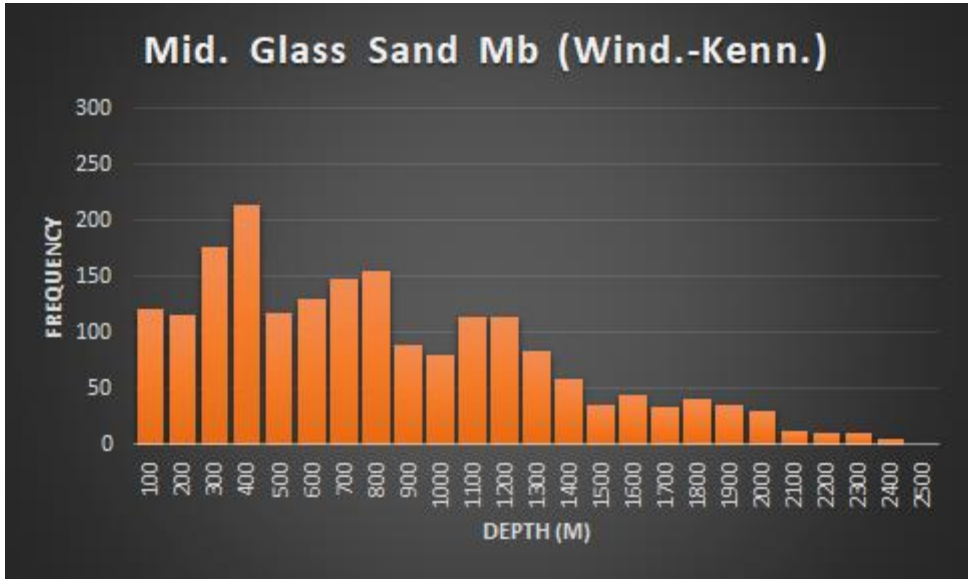


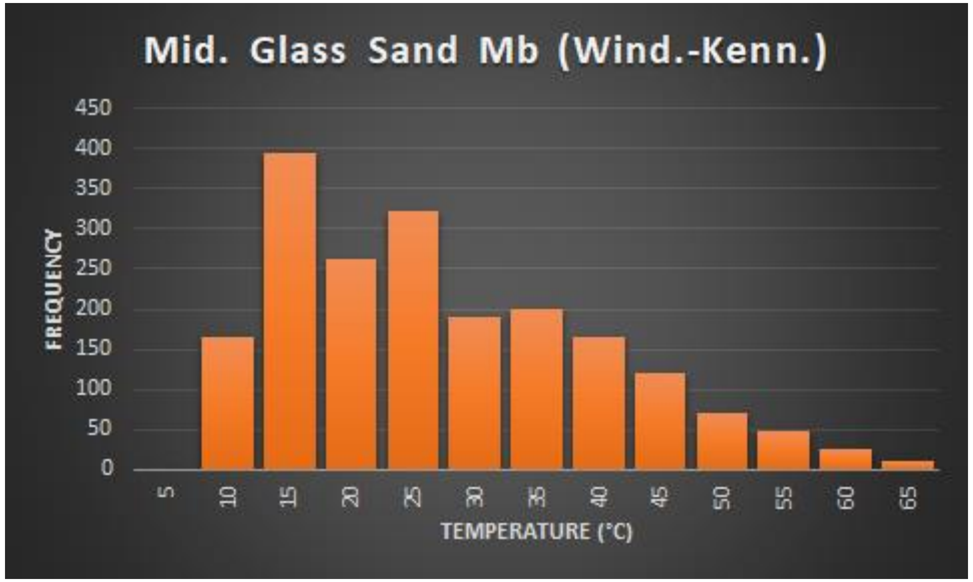
Depths and temperature variations for the Glass Sand Formation:

Windsor-Kennetcook

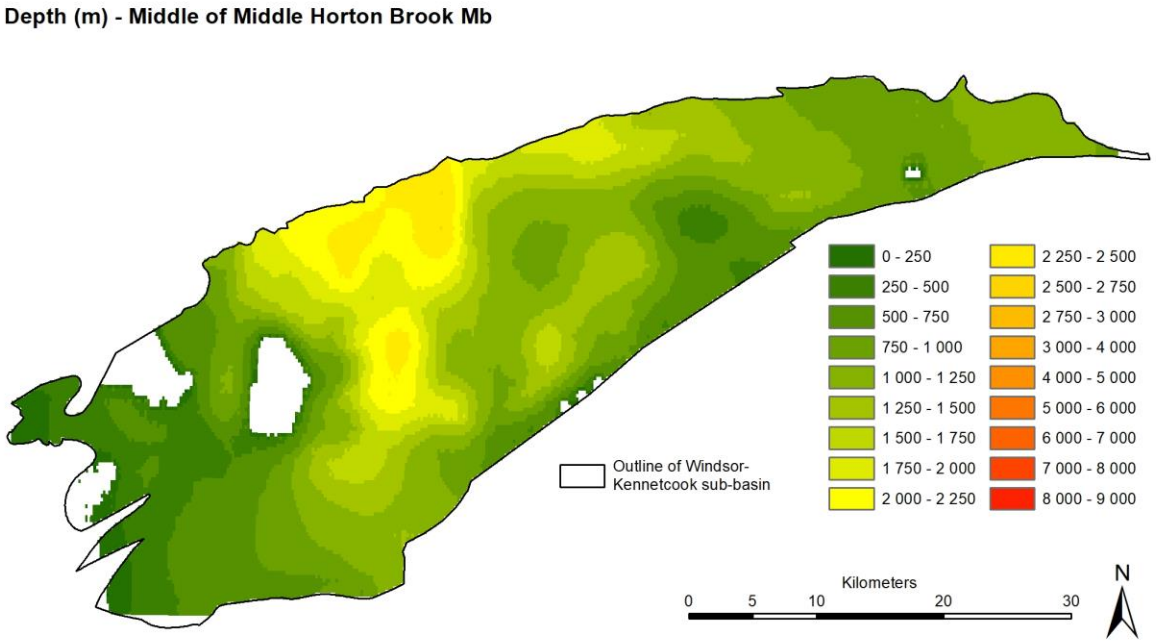


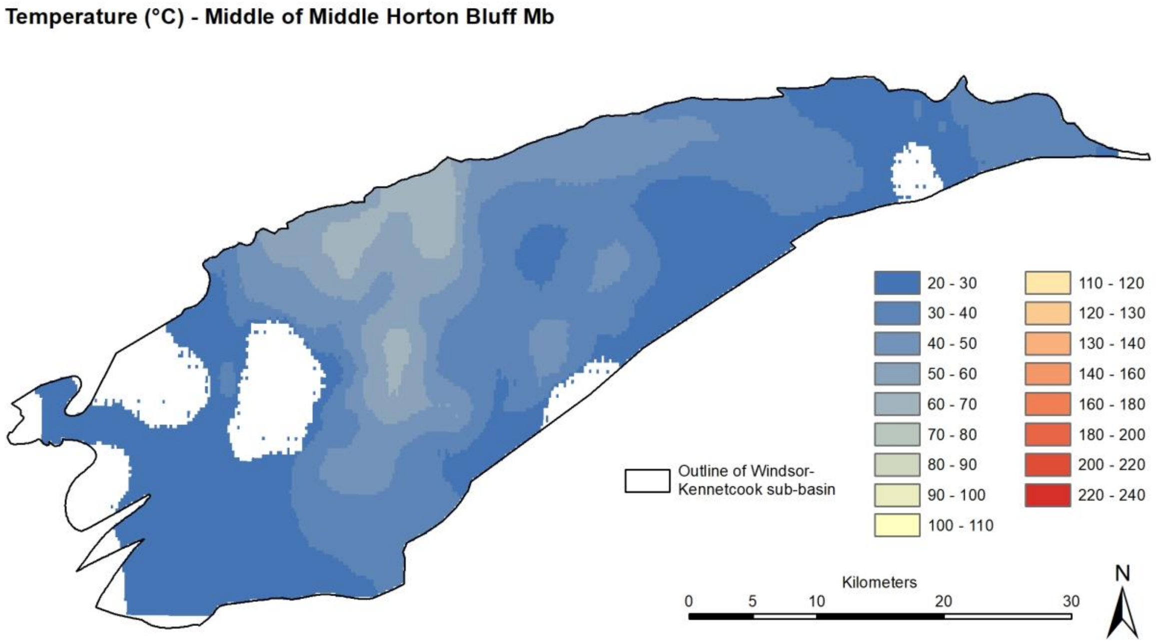


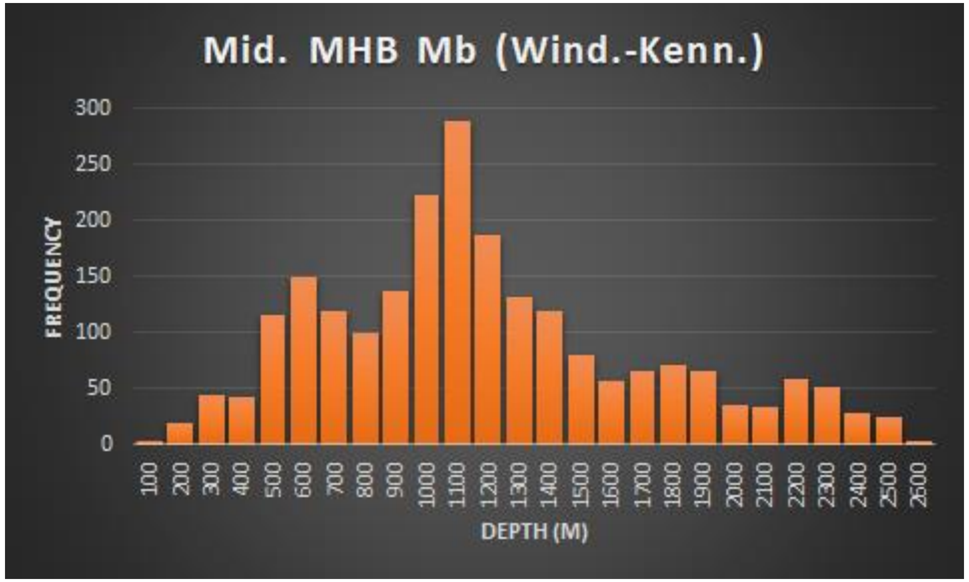


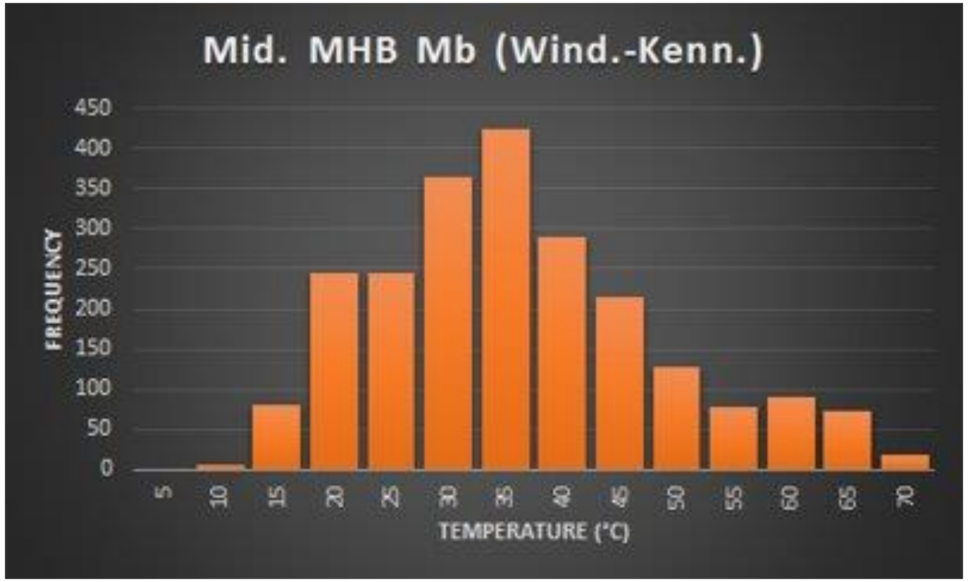


Depths and temperature variations for the Middle Horton Bluff Member: **Windsor-Kennetcook**









Data sources and assumptions

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<tr><td>Thorburn Mb</td><td rowspan="5">- Naylor. R.D., Kalkreuth, W., Smith, W.D., Yeo. G.M., 1989. Stratigraphy, sedimentology and depositional environments of the coal-bearing Stellarton Formation, Nova Scotia. Geological Survey of Canada, Contributions to Canadian Coal Geoscience, Paper 89-8, p. 2-13

- Smith, W.D., Naylor, R.D., Kalkreuth, W.D., 1989. Oil shales of the Stellarton basin, Nova Scotia, Canada: Stratigraphy, depositional environment, composition and potential uses. Atlantic Geology v. 25, p. 20-38

- Waldron, J. W.F., Gillis, K.S., Naylor, R.D., Chandler, F. W., 1995. Structural investigations in the Stellarton pull-apart basin, Nova Scotia. Geological Survey of Canada, ; Current Research, 1995-D, p. 19-25

- NSDOE, 2017. Schedule of 2D Seismic Data, onshore Nova Scotia. Nova Scotia Department of Energy Open File Report 2017-07</td><td rowspan="5">- For Thorburn, Coal Brook and Westville Mbs: Inferences from Boss Point and Cheverie Fms

- For Skinner River Mb and Middle River Fm: Inferences from Boss Point Fm and redbeds general properties

- Naylor. R.D., Kalkreuth, W., Smith, W.D., Yeo. G.M., 1989. Stratigraphy, sedimentology and depositional environments of the coal-bearing Stellarton Formation, Nova Scotia. Geological Survey of Canada, Contributions to Canadian Coal Geoscience, Paper 89-8, p. 2-13</td><td colspan="3" rowspan="3">Type stratigraphic section of Naylor et al. (1989)</td></tr>
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<tr><td>Westville Mb</td></tr>
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Waldron et al. (1995)</td></tr>
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Waldron et al. (1995)</td><td>Seismic line CHV80-12x_a4a37 (NSDOE Open File 2017-07)</td><td>Naylor et al. (1989)
Waldron et al. (1995)
Seismic line CHV80-12x_a4a37</td></tr>
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(Fm: Formation; Mb: Member; S.h.: Seismic horizon)

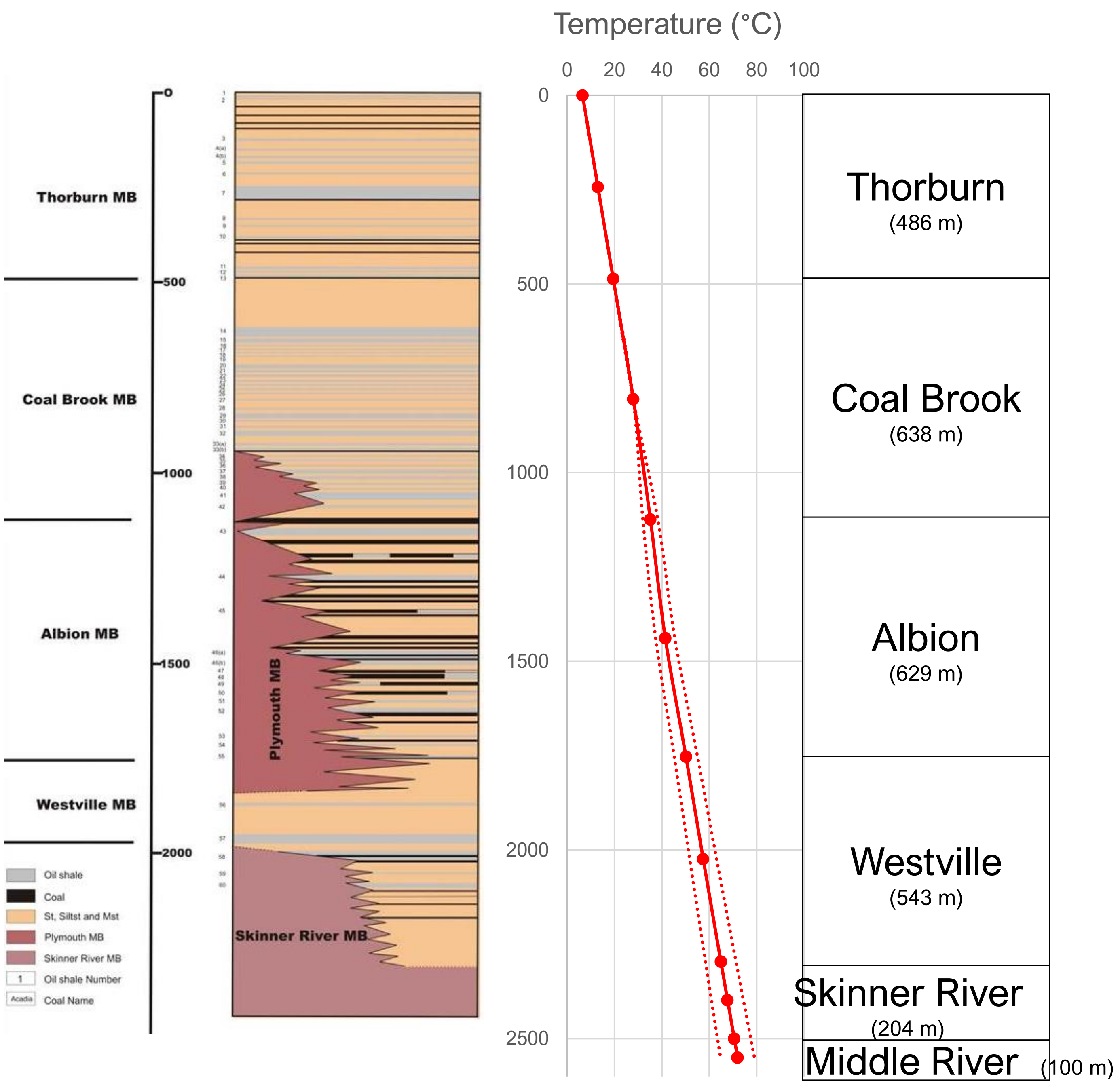
Lithology, porosity and permeability

Aquifer	Thickness (m)			Porosity Aquifer			Permeability Aquifer			Lithology	
	P10	P50	P90	Min (%)	Med (%)	Max (%)	Min (mD)	Med (mD)	Max (mD)	Aquifer	Non-Aquifer
Thorburn Mb	N/A	486	N/A	0.4	9.0	15.0	0.01	0.20	12.00	28% Sandstone	42% Siltstone / Mudstone - 30% Coal / Oil Shale
Coal Brook Mb	N/A	638	N/A	0.4	9.0	15.0	0.01	0.20	12.00	28% Sandstone	41% Siltstone / Mudstone - 31% Coal / Oil Shale
Westville Mb	N/A	543	N/A	0,3	4.0	10.0	0.01	0.20	10.00	21% Sandstone	63% Siltstone / Mudstone - 16% Coal / Oil Shale
Skinner River Mb	N/A	204	N/A	2,0	8.0	18.0	0.01	0.30	12.00	25% Sandstone	75% Siltstone / Mudstone
Middle River Fm	N/A	100	N/A	2,0	8.0	18.0	0.01	0.30	12.00	50% Sandstone / Conglomerate	50% Siltstone / Mudstone

Depth at mid-point and corresponding temperature (unique vertical profile: no statistics)

Aquifer	Mean Annual Surf. Temp. (°C)	Depth (m)	Temp. (°C)	Error (°C)
Thorburn Mb	6.46	243.0	12.93	0.00
Coal Brook Mb		805.0	27.91	0.00
Westville Mb		2024.5	57.43	5.69
Skinner River Mb		2398.0	67.71	6.74
Middle River Fm		2550.0	71.95	7.17

Stellarton



A single vertical profile is developed for the entire Stellarton sub-basin due to the low level of knowledge of its subsurface geometry

The Plymouth and Skinner River members are more developed along the margins of the sub-basin: the geothermal model considers only the basal part of the Skinner River Mb, and adds the basal Middle River Fm

All stratigraphic units considered here are potential aquifers, to the exception of the Albion Member in which sandstone intervals are rare and siltstone/mudstone, coal seams and oil shales account for about 95% of the lithologies.

The proportion of the lithological units in the thin, basal Middle River Fm is not known and arbitrary values have been attributed (50% aquifer, 50% aquitard)

Depths and thicknesses are in meters. Source for the stratigraphic column: Adapted from Smith et al. (1989), courtesy of NSDEM.

Enhanced Geothermal Systems

Low permeability rocks that cannot sustain economically viable flow rates can be engineered to enhance their deliverability, thus creating an Enhanced/Engineered Geothermal System (EGS). EGS can be created by thermal, chemical or hydraulic stimulation.

EGS developed by **thermal stimulation** consists in injecting cool water into the wellbore to create a thermal stress, thus cracking the rock when it cools. This method is mostly used in high-enthalpy volcanic and metamorphic environments and is unlikely to succeed in Nova Scotia considering the moderate geothermal gradients documented.

Chemical stimulation consists in injecting acid at high pressure to hydraulically fracture the rock while etching it at the same time. Low-pressure acidizing is not considered as an EGS practice and is only meant to clean the near wellbore area from the side effects of the drilling activity. The acid can be either HCl in carbonates or HF in sandstones.

Hydraulic stimulation increases the natural permeability of the rock by injecting fluids (generally water) at high pressure to create a new network of fractures (induced fractures). Alternatives to the large volumes of water typically required by hydraulic fracturation can also be contemplated. Especially, replacing water with supercritical CO_2 can provide a complex network of induced fractures while at the same time sequestrating a percentage of the CO_2 (see Kumari and Ranjith, 2019 and references therein). High-volume fracturation is necessary when the permeability is very low, but low-volume fracturation can also be contemplated when the natural permeability of the rock is sufficient. **This low-volume scenario is the one that is retained in the present geo-economic modeling, on account of the fact that the potential aquifer candidates are dominated by tight sands, not shales.**

A detailed evaluation of the feasibility of EGS in Nova Scotia is beyond the scope of the present study and would require a dedicated data acquisition program. For reference purposes only, the following slides provide some insights on the natural seismicity and the orientation of the principal stresses in the areas of interest, along with some recommendations on the type of EGS-relevant information that can be obtained using the available data.

For further readings:

- Breede, K., Dzebisashvili, K., Liu, X. et al., 2013. A systematic review of enhanced (or engineered) geothermal systems: past, present and future. Geotherm Energy 1, 4, 27 p. https://doi.org/10.1186/2195-9706-1-4
- Breede, K., Dzebisashvili, K., Falcone, G., 2015. Overcoming challenges in the classification of deep geothermal potential, Geoth. Energ. Sci., 3, p. 19-39. https://doi.org/10.5194/gtes-3-19-2015
- Kumari, W.G.P., Ranjith, P.G., 2019. Sustainable development of enhanced geothermal systems based on geotechnical research – A review. Earth-Science Reviews, v. 199, 102955, 22 p. https://doi.org/10.1016/j.earscirev.2019.102955
- Lu, S.M., 2018. A global review of enhanced geothermal system (EGS). Renewable and Sustainable Energy Reviews, v. 81, Part 2, p. 2902-2921. https://doi.org/10.1016/j.rser.2017.06.097
- Massachusetts Institute of Technology, 2006. The future of geothermal energy - Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st century. M.I.T. Publisher, 372 p. https://www1.eere.energy.gov/geothermal/pdfs/future_geo_energy.pdf
- Olasolo, P., Juárez, M.C., Morales, M.P., D´Amico, S., Liarte, I.A., 2016. Enhanced geothermal systems (EGS): A review. Renewable and Sustainable Energy Reviews, v. 56, p. 133-144. https://doi.org/10.1016/j.rser.2015.11.031

Enhanced Geothermal Systems, *cont.*

Natural seismicity

Natural seismicity is an important parameter to consider in the scope of EGS, as the baseline to monitor any possible induced seismicity during and after hydraulic fracturation.

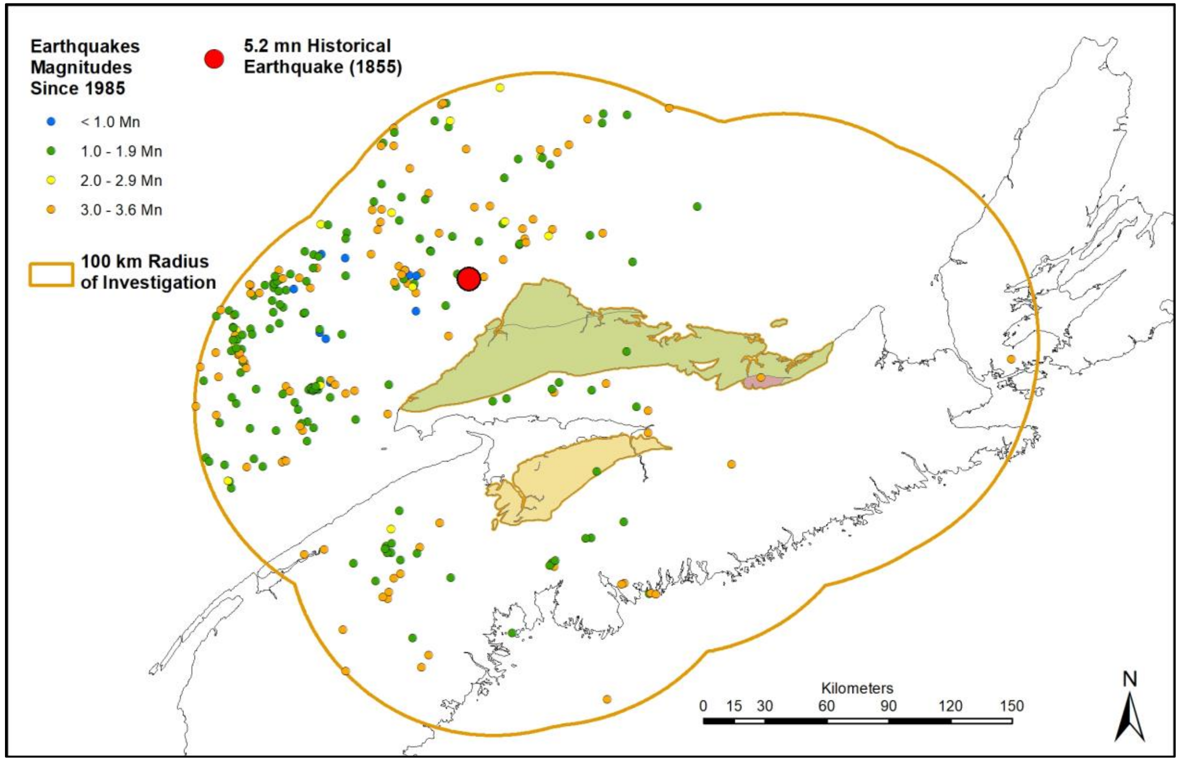
The seismicity in the area of interest is low, as shown by a search in the National Earthquake Database (NEDB, Earthquakes Canada, 2021). Results indicate that, since 1985 and within 100 km in and around the three sub-basins, 270 earthquakes have been documented, including the following:

- 14 occurrences with a magnitude lower than 1.0 M_N
- 143 occurrences with a magnitude comprised between 1.0 and 1.9 M_N
- 108 occurrences with a magnitude comprised between 2.0 and 2.9 M_N
- 5 occurrences with a magnitude comprised between 3.0 and 3.6 M_N

This dataset is complemented by an historical compilation (Lamontagne et al., 2018) showing that a single significant earthquake has been recorded in the same area since the year 1600, with a magnitude of 5.2 m_N in Moncton, in 1855. Minor damages were reported.

Most of these earthquakes are essentially located in New Brunswick and the Bay of Fundy. Only three occurrences are documented within the limits of the sub-basins:

- Cumberland:
  1.7 Mn at 5 km depth in the Nuttby Formation (April 13, 2021)
- Windsor-Kennetcook:
  1.8 Mn at 18 km depth in the Basement (December 5, 2013)
- Stellarton:
  2.1 Mn at 1 km depth in the Coal Brook Member (August 7, 1986)



References:
- Earthquakes Canada, 2018. GSC (Geological survey of Canada), Earthquake Search (On-line Bulletin), Nat. Res. Can. http://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bulletin-en.php
- Lamontagne, M., Halchuk, S., Cassidy, J.F., Rogers, G.C., 2018. Significant Canadian earthquakes 1600-2017, Geological Survey of Canada, Open File 8285, 1 .zip file. https://doi.org/10.4095/311183

Enhanced Geothermal Systems, *cont.*

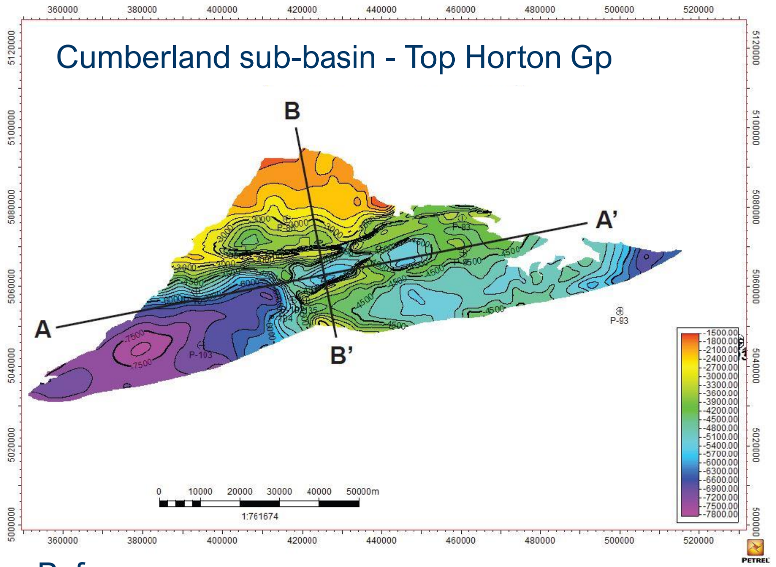
Orientation of regional stresses and induced seismicity

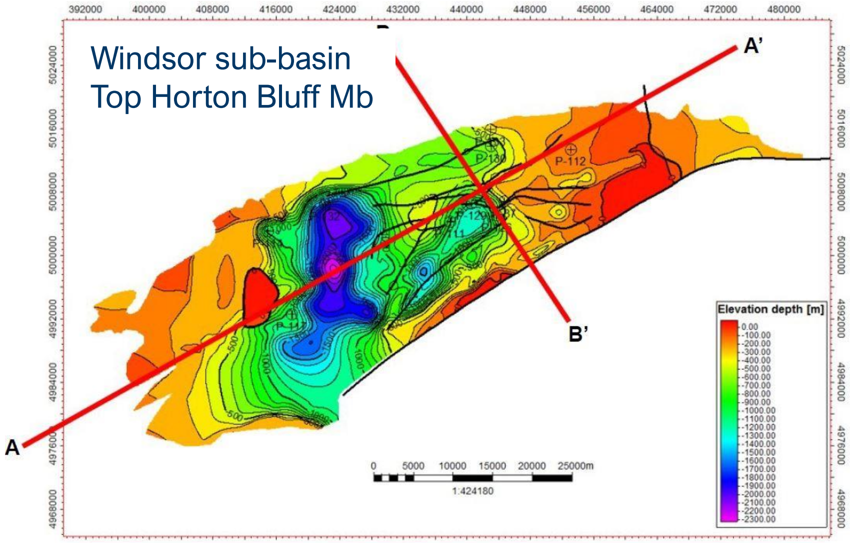
During hydraulic fracturation, the sustained injection of fluids at high pressure and high rate increases the pore pressure in the rock. As a result of this process, pre-existing faults that are optimally oriented with respect to the maximum horizontal stress (Sh_{max}) can become critically stressed and be reactivated, with the possibility to generate earthquakes during the shear motion along the fault planes. Determining when a fault can become critically stressed in Nova Scotia's sub-basins is beyond the scope of the present research, but at minimum it is recommended to avoid EGS close to optimally oriented faults.

Optimally oriented faults strike within 30° ± 5° to Sh_{max}. The orientation of Sh_{max} is estimated mainly from petroleum well data (borehole breakouts) and natural earthquakes measurements (focal mechanisms). **In Nova Scotia, the regional orientation of Sh_{max} is 47°N ± 6°**, based on the data extracted from the World Stress Map (Heidbach et al., 2016). Only data with a high level of confidence are retained here (levels A, B and C).

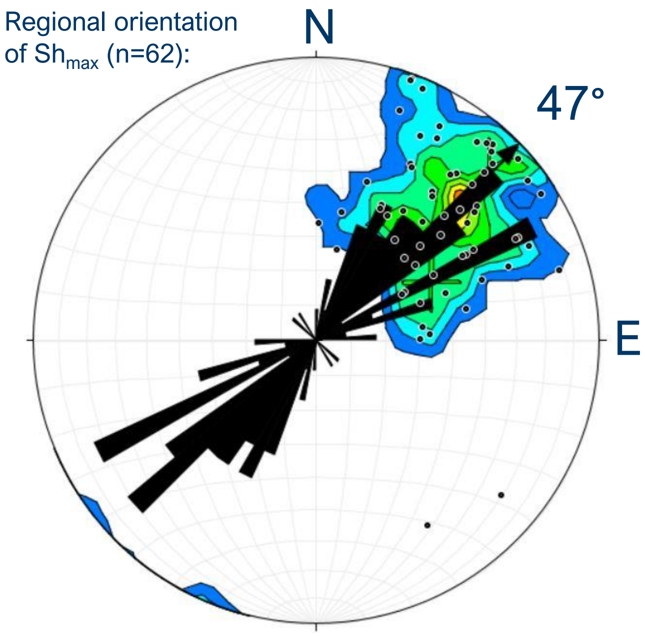
This regional orientation of Sh_{max} is sub-parallel to some faults interpreted on seismic in the Cumberland and Windsor-Kennetcook sub-basins (NSDOE, Open File 2017-03). No subsurface data is available to document the orientation of faults in the Stellarton sub-basin. Further evaluation is required to better document the orientations and properties of the faults in the areas of interest.

Structure maps with interpreted faults in black (modified from Hayes et al., 2017):





Regional orientation of Sh_{max} (n=62):



References:

- Hayes, B.J.R., Dorey, K., Longson, C.K., 2017. Assessment of Oil and Gas Potential, Windsor and Cumberland Basins, Onshore Nova Scotia. For Nova Scotia Department of Energy by Petrel Robertson Consulting Limited, Open File Report 2017-03
- Heidbach, O., Rajabi, M., Reiter, K., Ziegler, M., WSM Team, 2016. World Stress Map Database Release 2016. V. 1.1. GFZ Data Services. https://doi.org/10.5880/WSM.2016.001

Enhanced Geothermal Systems - Recommendations

Recommendations for additional investigations

Orientation of faults and Sh_{max}

The orientation of the stress fields can differ locally from the regional pattern, especially in the vicinity of existing faults. Available subsurface data can help refining the local orientation of Sh_{max} with respect to faults prior to any EGS development, in particular:

- In the Windsor-Kennetcook sub-basin, two petroleum wells have FMI (Formation Micro Imager) log data available that can be analysed for borehole breakouts and drilling induced fractures (well P-126, from 700 to 1,331 mMD(*) and well P-129 from 1,150 to 1,934 mMD).
- In the Stellarton sub-basin, one well has been analysed for borehole ovalisation (well P-115, from 7 to 847 mMD).
- In the Cumberland and Windsor-Kennetcook sub-basins, the available seismic lines can be used to map into detail the orientation and extent of the faults.

Caprock integrity and propagation of induced fractures

The integrity of the caprock overlying the interval considered for hydraulic fracturation should be evaluated to confirm the presence of geomechanical barriers to the upward propagation of induced fractures and fluids toward the shallow aquifers. Thick layers of shale and salt provide the best barriers:

- In the Cumberland sub-basin, salt is present above the lowermost potential aquifer (Nuttby Formation).
- In the Windsor-Kennetcook sub-basin, the salt is only present at shallow depths across most of the sub-basin, although thick accumulations can be locally developed.
- In the Stellarton sub-basin, the Albion Member is likely the most ductile interval of the whole sequence.

A thorough evaluation of the relative ductility of the mechanical barriers is beyond the scope of the present study, but it can be undertaken with the data available at a pre-feasibility stage of the planning of an EGS development in the Windsor-Kennetcook sub-basin, where the S and P waves are recorded in the sonic logs of the petroleum wells P-126 and P-129 (respectively from 271 to 1,344 mMD and from 284 to 1,937 mMD). Elsewhere, a brittleness index can also be estimated from the various lithologies to establish a semi-quantitative geomechanical stratigraphy, although with less accuracy than with sonic log data.

(*) MD: Measured Depth.

Miscellaneous Information (1/2)

Miscellaneous information scattered in petroleum well data have been gathered in the scope of the present study, that shed additional light on some geological properties of importance to determine the viability of a deep geothermal project in Nova Scotia. These data were not accounted for in the geo-economic model due to their geographically limited representativity but are reproduced here for the benefit of future research.

Formation water chemistry

Water chemistry has an impact on the type of equipment installed and its longevity. Only one water analysis has been identified, in the Cumberland sub-basin.

- Well P-125 – Water sample collected between 700 and 1,100 mMD depth in coal seams:
  - Dissolved Chloride (Cl): 99,000 mg/L
  - Dissolved Manganese (Mn): 12,000 µg/L
  - Dissolved Iron (Fe): 140,000 µg/L
  - Dissolved Calcium (Ca): 16,000 µg/L
  - Calculated TDS: 154,000 mg/L
  - pH: 5.52
  - Hardness ($CaCO_3$): 50,000 mg/L

Direct evidence of aquifers

In rare occasions, direct observations reported in end of drilling reports document water influx and/or intervals with a better than average permeability. These occurrences suggest that the actual permeability can be locally significantly higher than the regional values considered in the present geo-economic modeling. For example:

- Well P-86 (Cumberland): A two-feet drilling break with *“fine grained friable sand with good porosity, flowing salt water at 200 psi”* is reported near the base of the Boss Point Formation at 2,636 mMD.
- Well P-111 (Windsor-Kennetcook): *“Good intergranular porosity”* is reported in the Glass Sand Member
- Well P-112 (Windsor-Kennetcook): *“Open vertical fractures”* are reported in the sandstone beds throughout the Horton Bluff Formation between the Cheverie Member and the basement.

As a general rule, the deliverability of potential aquifers can also improve significantly in the vicinity of faults, where a network of open, natural fractures can be present, especially if these fractures are sub-parallel to Sh_{max}. Although such sites are not suitable for EGS (see previous), they could be considered for a conventional geothermal system so long as the injection pressure does not exceed the maximum sustainable injection pressure.

Miscellaneous Information (2/2)

Increased geothermal gradients in the vicinity of permeable faults

Deep-rooted, permeable faults are excellent conduits for hydrothermal fluids and they often represent primary targets in geothermal exploration.

As mentioned in the Phase 1 Report, Chapter 6.1.3.1 (Comeau et al., 2020), Drury et al. (1987) discuss the existence of such deep-seated hydrothermal fluids migrating through fault conduits to explain the unexpectedly high geothermal gradients observed locally at shallow depths (less than 400 m) in the Stellarton sub-basin.

The original text from Drury et al. (1987) is reproduced below:

> *"402 (New Glasgow)*
>
> *Several holes were logged at site 402 in the Pictou basin of Nova Scotia, as part of an assessment of the geothermal energy potential of the area. Data from holes shallower than 400 m indicated gradients considerably higher-up to 32 mK/m-than those usually found in the region. One hole, however, was logged to a depth of 750 m; it penetrated mudstones and sandstones. A shear zone was detected at approximately 480 m. The temperature gradient in the hole changes from 32 mK/m above the zone to 14 mK/m below it. The shear zone also marks a lithological boundary, with mudstones above and sandstones below. A change in conductivity is associated with this lithological break, but it is insufficient to account for the change in gradient. Heat flow in the section 100-400 m is 19% higher than that in the interval 500-750 m. […] it is likely that the shear zone is a temperature control boundary caused by the upward flow of water from some greater depth."*

Reference:

- Drury, M.J., Jessop, A.M., Lewis, T.J., 1987. Thermal nature of the Canadian Appalachian crust. Tectonophysics, v. 133, p. 1-14. https://doi.org/10.1016/0040-1951(87)90276-9

Appendix B: Results Tables

Deep Geothermal, Base Cases, Greenhouse

Sub-Basin	Potential Aquifer	Facility	Depth (m)	Temp (°C)	Doublet (kW)	% Peak	% Energy	Number of borehole	Flowrate	NPV	Payback (years)	Monthly IRR
Cumberland	Boss Point Fm	Greenhouse (tomatoes)	1921	47	932	27%	36%	2	10	(37 690 000.00) $	N/A	N/A
	Claremont Fm		2300	55.03	1074	31%	41%	2	10	(33 988 000.00) $	N/A	N/A
	Lime-Kiln Brook Fm		2713	63.77	3696	106%	100%	2	30	(29 467 000.00) $	N/A	N/A
	Nuttby Fm		5092	114.31	3168	91%	94%	2	15	(58 321 000.00) $	N/A	N/A
Windsor-Kennetcook	Cheverie Fm		1384	40	810	23%	31%	2	10	(47 473 000.00) $	N/A	N/A
	Glass Sand Mb		1573	42.29	845	24%	33%	2	10	(56 931 000.00) $	N/A	N/A
	Mid. Horton Bluff Mb		1927	51.59	1021	29%	39%	2	10	(37 806 000.00) $	N/A	N/A
Stellarton	Thorburn Mb		243	12.93	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Coal Brook Mb		805	27.91	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Westville Mb		2024	57.43	1109	32%	42%	2	10	(38 473 000.00) $	N/A	N/A
	Skinner River Mb		2398	67.71	1303	37%	48%	2	10	(37 389 000.00) $	N/A	N/A
	Middle River Fm		2550	71.95	1373	39%	51%	2	10	(36 201 000.00) $	N/A	N/A

Notes:

- Cumberland/Lime-Kiln Brook (highlighted in green) is used as optimal base case and results presented in body of report.
- Thorburn and Coal Brook potential aquifers in the Stellarton sub-basin are not deep or hot enough for direct heating (243m at 14°C for Thorburn; 800m at 28°C for Coal Brook) and therefore omitted.

Deep Geothermal, Sensitivities, Greenhouse

Sensitivity analysis for the Cumberland sub-basin, Lime-Kiln Brook potential aquifer, including "best case" scenario:

		NPV ($)	NPV (% Impact)	Payback (years)	Payback (% Impact)	Monthly IRR	Monthly IRR (% Impact)
CAPEX	-25%	(35 971 000.00) $	-22.07%	N/A	N/A	N/A	N/A
	+25%	(40 046 000.00) $	-35.90%	N/A	N/A	N/A	N/A
Temperature & Depth	p90 = 90°C	(28 029 000.00) $	4.88%	N/A	N/A	N/A	N/A
	p10 = 41°C	(47 071 000.00) $	-59.74%	N/A	N/A	N/A	N/A
Permeability	min = 0.01 mD	(25 683 000.00) $	12.84%	N/A	N/A	N/A	N/A
	max = 400 mD	(24 685 000.00) $	16.23%	N/A	N/A	N/A	N/A
Cashdown	20%	(63 186 000.00) $	-114.43%	N/A	N/A	N/A	N/A
Discount Rate	7%	(24 608 000.00) $	16.49%	N/A	N/A	N/A	N/A
Subsidies	50%	(22 179 000.00) $	24.73%	N/A	N/A	N/A	N/A
	75%	(28 958 000.00) $	1.73%	N/A	N/A	N/A	N/A
Electricity Rates	-15%	(28 450 000.00) $	3.45%	N/A	N/A	N/A	N/A
	+30%	(30 067 000.00) $	-2.04%	N/A	N/A	N/A	N/A
Biomass Costs	$60/t	(28 867 000.00) $	2.04%	N/A	N/A	N/A	N/A
	$90/t	(28 228 000.00) $	4.20%	N/A	N/A	N/A	N/A
Facility Size	Base (8 acres) x2	(27 984 000.00) $	5.03%	N/A	N/A	N/A	N/A
	Base (8 acres) x3	(29 252 000.00) $	0.73%	N/A	N/A	N/A	N/A

			NPV ($)	NPV (% Impact)	Payback (years)	Payback (% Impact)	Monthly IRR	Monthly IRR (% Impact)
Greenhouse "Best Case"	CAPEX	-25%	(15 627 000.00) $	47%	N/A	N/A	N/A	N/A
	Temperature & Depth	Base: p50						
	Permeability	12 mD						
	Cashdown	20%						
	Discount Rate	20%						
	Subsidies	50%						
	Electricity Rates	-15%						
	Biomass Costs	Base: $75/t						
	Facility Size	Base x2						

Ground Source Heat Pump, Base & Sensitivity, Greenhouse

dunsky

Ground source heat pump base case and sensitivity financial analysis results for the greenhouse archetype:

		Higher CAPEX (+25%)	Lower CAPEX (-25%)	Double tomato production	Lower Biomass Price (-20%)	Higher Biomass Price (+20%)	Lower Electricity Price (-15%)	Lower Electricity Price (-30%)	Subsidies (50%)	Subsidies (75%)
	Baseline	S1	S2	S3	S4	S5	S6	S7	S8	S9
Parameters										
Capex (multiplier)	**1**	**1.25**	**0.75**	1	1	1	1	1	1	1
Crop	Tomato	Tomato	Tomato	**tomato x 2**	Tomato	Tomato	Tomato	Tomato	Tomato	Tomato
Biomass price ($/T)	75	75	75	75	**60**	**90**	75	75	75	75
Electricity price (multiplier)	Large Commercial	Large Commercial	Large Commercial	Large Commercial	Large Commercial	Large Commercial	**85%**	**70%**	Large Commercial	Large Commercial
Cashdown (%)	20	20	20	20	20	20	20	20	20	20
Discount rate	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%
Subsidies	0%	0%	0%	0%	0%	0%	0%	0%	**50%**	**75%**
Results										
NPV	-$ 4,831,696.40	-$ 6,013,020.37	-$ 3,650,372.43	-$ 8,862,604.64	-$ 5,959,941.31	-$ 3,703,451.48	-$ 4,543,260.32	-$ 4,254,824.24	-$ 2,469,048.46	-$ 1,287,724.48
Return period (Years)	No payback	No payback	No payback	No payback	No payback	No payback	No payback	No payback	No payback	No payback
IRR	NAN	NAN	NAN	NAN	NAN	NAN	NAN	NAN	NAN	7%
NPV relative to baseline	-	-24.4%	24.4%	-83.4%	-23.4%	23.4%	6.0%	11.9%	48.9%	73.3%

Deep Geothermal, Base Cases, Aquaculture

dunsky

Sub-Basin	Potential Aquifer	Facility	Depth (m)	Temp (°C)	Doublet (kW)	% Peak	% Energy	Number of borehole	Flowrate	NPV	Payback (years)	Monthly IRR
Cumberland	Boss Point Fm	Aquaculture	1921	47	932	18%	23%	2	10	(24 148 000.00) $	N/A	N/A
	Claremont Fm		2300	55.03	1611	32%	38%	2	15	(17 842 000.00) $	N/A	N/A
	Lime-Kiln Brook Fm		2713	63.77	4313	85%	91%	2	35	(5 019 000.00) $	N/A	0.93%
	Nuttby Fm		5092	114.31	3168	63%	71%	2	15	(38 974 000.00) $	N/A	N/A
Windsor-Kennetcook	Cheverie Fm		1384	40	809	16%	20%	2	10	(41 366 000.00) $	N/A	N/A
	Glass Sand Mb		1573	42.29	844	17%	21%	2	10	(53 778 000.00) $	N/A	N/A
	Mid. Horton Bluff Mb		1927	51.59	1021	20%	25%	2	10	(24 256 000.00) $	N/A	N/A
Stellarton	Thorburn Mb		243	12.93	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Coal Brook Mb		805	27.91	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Westville Mb		2024	57.43	1109	22%	27%	2	10	(27 035 000.00) $	N/A	N/A
	Skinner River Mb		2398	67.71	1303	26%	31%	2	10	(23 718 000.00) $	N/A	N/A
	Middle River Fm		2550	71.95	1373	27%	33%	2	10	(21 277 000.00) $	N/A	N/A

Notes:

- Cumberland/Lime-Kiln Brook (highlighted in green) is used as optimal base case and results presented in body of report.
- Thorburn and Coal Brook potential aquifers in the Stellarton sub-basin are not deep or hot enough for direct heating (243m at 14°C for Thorburn; 800m at 28°C for Coal Brook) and therefore omitted.
- Initial runs in the Cumberland sub-basin included biomass as the reference fuel. These scenarios were omitted in the end since biomass always proved to be more profitable than fuel (confirmed for the Nuttby with the use of an aux. biomass system).

Deep Geothermal, Sensitivities, Aquaculture

Sensitivity analysis for the Cumberland sub-basin, Lime-Kiln Brook potential aquifer, including "best case" scenario:

		NPV ($)	NPV (% Impact)	Payback (years)	Payback (% Impact)	Monthly IRR	Monthly IRR (% Impact)
CAPEX	-25%	1 493 200.00 $	130%	13.21	N/A	2%	78%
	+25%	(11 531 000.00) $	-130%	N/A	N/A	0%	-55%
Temperature & Depth	p90 = 90°C	(10 350 000.00) $	-106%	N/A	N/A	1%	-30%
	p10 = 41°C	(10 807 000.00) $	N/A	N/A	N/A	N/A	N/A
Permeability	min = 0.01 mD	(12 913 000 000.00) $	-257182%	N/A	N/A	N/A	N/A
	max = 400 mD	5 423 800.00 $	208%	7.96	N/A	2%	119%
Cashdown	20%	(231 490.00) $	95%	N/A	N/A	1%	58%
Discount Rate	7%	9 759 600.00 $	294%	16.04	N/A	1%	0%
Subsidies	50%	(154 570.00) $	97%	N/A	N/A	1%	56%
	75%	2 277 700.00 $	145%	8.21	N/A	2%	140%
Electricity Rates	-15%	(3 612 100.00) $	28%	N/A	N/A	1%	16%
	+30%	(6 426 000.00) $	-28%	N/A	N/A	1%	-17%
Fuel Oil Costs	$1/L	(8 185 900.00) $	-63%	N/A	N/A	1%	-38%
	$1.5/L	3 994 400.00 $	180%	9.38	N/A	2%	102%
Tank Volume Changes (per hour)	Base (2.5 volume changes) x 0.5	(17 141 000.00) $	-242%	N/A	N/A	N/A	N/A
	Base (2.5 volume changes) x 2	(3 132 100.00) $	38%	N/A	N/A	1%	21%
Tank Water Temperatures	12C	(9 865 700.00) $	-97%	N/A	N/A	0%	-64%
	10C	(12 350 000.00) $	-146%	N/A	N/A	0%	-133%

			NPV ($)	NPV (% Impact)	Payback (years)	Payback (% Impact)	Monthly IRR	Monthly IRR (% Impact)
Aquaculture "Best Case"	CAPEX	-25%	19 521 000.00 $	489%	2.75	NAN	4%	326%
	Temperature & Depth	Base: p50						
	Permeability	12 mD						
	Cashdown	20%						
	Discount Rate	7%						
	Subsidies	50%						
	Electricity Rates	-15%						
	Fuel Oil Costs	Base: $1.13/L						
	Tank Volume Changes	Base: 2.5						
	Tank Water Temperature	14°C						

Ground Source Heat Pump, Base & Sensitivity, Aquaculture

Ground source heat pump base case and sensitivity financial analysis results for the aquaculture archetype:

		Higher CAPEX (+25%)	Lower CAPEX (-25%)	75% Less Flow	90% Less Flow	100% More Flow	Lower Tank Water Temp (10 Celsius)	Lower Tank Water Temp (12 Celsius)	Lower Fuel Oil Prices ($1/L)	Higher Fuel Oil Prices ($1.5/L)	Higher Electricity Prices (+15%)	Lower Electricity Prices (-15%)	Subsidies (50%)	Subsidies (75%)
	Baseline	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
Parameters														
CAPEX (multiplier)	1.00	1.25	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Tank flowrate (L/S)	208.33	208.33	208.33	**52.08**	**20.83**	**416.67**	208.33	208.33	208.33	208.33	208.33	208.33	208.33	208.33
Tank water temperature (C)	14	14	14	14	14	14	**10**	**12**	14	14	14	14	14	14
Fuel price ($/L)	$ 1.13	$ 1.13	$ 1.13	$ 1.13	$ 1.13	$ 1.13	$ 1.13	$ 1.13	**$ 1.00**	**$ 1.50**	$ 1.13	$ 1.13	$ 1.13	$ 1.13
Electricity price (multiplier)	1	1	1	1	1	1	1	1	1	1	**1.15**	**0.85**	1	1
Cashdown (%)	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Discount rate	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%
Subsidies	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**50%**	**75%**
Results														
NPV	$ 50,784,513.45	$ 49,065,753.18	$ 52,503,273.73	$ 28,379,831.90	$ 23,898,895.59	$ 80,657,422.19	$ 44,231,528.05	$ 48,408,234.86	$ 42,784,561.82	$ 73,553,606.56	$ 48,846,230.96	$ 52,722,795.94	$ 54,222,034.00	$ 55,940,794.27
Return period (Years)	0.33	0.83	0.25	0.33	0.33	0.33	0.75	0.5	0.833333333	0.25	0.416666667	0.333333333	0.083333333	0
IRR	16%	11%	25%	23%	30%	14%	14%	15%	13%	26%	15%	17%	49%	188%
NPV relative to baseline	-	-3%	3%	-44%	-53%	59%	-13%	-5%	-16%	45%	-4%	4%	7%	10%

Deep Geothermal, Base Cases, District Heating

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Sub-Basin	Potential Aquifer	Facility	Depth (m)	Temp (°C)	Doublet (kW)	% Peak	% Energy	Number of borehole	Flowrate	NPV	Payback (years)	Monthly IRR
Cumberland near the city of Amherst	Boss Point Fm	District heating	2812.3	65.72	1267	113%	100%	2	10	(66 210 000.00) $	N/A	N/A
	Claremont Fm		3191.3	73.75	1408	126%	100%	2	10	(70 875 000.00) $	N/A	N/A
	Lime-Kiln Brook Fm		3459	78.21	1479	132%	100%	2	10	(75 903 000.00) $	N/A	N/A
	Nuttby Fm		Absent	Absent	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Windsor-Kennetcook (values taken from aquaculture and greenhouse)	Cheverie Fm		1384	40	810	73%	99%	2	10	(69 929 000.00) $	N/A	N/A
	Glass Sand Mb		1573	42.29	845	76%	100%	2	10	(84 853 000.00) $	N/A	N/A
	Mid. Horton Bluff Mb		1927	51.59	1021	91%	100%	2	10	(60 458 000.00) $	N/A	N/A
Stellarton	Thorburn Mb		243	12.93	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Coal Brook Mb		805	27.91	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Westville Mb		2024	57.43	1109	99%	100%	2	10	(57 538 000.00) $	N/A	N/A
	Skinner River Mb		2398	67.71	1303	117%	100%	2	10	(60 797 000.00) $	N/A	N/A
	Middle River Fm		2550	71.95	1373	123%	100%	2	10	(61 748 000.00) $	N/A	N/A

Notes:

- Stellarton/Westville (highlighted in green) is used as optimal base case and results presented in body of report.
- Thorburn and Coal Brook potential aquifers in the Stellarton sub-basin are not deep or hot enough for direct heating (243m at 14°C for Thorburn; 800m at 28°C for Coal Brook) and therefore omitted.

Deep Geothermal, Sensitivities, District Heating

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Sensitivity analysis for the Stellarton sub-basin, Westville potential aquifer, including "best case" scenario*:

		NPV ($)	NPV (% Impact)	Payback (years)	Payback (% Impact)	Monthly IRR	Monthly IRR (% Impact)
CAPEX	-25%	(46 357 000.00) $	19%	N/A	N/A	N/A	N/A
	+25%	(68 719 000.00) $	-19%	N/A	N/A	N/A	N/A
Temperature & Depth	p90 = 90°C	N/A	N/A	N/A	N/A	N/A	N/A
	p10 = 41°C	N/A	N/A	N/A	N/A	N/A	N/A
Permeability	min = 0.01 mD	(248 360 000.00) $	-332%	N/A	N/A	N/A	N/A
	max = 400 mD	(47 695 000.00) $	17%	N/A	N/A	N/A	N/A
Cashdown	20%	(56 613 000.00) $	2%	N/A	N/A	N/A	N/A
Discount Rate	4%	(84 269 000.00) $	-46%	N/A	N/A	N/A	N/A
Subsidies	50%	(53 543 000.00) $	7%	N/A	N/A	N/A	N/A
	75%	(51 545 000.00) $	10%	N/A	N/A	N/A	N/A
Electricity Rates	-15%	(56 159 000.00) $	2%	N/A	N/A	N/A	N/A
	+30%	(58 916 000.00) $	-2%	N/A	N/A	N/A	N/A
Fuel Oil Costs	$1/L	(58 324 000.00) $	-1%	N/A	N/A	N/A	N/A
	$1.5/L	(55 300 000.00) $	4%	N/A	N/A	N/A	N/A
Number of Units	Base x 0.5 (25 units)	(57 633 000.00) $	0%	N/A	N/A	N/A	N/A
	Base x 2 (100 units)	(58 482 000.00) $	-2%	N/A	N/A	N/A	N/A
Project Load Factor	Base x 3	(58 446 000.00) $	-2%	N/A	N/A	N/A	N/A
	Base x 2	(59 964 000.00) $	-4%	N/A	N/A	N/A	N/A

			NPV ($)	NPV (% Impact)	Payback (years)	Payback (% Impact)	Monthly IRR	Monthly IRR (% Impact)
District Heating "Best Case"	CAPEX	-25%	12 392 000.00 $	1.22 $	6.21	NAN	2%	NAN
	Temperature & Depth	Base: p50						
	Permeability	12 mD						
	Cashdown	20%						
	Discount Rate	7%						
	Subsidies	50%						
	Electricity Rates	-15%						
	Fuel Oil Costs	Base: $1.13/L						
	Number of Units	Base x 2 (200 units)						
	Project Load Factor	Base x 2						

***Note:** The "Best Case" scenario was relocated to Cumberland/Lime-Kiln Brook potential aquifer with a doublet capable of supplying 2,957 kW, operated at 20 L/s and a heating load of four times the base case. The reference system uses fuel oil and covers up to 4,000 kW of a 4,467 kW peak.

Results Tables

Ground Source Heat Pump, Base & Sensitivity, District Heating

Ground source heat pump base case and sensitivity financial analysis results for the district heating archetype:

		Lower CAPEX (-25%)	Higher CAPEX (+25%)	Less buildings (25 Homes + Shops)	More buildings (100 Homes + Shops)	More buildings (200 Homes + Shops)	Smoother Load (Max/Avg = 3)	Smoother Load (Max/Avg = 2)	Lower Fuel Oil Prices ($1/L)	Higher Fuel Oil Prices ($1.5/L)	Lower Electricity Prices (-15%)	Higher Electricity Prices (+15%)	Subsidies (50%)	Subsidies (75%)
	Baseline	S1	S2	S3	S4		S5	S6	S7	S8	S9	S10	S11	S12
Parameters														
CAPEX (multiplier)	1.00	0.75	1.25	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Number of units	50.00	50.00	50.00	25.00	100.00	200.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
Load factor	4.28	4.28	4.28	4.28	4.28	4.28	3.00	2.00	4.28	4.28	4.28	4.28	4.28	4.28
Fuel price ($/L)	$ 1.13	$ 1.13	$ 1.13	$ 1.13	$ 1.13	$ 1.13	$ 1.13	$ 1.13	$ 1.00	$ 1.50	$ 1.13	$ 1.13	$ 1.13	$ 1.13
Electricity price (multiplier)	1	1	1	1	1	1	1	1	1	1	0.85	1.15	1	1
Cashdown (%)	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Discount rate	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%
Subsidies	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	50%	75%
Results														
NPV	$5,153,715.73	$5,777,682.01	$4,529,749.44	$4,037,488.89	$7,386,168.88	$11,850,962.01	$8,403,993.86	$13,829,544.45	$4,095,608.14	$8,165,252.71	$5,453,640.35	$4,853,791.10	$6,401,648.29	$7,025,614.58
Return period (Years)	3.83	2.00	6.08	3.25	4.00	4.08	2.00	1.08	5.08	2.00	3.08	4.08	1.00	0.08
IRR	3%	4%	2%	3%	2%	2%	4%	7%	2%	5%	3%	2%	9%	45%
NPV relative to baseline	-	12.1%	-12.1%	-21.7%	43.3%	129.9%	63.1%	168.3%	-20.5%	58.4%	5.8%	-5.8%	24.2%	36.3%

Appendix C: GHG Emissions

Emissions Intensity Factors by Fuel Type

	Emissions Factor (CO_2e/unit)	System Efficiency (%)	Notes
Biomass	21.1 g of CO2e/kg of wood (residual biomass @ 35% humidity)	Biomass boiler = 75% efficiency	Based on an emissions factor of 35.9 g of CO2e/kg of dry wood; this factor considers the carbon cycle of wood as opposed to emissions at source.
Propane	1.54 kg of CO2/L	Propane boiler = 82% efficiency	
Fuel Oil	2.72 kg CO2/L	Oil boiler = 85% efficiency	
Electricity	Varies by year; average of 0.03041 tCO_2e/GJ from 2021-2061	Electric systems = 100% efficiency	Annual emissions factor from NSPI IRP Scenario 3.1C that assumes a coal phase out by 2030.

Note on Carbon Pricing:

Carbon costs are added to electricity rates and fuel costs. For electricity, Nova Scotia-specific costs are used is 2021-2023, after which the federal backstop is used.

Appendix D: Sources & References

List of Industry Experts

Name	Title and Organisation
Greenhouse and biomass industry experts	
Arjen van Eekelen	Sales representative, Prins Greenhouses
Kraig Porter	Onsite Energy Manager: Agriculture, Efficiency Noca Scotia
Luke den Haan	Greenhouse owner, Den Haan Greenhouse
Andy Wright	Project Manager, Great Northern Timber
Cory	Project Manager, Taylor Lumber
Dany Boudreault	Greenhouse agronomist, Climax-Conseil
Aquaculture industry expert	
Donald Davis	Director of Corporate Services, Wycobah First Nation Fishery

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Greenhouse	
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Halifax hourly temperature:	Canadian Weather Year for Energy Calculation (CWEC): https://climate.weather.gc.ca/prods_servs/engineering_e.html
Mean daily global insolation (MJ/m^2):	NRCan insolation web-based maps: https://fgp-pgf.maps.arcgis.com/apps/webappviewer/index.html?id=c91106a7d8c446a19dd1909fd93645d3
Halifax monthly average sunshine hours:	https://www.currentresults.com/Weather/Canada/Cities/sunshine-annual-average.php
Halifax sunrise and sunset:	https://www.sunrise-and-sunset.com/en/sun/canada/halifax
Halifax dry bulb temperature (design conditions):	American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE), 2009, Chapter 14: Climatic Design Information
Greenhouse setpoint temperatures:	Greenhouse agronomist consulting firm Climax Conseils
Glass solar radiation transmission:	Greenhouse industry manufacturers (Prins Greenhouse, Kubo and Havecon)
Thermal screen heat transfer coefficient:	Greenhouse industry manufacturer (Svensson)

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