NOVA SCOTIA GEOTHERMAL INVESTIGATION PROPOSAL

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Introduction

Over the past few years, Netzero Atlantic [previously the Offshore Energy Research Association of Nova Scotia (OERA)] has funded research aimed at reducing the risk of and encouraging geothermal development within the province. This work was conducted in two phases. Phase 1 provided a province-wide assessment of geothermal potential that used relevant data to characterize the properties and rank the geothermal favourability of different regions for future development (OERA, 2020). Phase 2 complimented the initial assessment by providing an economic analysis of 3 types of direct-use geothermal projects based on the parameters from the province-wide assessment (OERA, 2021). Both Phase 1 and Phase 2 have identified significant gaps in subsurface understanding that could be filled to better evaluate the potential for, and feasibility of, a future geothermal project in Nova Scotia. Specifically, more subsurface data needs to be gathered to better constrain subsurface temperature, structure, porosity, permeability, and water composition.

To pursue any future geothermal energy developments, Nova Scotia needs to gather this data. We do not see any option for advancement except drilling one or more exploration wells. For these wells to be helpful, they not only need to be located in geologically preferred settings, they also need to be located in commercially viable settings. This is to say that, while scientifically helpful, exploration wells drilled outside of an economic radius of relevant demand will have no value from a development perspective.

However, before drilling there may be additional exploration work that could be done to help site these wells. Following this potential additional exploration work, new wells could be drilled and tested to gather information and constrain important reservoir properties.

The data gathered from these exploration wells could be used to ultimately determine if geothermal development is feasible in Nova Scotia and outline a plan for future development.

Base Assumptions

What follows assumes that geothermal is the only exploration priority in the region. Were this false, and other mineral and/or hydrocarbon exploration also be a priority, then the proposed program would have a naturally different character and scope, as all efforts would need to be made to optimize the program to obtain information for all relevant exploration priorities.

Further, we have not tested the possibility of drilling outside of Nova Scotia, elsewhere in the Atlantic region. There may be more prospective areas to develop geothermal within Atlantic Canada, but this is not part of this work.

Current Subsurface Understanding

From the previous work, a high-level understanding of the geothermal potential of Nova Scotia has been formed to help guide future, more detailed studies. This includes the characterization of geothermal gradients across the province, which were generally found to be at or below the continental average of 25-30 °C/km. Metamorphic and igneous bedrock in the southern portion of the province have the lowest gradients at 12.6-17.9 °C/km. Slightly higher gradients are found in the many subbasins of the Maritimes Basin, the highest of which occur in the Cumberland, Stellarton, and Windsor-Kennetcook basins at 21.2-26.2 °C/km (OERA, 2020). To accommodate for these low gradients, future geothermal projects will need to drill deep wells to reach useable temperatures.

Additionally, the current record of rock property data suggests that the formations that make up the sedimentary basins in Nova Scotia are only modestly permeable with permeabilities in the low 10's of mD for the most prospective aquifers (Cen, 2017). With permeabilities in this range, horizontal production and injection wells would need to be drilled to achieve the required flow rate for direct use geothermal. Both the deeper drilling depths and requirements for horizontal drilling increase the capital costs of future geothermal projects.

However, these permeability values have been obtained from a limited amount of surface and subsurface data, mostly collected for onshore hydrocarbon exploration in the province, and it is possible for select areas of the subsurface to have both higher temperatures and permeability. Rock formations are heterogenous and will contain zones related to their original depositional setting that are more permeable than other parts of the formation. Additionally, the previous studies have recognized that features such as faults or salt diapirs could locally increase the temperature and/or permeability of the subsurface in some unexplored parts of the province.

In our opinion, moving directly to production drilling, in Nova Scotia's current state of knowledge, would be too risky. We would recommend that further exploration could better identify and characterise the geothermal zones of high potential and improve the economics for future geothermal energy in the region.

Exploration Plan

To improve the understanding of the subsurface and better evaluate the province's geothermal potential, Nova Scotia needs to drill and collect data from exploration wells.

Wells provide an opportunity to directly test the formations examined in the previous studies and evaluate their potential, as well as provide an opportunity examine areas not previously explored by the oil and gas industry, helping to fill in gaps in subsurface knowledge. If an economically viable geothermal resource is found in this evaluation, then plans can be made to drill a pair of production and injection wells and construct surface infrastructure.

Drilling exploration wells is costly and drilling across all basins in the province can not reasonably be funded. Instead, efforts should focus on the most prospective area in the province, with the goal of developing a working project. After evaluation of the most prospective area in the province, it can be determined whether exploration into other parts of the province is worthwhile.

The Cumberland Basin has been identified by prior work as the area with the highest estimated geothermal temperature gradients in Nova Scotia and is also one of the basins in the province with the most subsurface data. It is the best region to focus future geothermal exploration efforts. The adjacent Stellarton Basin should also be considered in the analysis as it has some exceedingly high geothermal gradients (over 30 °C/km with a “good” level of confidence); however, it has much less data than the Cumberland basin and will play a limited role in the analysis unless more data is gathered in the region.

PRE-DRILLING

Before exploration wells can be drilled, careful evaluation of the subsurface must be done to site the wells including:

- Examination of seismic data collected by the government for hydrocarbon exploration.
- Correlation of porosity and permeability of formations from well logs and core samples to model the distribution of permeable zones in the subsurface, with consideration to how they relate to their original depositional settings.
- Careful consideration of locations of geothermal gradient measurements and potential structures that could locally increase thermal gradients.
- Incorporation of all data into a 3D model to help site the drilling targets.

Further exploration work could also be done before drilling, such as:

- Acquiring the internal interpretation and analysis from Oil & Gas explorers, subject to their willingness to share.
- Reprocessing of existing seismic data to improve resolution.
  - Seismic data from the Cumberland County could also be further processed with a depth conversion, allowing for modeling the of the seismic in 3D.
- Collection of additional seismic data to fill in gaps near a location of interest (as needed).
- Possibly the re-measurement of temperature gradients in suspended wells.

If possible, the measurement of new temperature data from existing hydrocarbon wells could help direct exploration. In the Nova Scotia Petroleum Well Database there are 7 wells listed as “suspended” that might be possible to re-enter (Table 1). They are located in the western portion of the Cumberland Basin and the Stellarton Basin. Phase 1 ranked most of the temperature measurements as “good” quality. The temperature gradients calculated for these wells range from ~26 °C/km in the Cumberland Basin to 26.7-38.7 °C/km in the Stellarton Basin (OERA, 2020).

Confirmation of these gradients could help justify the selection of a smaller area for a focused exploration campaign, but the status of these wells and the ability to re-enter the well would need to be confirmed.

Table 1. A list of the onshore oil wells in Nova Scotia that are classified as suspended (Nova Scotia Department of Energy, n.d.)

Well #	Well Name	Company	Spud Date	Rig Release	Total Depth (m)	Latitude, Longitude	Geographic Location
115	ECA 400-2	EnCana Corporation	05-Nov-02	18-Nov-02	912	45.57425, -62.61661	Stellarton; Pictou Count
118	Priestville #3	Amvest Oil & Gas	02-Nov-02	15-Jan-05	619.7	45.5634578, -62.609977	MacLellans Brook; Pictou County
122	Coal Mine Brook #3	Stealth Ventures Ltd.	22-Jan-06	25-Feb-06	1,270.13	45.646944, -64.091667	Cumberland County
124	Coal Mine Brook #12	Stealth Ventures Ltd.	23-Aug-06	14-Sep-06	1,040.17	45.6418066, -64.092139	Springhill; Cumberland County
125	Coal Mine Brook #13	Stealth Ventures Ltd.	17-Sep-06	06-Oct-06	1,156.55	45.6415278, -64.092	Springhill; Cumberland County
138	ECE-13-P1	East Coast Energy Inc.	06-Nov-13	16-Nov-13	700	45.5667069, -62.6145333	Pictou County
139	ECE-13-P2 Hz	East Coast Energy Inc.	21-Nov-13	03-Dec-13	622	45.5614194, -62.621268	Pictou County

DRILLING TARGET SELECTION

For these new exploration wells to be helpful, they not only need to be located in geologically preferred settings, they also need to be located in commercially viable settings. This requires several other factors to be considered when siting the wells including:

- A minimum aquifer temperature for useful heat production, approximately 60 °C assuming a 30 °C cut off for return temperature for produced geothermal fluid.
- Surface location, must be within ~5 km of a potential heat market, preferably an industrial load with high uptime.

- The heat market at the surface should have enough demand to make full use of the available produced heat.
    - With a minimum practical temperature of 60 °C and 97% uptime, this suggests minimum market size of ~ 135,000 GJ/year
    - Higher temperature geothermal plays will require commensurately larger energy sales

With both a prospective customer and model of the subsurface, a preliminary economic analysis can be done to determine if the project is feasible using the hypothesized parameters before any actual drilling is done. These results need to be positive to justify drilling exploration wells.

The key economic output is the $/GJ for heat at customer plant gate. In arriving at this figure, the analysis needs to rely on actual quotes from drilling and facilities vendors for geothermal drilling and surface construction in and around the Cumberland basin.

With these considerations and the results of the pre-drilling exploration and economic analysis in mind, a location for a set of exploration wells can be selected. Targets should be selected at depths no deeper than ~4 km, as that is the practical drilling limit for placing a ~1 km horizontal in the subsurface. Ideally, multiple wells would be drilled to investigate a single area as each well only provides a good snapshot of the subsurface for near wellbore regions and heterogeneity in reservoir properties, even on relatively short distances, can be significant.

The number of wells drilled, and depth of these wells, will likely be constrained by the budget. For the purposes of a stratigraphic/exploration well, the well should remain vertical to reduce exploration costs. Given the expected permeability of the subsurface, a vertical well will not be able to supply the flow rates required for a production well; however, it may be possible to re-enter the well and drill a horizontal leg at a later date. While the cost of drilling in Nova Scotia in not known, in Alberta and Saskatchewan where equipment is readily available, costs are typically ~$1,000/m. The mobilization fees to transport equipment to Nova Scotia will significantly increase these costs, but the amount of this increase is not known.

It is recommended that the first well is drilled the deepest target depth to allow for testing of all formations of interest on the initial hole. The results from the initial well will then dictate what formations are targeted with subsequent wells. Alternatively, if only one exploration well is to be drilled it is also recommended to drill to the deepest target as the incremental cost of adding depth is minimal compared to the cost of organising a second campaign and drilling another well. Lastly, in addition to drilling costs, the costs of testing while drilling and associated laboratory fees should be budgeted for.

DRILLING AND TESTING

With targets identified, data can be collected through drilling. Developing a solid drill plan will be critical as there are not many data points so choice of equipment such as bit and rig type will be critical to maintaining a decent rate of penetration (ROP). Consultation should be done with the drilling contractor to ensure that the appropriate equipment is selected for drilling and flow testing. During the drilling of the wells various parameters will be continuously monitored for including:

- Lithology of the returned cuttings and their correlation to the expected subsurface lithology.
- Temperature/conductivity of the drilling returns, useful for identifying when different aquifers are encountered.
- Pressure of the subsurface.
- Various drilling parameters such as torque, ROP, etc.

At the target intervals, flow testing will be conducted using a triple or double packer system to isolate the interval from the rest of the well bore. Packers should be set in competent formations above and below (if necessary) the interval to prevents fluid from other formations from leaking into the producing zone. Each flow test will start with a short flow and shut-in period, followed by a longer flowing period of at least 2 hours with a recovery period at least as long, if not longer. The second portion of the test should be run for as long as possible to investigate a larger portion of the subsurface formation and get a better estimate of reservoir properties. Each of the flow tests will provide the following information:

- Reservoir pressure
- Temperature of produced fluids
- An estimate of reservoir permeability
- Multiple fluid samples of the reservoir

A key assumption which lowers overall costs is that the wells will not be cored, unless there is some other overriding reason for doing so. The best estimate of formation permeability will result from a pressure test, and not lab measurements of core properties. Accordingly, we have excluded coring from the testing plan.

For budgeting purposes, it is estimated that each flow test will take 1-2 days and that anywhere between 3-7 zones will be tested per well (the Phase 1 study identified 5 formations of interest in the Cumberland Basin: Boss Point Formation, the Claremount Formation, the Windsor Group Carbonates, the upper Horton Group, and the basal sediments above the basement). Upon completion of drilling, wireline tools will be run down the well in addition to an initial thermal gradient measurement.

Following these last wireline surveys, a decision can be made on how to complete the well. The results from the flow test will dictate which intervals are of interest for continued monitoring and which intervals can cased over. After completion, several temperature measurements should be taken in the following weeks and months to get a reliable geothermal gradient for the well. The completion scheme may allow for the permanent installation of fibre optic cable for continuous temperature monitoring. Additionally, if the well completion scheme and budget allow, a longer flow test could be conducted after the drilling rig has moved offsite to better estimate reservoir properties.

In addition to the drilling, we may want to measure the local heat flux, at a few locations, in and around the well bore, as this will provide a measure of the regenerative capability of the production well.

FINAL ANALYSIS

With exploration complete, the newly collected data will need to be evaluated to determine if it is feasible to build a geothermal project in the newly explored area. With the results of the flow testing, the flow rate, temperature, and chemistry of the prospective geothermal reservoir(s) will have low uncertainty, allowing for the production potential of a production well to be accurately calculated. Using the new data, a production and injection well pair will be designed and targeted, and this design will be used in an economic analysis. This analysis will determine the feasibility of a geothermal project using the following parameters:

- Production capability and temperature of the geothermal aquifer
- Depth/cost of the production and injection wells
- Length of the horizontal producing and injection zones within the wells
- Capital cost of constructing surface facilities
- Future interest rates
- Carbon credit pricing
- Customer demand
- Cooling of the reservoir over time

This will ultimately determine if a project is feasible. If results are positive, plans can then be made to drill a pair of production and injection wells. Additional budget and permits should be reserved for the drilling for more than 2 wells as subsurface heterogeneities make it impossible to guarantee that the first 2 wells will form a suitable production/injection system. Thought should also be given to the drilling of additional wells after the project is operational for expansion purposes or maintenance of the reservoir. If it is not economically feasible to go forward with the project, and if the budget allows, another area could be investigated using a similar exploration plan. Otherwise, further exploration and development may need to wait until new technologies are developed that make geothermal projects more feasible.

Execution Timeline

Table 2. A summary of the time, cost, tasks and results for each phase of the proposed project.

Work Phase	Time	Cost	Tasks	Results
Desktop Study	2 weeks to 1 month	TBD	- Gather compiled data and models from the Phase 1 and 2 studies - Research depositional history of previously identified potential aquifers - Interpret seismic data, determine benefit of reprocessing/collecting more data - Map locations of potential heat customers	- Greater understanding of the subsurface and hypothesized model of permeability distributions for the potential aquifers - Initial model of subsurface, with initial areas of interest near potential customers identified - Plan for the collection of additional data
Additional Seismic Surveys (Optional)	Up to 6 months to permit, 1 month to collect, 1 month to process	TBD	- Target and permit locations for the survey - Find contractors to collect and process the seismic data - Interpret the data and incorporate into subsurface model	- New, interpreted seismic data - Better constrained subsurface target locations
Seismic Data Re-processing (Optional)	1 month, provided old reports and data can be found	TBD	- Gather raw seismic data and previous processing reports - Contract out and reprocess the seismic data - Interpret the data and incorporate into subsurface model	- Depth converted seismic data and a 3D model made using this data - Better constrained subsurface target locations
Well Gradient Measurement (Optional)	3 months to permit, 1-2 weeks to collect	TBD	- Determine which wells, if any, can be re-entered, and get permission to measure the well - Create and conduct a measurement program for the well - Interpret the data and incorporate into subsurface model	- Confirmation of surface temperatures - Better constrained subsurface target locations

Work Phase	Time	Cost	Tasks	Results
Acquisition of Oil and Gas Data (Optional)	1-4 weeks	TBD	- Contact companies that have previously conducted exploration in the province and ask for additional data - Incorporate new data and interpretations into subsurface model	- Additional data and interpretation of the subsurface - More accurate subsurface model
Drilling Target Selection	1-2 weeks to select targets, 6 months to permit and select drilling company	TBD	- Gather all data into a subsurface model - Identify target aquifers near potential customers - Select surface drilling locations and design wells - Conduct a preliminary economic analysis to determine if predicted reservoir properties result in an economic project - Apply for drilling permits - Determine costs and select contractors for drilling and testing	- Surface and subsurface drilling locations - Confirmation that the hypothesized reservoir is an economic target - Completed well designs - Drilling permits - Drilling contractor with suitable equipment for drilling and testing
Drilling and Testing	1-2 months per well	TBD	- Move equipment into the province - Drill the wells, test at selected intervals - After drilling, conduct final well logs and complete the well - Continue with longer term testing as required - Send samples to lab for analysis	- New geothermal exploration wells - Information of reservoir properties, confirmation of reservoir temperature
Economic Analysis	2-3 weeks	TBD	- Interpret results of drilling campaign, design a theoretical production well - Use theoretical production well design and formation properties to accurately determine the feasibility of a future project - Make recommendations for future development	- Preliminary production well design - Ultimate determination of the feasibility of geothermal in Nova Scotia - Plans for future development

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