PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 11-13, 2019
SGP-TR-214

Reconnaissance Study of Low-temperature Geothermal Resources in Southwestern Ontario

Sara Shahmohammadi[1], Pooneh Maghoul[2]

[1]HYBRIXCEL INC., [2]Civil Engineering Department, University of Manitoba, Winnipeg, Canada

[1]Sara.Shahmohammadi@hybrixcel.com, [2]Pooneh.Maghoul@umanitoba.ca

Keywords: Reconnaissance, geothermal resources assessment, low temperature, EGS, sedimentary basin, Canada geothermal

ABSTRACT

The interest in recovering the geothermal energy stored in sedimentary basins for electricity production is growing. Most sedimentary basins have been explored for oil and gas and therefore reservoir and geophysical data such as depth to basement and formation thickness are well known. The availability of this data reduces the exploration risk and allows the development of geologic exploration models for each basin.

The main goal of this paper is to carry out a reconnaissance study of the potential thermal energy stored in deep subsurface (3-5 km depth) from the Engineered Geothermal System (EGS) sedimentary resources in Southwestern Ontario and identify a prospective production area for geothermal energy exploitation. The industrial thermal data from the bottom-hole temperature resources of the oil sand regions of Michigan Basin was applied in order to provide a first order assessment of deep geothermal potential for electricity and heat generation. A technical and an economical resource assessment were performed based on the USGS volumetric estimation method to improve current Canada geothermal resources base estimates for innovative applications. It is concluded that low-temperature between (80°C–120°C) EGS resources in Southwestern of Ontario contain approximately 175 million MWh of heat-in-place and expected that within the coordinate ranges of (81°-82.5°)*W* and (41°-42.5°)*N*, there exist an area of interest within the region for geothermal energy exploitation.

1. INTRODUCTION

1.1. Background

Geothermal energy plays a key role in realizing targets in energy security, economic development and mitigating climate change. Through harnessing the stored thermal energy trapped within rocks, this resource can be utilized in generating electricity and in direct applications. However, before the energy can be extracted from depths within the Earth, exploratory methods are crucial in locating and prospecting the potential of a geothermal system (Sanyal, 2010).

Canadian resources include all types of geothermal energy from high to low temperature. Geothermal energy plays a small role in the Canadian energy market - only through direct-use heating applications. Currently there are no geothermal power plants in Canada despite the presence of high temperature resources associated with the Pacific Ring of Fire (Grasby et al., 2012). The majority of high-temperature geothermal sites are located in the western part of Canada, (British Columbia and Yukon) (Jessop et al., 1991).

The first attempts to extract geothermal energy in Canada go back to 1973 following the first major oil crisis. But as oil prices stabilized in the early 1980s essentially all geothermal exploration activities stopped in 1985. Clearly, geothermal power generation does not yet make even a small contribution to the Canadian energy market despite the presence of high temperature resources in the west. However, in recent years, increasing energy prices and rising efforts to reduce greenhouse gas emissions may be turning the tide back to this resource.

The approach of the paper is to produce a resource assessment of the thermal conditions in the crust beneath Southwestern region of Ontario, in search of a geothermal prospect and an estimate of the energy potential accessible by EGS technique. For this purpose, we have analyzed the non-geothermal resources identified in previous studies from Michigan Basin into a single assessment of deep (3-5 km), low-temperature (90°–110°C) geothermal resource potential within the region.

Insufficient data across many regions of Canada renders categorizing geothermal resources a difficult task. As a result, computer modeling coupled with laboratory investigations to fill data gaps are being encouraged under the Executive Summary, Research Needs of the Geological Survey of Canada Open File 6914 (Grasby et al., 2012). Southwestern Ontario has been of prime interest for geothermal exploitation located in the east of the Michigan Basin. The paper presents a preliminary thermal investigation into this area and highlights a potential production field region. Figure 1.1 indicates the location of the study to perform these investigations.

Figure 1.1: Ontario Regions Map-Zone 1, 2 and 3 of Southwestern Ontario (derived from MROO)

1.2. Area of Study

The sedimentary basin of Southwestern Ontario consists of many aquifers covering approximately 37,000 km^2 land. It is surrounded by Canadian Shield to the north and east, and Great Lakes to the south and on the west by the Detroit River, Lake St. Clair, the St. Clair River and Lake Huron. The Canadian Shield stands out as a low heat flow area (Blackwell and Richards, 2004; Jaupart and Mareschal, 2008), with heat flux values within 30 to 50 mW/m^2 range in contrast to values that often exceed 80 mW/m^2 in the active regions of Western North America.

In Eastern Canada (Figure1.2), the average geothermal heat flux is much lower than in Western Canada (Majorowicz and Grasby, 2010). This is because a large part of Eastern Canada, including the province of Ontario (East-central), is located in the geothermal “cold” Canadian Shield, while some areas are located in a “hotter” sedimentary platform related to the Appalachian basins.

The first geothermal assessments by (Jessop et al., 1991) indicate the potential for the Eastern Provinces to produce power using hot dry rock technology. The choice of the heat extraction technique depends on geological factors (sedimentary vs. crystalline rocks) and the thermal potential of the available heat.

In the case of deep dry hot rocks, artificially created Enhanced Geothermal Systems (EGS) (Tester et al., 2006) may be the only way to tap into the high temperature heat >120°C available in the crystalline basement rocks. To achieve this, a thermal carrier fluid (water, etc.) needs to be pumped into a closed loop system through the underground reservoir to extract the geothermal heat and through the power plant boiler, prior to being re-injected in the ground.

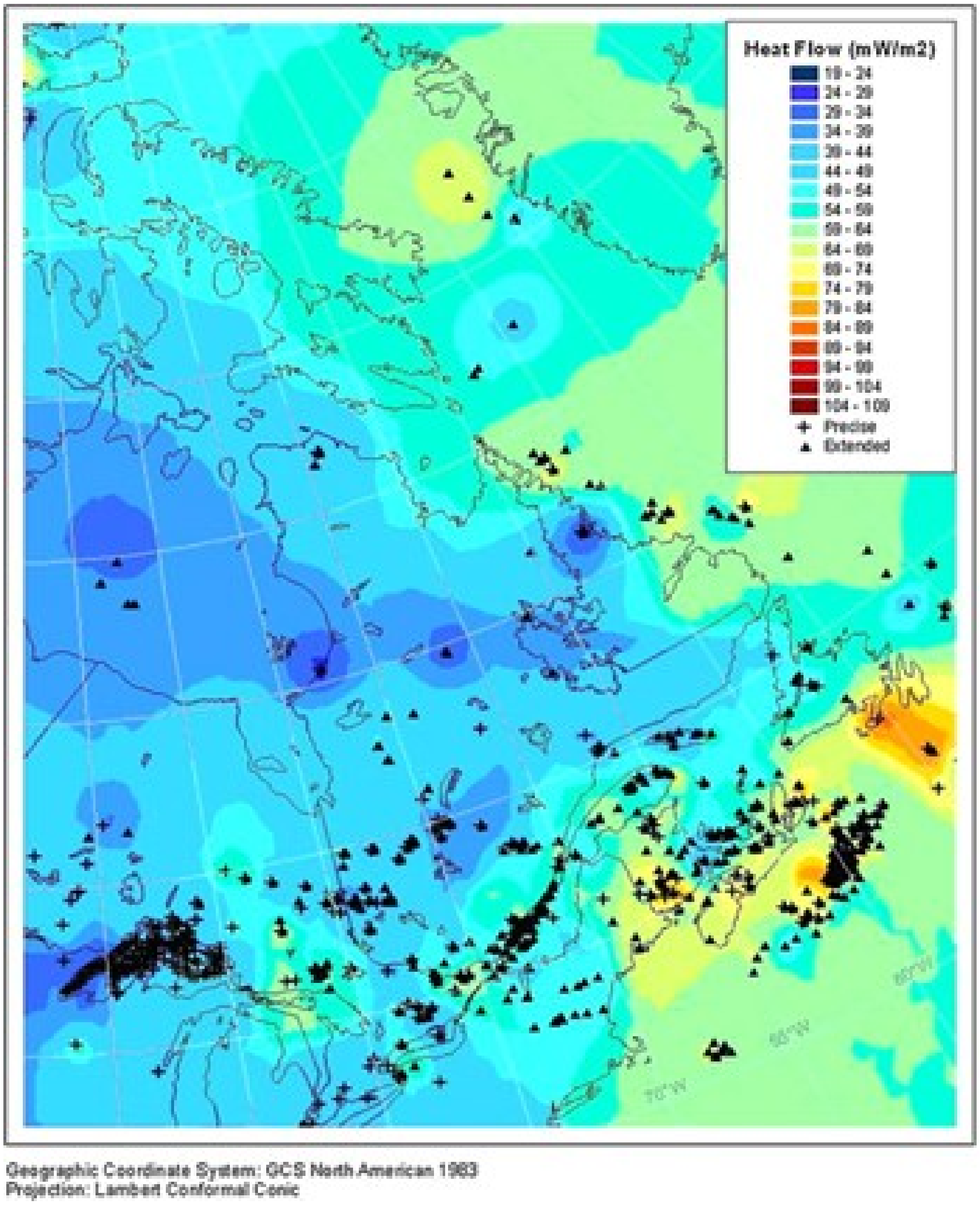

Figure 1.2.: Heat flow contour map for Eastern Canada based on IHFC (International Heat Flow Commission) heat flow density data base.

2. GEOLOGICAL HISTORY OF SOUTHERN ONTARIO

The Paleozoic rocks in southern Ontario are principally shales, limestones, dolomites and sandstones. A large number of Paleozoic groups, formations, and members of Cambrian, Ordovician, Silurian, and Devonian age have been identified in southern Ontario. Many oil and gas exploration wells were drilled there in the past and oil and gas reservoirs in Ontario are found at a variety of depths and in different rock types. Common reservoirs include Cambrian sandstones (at depths of 800 to 1200 m), Ordovician carbonates (800 to 900 m), Silurian carbonates (500 to 700 m and 350 to 450 m), and Devonian carbonates (110 to 140 m) all of which occur in southwestern Ontario. With this preponderance of wells in the area, there is an opportunity to gain useful information for geothermal purposes by analyzing the recorded borehole logs of the wells. However the well data is not available for all these wells.

Four major sedimentary basins occur within Ontario. The sedimentary basins cover approximately 320,000 km^2, which is almost one third of the total surface area of the province. It includes northern Ontario and Hudson Bay and the entire area of southern Ontario (Figure, 2.1).

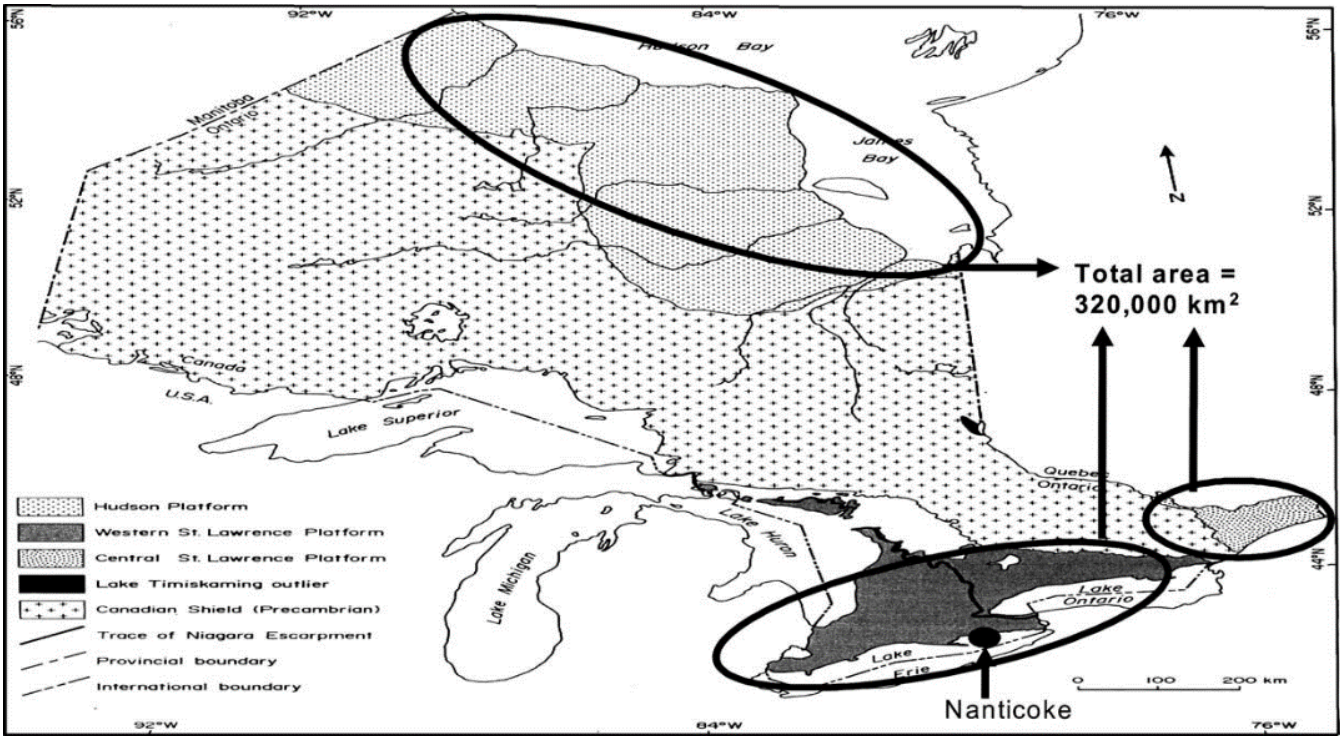

Figure 2.1: Area of Sedimentary Basins in Ontario (modified from Johnson et al.)

In southern Ontario, thick accumulations of sedimentary rocks are present between the Michigan and Appalachian basins (Figure, 3.2). Extensive development of porosity and permeability is evidenced by the presence of oil and gas reservoirs and regional saline water aquifers in these basins. The sedimentary rocks within the Michigan and Appalachian basins are distinguished by geologic age and further subdivided into formations that can be mapped in the subsurface. The oldest and lower most rocks are of Cambrian age and consist mainly of sandstones. Younger sandstone, shale, and limestone rocks of Ordovician, Silurian, and Devonian age overlie the Cambrian rocks.

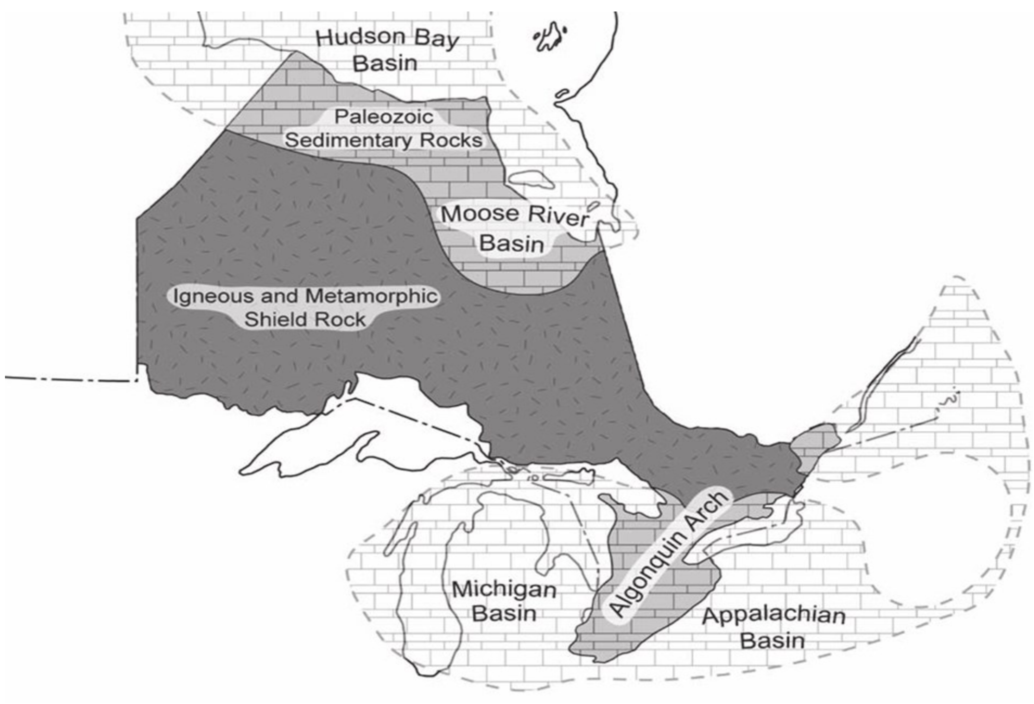

Figure 2.2: Major rock types and sedimentary basins occur within Ontario

3. LITERATURE REVIEW

3.1. Geothermal Low-Temperature EGS systems

Geothermal resources can be categorized into two models: hydrothermal and EGS. Each category is then subdivided into multiple system types. A hydrothermal system is a reservoir with the following characteristics:

- Porosity and/or permeability levels permitting the flow of water,
- Higher than average regional thermal gradients,
- A source and recharge system of flowing water.

In contrast to hydrothermal systems, EGS systems are geologic systems that would require additional stimulation and enhanced recovery methods for extraction of the available heat content. This category includes two primary subtypes:

- Sedimentary basins – differ from “hydrothermal” sedimentary systems in that they may lack water and/or permeability.
- Low conductivity, hot dry rock (HDR) – hot rock that lacks one or more of the above stated characteristics; in theory, may be accessed in any location given sufficient depth and reservoir stimulation.

(Breede et al., 2013), (Olasolo et al., 2016), and (Dipippo, 2012) provided comprehensive reviews of existing enhanced geothermal systems including reservoir stimulation techniques that have been applied.

3.2. Volumetric Heat in Place Assessments

Soaring prices of fossil fuels caused by the oil-crises of 1973 and 1979 stimulated research to quantify the potential of alternative energy sources including geothermal energy. At early stages of geothermal development, the size or potential megawatt output of a geothermal resource can be estimated by different methods with relatively little data available. A theoretical maximum potential output can be determined by the volumetric heat-in-place method developed by the U. S. Geological Survey (USGS) decades ago. In this method, the amount of heat in a block of earth is largely assumed with commonly used factors. For this method, the area or region below the Earth's surface is divided into separate volumes. For each volume, the thermal energy in place (heat in place) is estimated based on measured or modeled subsurface temperatures.

Estimating the heat in place is straightforward, but it is more difficult to delimit the share that is technically producible. To direct this issue, it is common to apply an average value for the recovery factor to obtain the technical potential. However, little data is available on actual recovery factors, making it hard to assess whether a chosen recovery factor is realistic and appropriate for resource assessments of individual basins or entire regions. More realistic recovery factors are used when data on location-specific aquifer permeability and temperature are available. For areas without any prior information or for global-scale assessments, a low recovery factor is more appropriate.

One of the main challenges for all resource assessments is uncertainty quantification, especially when dealing with geological data. Volumetric resource assessments are therefore often combined with probabilistic methods like the Monte-Carlo method. Multiple model runs yield a probability distribution of the potential, by allowing variation in parameters. Uncertainty quantification for a geothermal resource assessment is challenging because it requires assumptions on suitable ranges for parameters that can show a strong spatial variation and that depend on local unknown geological conditions.

4. TECHNICAL AND ECONOMICAL RESOURCE ASSESSMENT

This section is used to describe the method we use for our resource assessment and to present the results.

4.1. Methodology

In order to assess the potential amount of heat that could be extracted from deep geothermal reservoirs, the following assumptions have been made: (i) two temperature limits, i.e. minimum of 90°C and maximum of 110°C, are taken as examples for the extreme geothermal conditions available (see figure 4.1 for the predicted depths to reach 120°C); (ii) the rejection temperature is taken to be 40°C; a typical standard value for the condenser temperature (Tester et al., 2006); (iii) an average thermal gradient of 30°C/Km; (iv) a minimum recovery factor of 0.001 was chosen according to Sorey et al., (1982); and (v) an efficiency of 10% after passing the fluid through a binary Organic Rankin Cycle. We defined a set of both rock and fluid parameters for describing and quantifying as listed in Table 1.

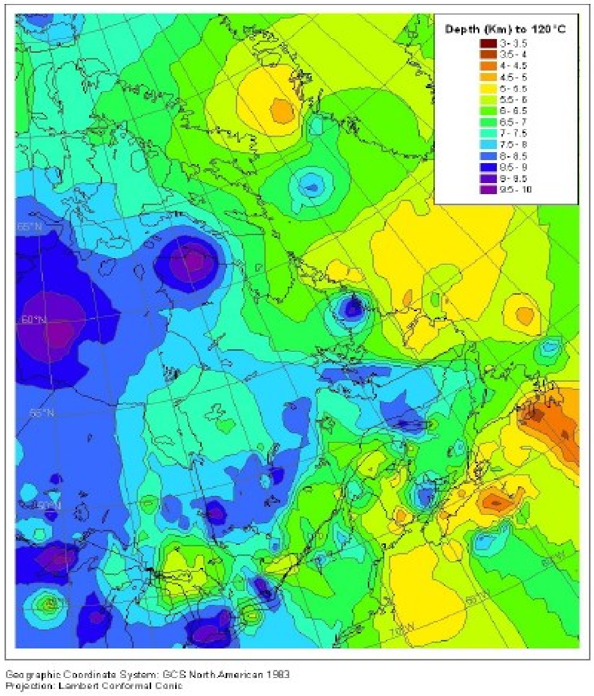

Figure 4.1: New contour map of predicted drilling depths to potentially reach 120 °C in Eastern Canada, including the province of Ontario, and part of the United States.

Table 1: Input variables with associated units and default values.

Parameters	Range	Unit
Area	37000	km^2
Thickness (Interval)	500	m
Rock Density (the average for sediment and sandstone)	2.30E×12	kg/km^3
Porosity	0.1	
Thermal Recovery Factor	0.001	
Rock Specific Heat (typical dolomite rock and sandstone)	0.92	kJ/kg°C
Reservoir Temperature	(90-110)	°C
Fluid Specific Heat	4.18	kJ/kg°C
Fluid Density	1E×12	kg/m^3
Re-injection Temperature	40	°C
Conversion Efficiency	0.10	
Plant Life	30	
Plant Capacity Factor (%)	90%	

It is difficult to predict the actual temperature and pressure gradients for some selected areas due to the absence of necessary field data related to subsurface temperatures and pressures and the drilling depth required to reach the temperatures needed for power or heat production. From Bottom Hole Temperature (BHT) datasets, and through different methodologies, the thermal profile of sedimentary formations can be estimated. The following equation results of a linear regression of 405 BHT vs. associated depths from Michigan's Peninsula provided by (Raymond Vugrinovich, 1989): BHT (°C) = 14.5 + 0.0192 × depth (m), is used to determine the subsurface temperatures.

4.2. Resource estimation

For our assessment the available heat in place is estimated based on equation, as used by Brook et al. (1978):

$$Q = \rho \, Cp \, V \, \Delta T \quad [kJ] \tag{1}$$

in which ρ is the density of the rock, Cp is the heat capacity of the rock, V is the volume of the rock, and ΔT is the change in temperature, respectively.

The assumed interpolated horizontal surface areas from the 90°C+, 100°C+, and 110°C+ intervals were multiplied with the 0.5 kilometer (km) thicknesses, yields the total effective volume.

Table 2: Parameters and available heat in place for the 3000-3500 meter depth interval

Temp. Interval	Area (km^2)	Volume (km^3)	Average Temp. (°C)	ΔT	Q (J)	Recoverable (J)	MWt
90°C +	37000	18,500	76.9 °C	36.9 °C	$14{,}445 \times 10^{17}$	$14{,}445 \times 10^{14}$	$40{,}125 \times 10^{4}$
100°C +	500	250	76.9 °C	36.9 °C	195×10^{17}	195×10^{14}	542×10^{4}
110°C +	5	2.5	76.9 °C	36.9 °C	2×10^{17}	2×10^{14}	6×10^{4}

1MWh=3.6×10^9 J

Table 3: Parameters and available heat in place for the 3500-4000 meter depth interval

Temp. Interval	Area (km^2)	Volume (km^3)	Average Temp. (°C)	ΔT	Q (J)	Recoverable (J)	MWt
90°C +	17000	8,500	86.5 °C	46.5 °C	$8{,}363 \times 10^{17}$	$8{,}363 \times 10^{14}$	$23{,}230 \times 10^{4}$
100°C +	15000	7500	86.5 °C	46.5 °C	$7{,}380 \times 10^{17}$	$7{,}380 \times 10^{14}$	$20{,}500 \times 10^{4}$
110°C +	1000	250	86.5 °C	46.5 °C	492×10^{17}	492×10^{14}	$1{,}360 \times 10^{4}$

Table 4: Parameters and available heat in place for the 4000-4500 meter depth interval

Temp. Interval	Area (km^2)	Volume (km^3)	Average Temp. (°C)	ΔT	Q (J)	Recoverable (J)	MWt
90°C +	9000	4,500	96.1 °C	56.1 °C	$5{,}342 \times 10^{17}$	$5{,}342 \times 10^{14}$	$14{,}839 \times 10^{4}$
100°C +	17000	8,500	96.1 °C	56.1 °C	$10{,}090 \times 10^{17}$	$10{,}090 \times 10^{14}$	$28{,}020 \times 10^{4}$
110°C +	2000	500	96.1 °C	56.1 °C	1188×10^{17}	1188×10^{14}	$3{,}300 \times 10^{4}$

Table 5: Parameters and available heat in place for the 4500-5000 meter depth interval

Temp. Interval	Area (km^2)	Volume (km^3)	Average Temp. (°C)	ΔT	Q (J)	Recoverable (J)	MWt
90°C +	7000	3,500	105.7 °C	65.7 °C	$4{,}866\times10^{17}$	$4{,}866\times10^{14}$	$13{,}510\times10^{4}$
100°C +	12000	6000	105.7 °C	65.7 °C	$8{,}341\times10^{17}$	$8{,}341\times10^{14}$	$23{,}170\times10^{4}$
110°C +	4000	2000	105.7 °C	65.7 °C	2780×10^{17}	2780×10^{14}	$7{,}700\times10^{4}$

Table 6: Final estimate of energy in place, after recovery factor and taking power plant efficiency into account

Temp. Range (°C)	Recoverable (J)	MWt	After Efficiency of (10%) (MWt)
90	$33{,}016\times10^{14}$	92×10^{7}	92×10^{6}
100	$26{,}006\times10^{14}$	67×10^{7}	67×10^{6}
110	$4{,}462\times10^{14}$	12.5×10^{7}	12.5×10^{6}

The heat in place that can be realistically exploited is limited by technical and economic conditions. These include surface and subsurface limitations, such as plant facilities and drilling technologies. Following recommendations from the review paper by (Grant, 2014), and (Sorey et al., 1982) the technical potential is calculated as a fraction of the heat in place using a recovery factor of 0.001.

By assuming a power plant lifetime of 30 years and capacity factor of 90%, there is the possibility to develop a power plant with a capacity of 600 MWe over the production period.

5. RESULTS & CONCLUSIONS

The Southwestern Ontario basin has temperatures over 90°C below a depth of 3000 meters. An analysis for 3000-5000 meter depth interval was carried out. The available energy in place for each depth interval is listed in Tables 2 to 5.

Although the Southwestern Ontario has limited potential for large-scale power production, the subsurface findings clearly point towards a potential production field within the coordinate ranges of $(81°\text{-}82.5°)W$ and $(41°\text{-}42.5°)N$ displaying known temperature between (80°C-120°C). It is expected that low temperature geothermal electricity generation and direct use may still be viable with the development of deep EGS sedimentary resources and by means of a binary cycle power plant.

The energy summary, along with the estimate after passing the fluid through a binary Organic Rankin Cycle with an efficiency of 10% can be found in Table 6. Accordingly the total accessible resource base in this assessment was found to be around 175 million MWt. However given physical and technical limitations, the portion of this resource that can be extracted could be significantly less.

REFERENCES

Blackwell, D. and M. Richards, 2004. Geothermal map of North America., American Association of Petroleum Geologists (AAPG). 1 sheet, scale 1:6,500,000.

Breede K, Dzebisashvili K, Liu X, Falcone G. A systematic review of enhanced (or engineered) geothermal systems: past, present and future, Geothermal Energy 1 (2013) 1–27.

Brook, C. A., Mariner, R. H., Mabey, D. R., Swanson, J. R., Guffanti, M., and L. J. P. Muffler, (1978). “Hydrothermal Convection Systems with Reservoir Temperatures ≥ 90°C,” in Assessment of Geothermal Resources of the United States – 1978, United States Geological Survey Circular 790, p. 18-43.

DiPippo, R. (2005). Geothermal power plants-principles, applications, and case studies and environmental impact: Elsevier, Oxford, 450 p.

Gargs, S., Combs J.: A reformulation of USGS volumetric heat in place resource es-timation method. Geothermics 2015;55:150–8.

GeothermEx, Inc. (2004). New Geothermal Site Identification and Qualification, Consultant Report for the California Energy Commission PIER Report No. P500-04-051, April 2004, located at (http://www.geothermex.com/CEC- PIER_Reports.htm).

Grant, M. Stored-heat assessments: a review in the light of field experience. Geotherm Energy Sci 2014; 2:49–54.

Grasby SE, Allen DM, Bell S, Chen Z, Ferguson G, Jessop A, et al. Kelman M, Ko M, Majorowicz J, Moore M, Raymond J, Therrien R. Geothermal Energy Resource Potential of Canada., Geological survey of Canada open file 6914, 2012.

Hobbs, M.Y., Frape S.K. (University of Waterloo), O. Shouakar-Stash (University of Waterloo), L.R. Kennell. Regional Hydrogeochemistry – Southern Ontario – Ontario Power Generation, March 2011.

Jessop, A., Ghomshei, M., & Drury, M. (1991). Geothermal Energy in Canada. Geothermics, 20(5-6), 369-385.

Minea,V., Majorowicz, J. Geological, Economical and Environmental Assessment of Combined Geothermal Power and Heat Generation in Québec, Canada World Geothermal Congress 2015 Melbourne, Australia, (2015), April, 19-25.

Muffler, P. & Cataldi, R., (1978). Methods for regional assessment of geothermal resources. Geothermics, 7(2-4), pp.53–89.

Olasolo P, Juárez M, D'Amico S, Liarte I. Enhanced geothermal systems (EGS). a review. Renew Sustain Energy Rev 2016; 56: 133–44.

Rybach L. Classification of geothermal resources by potential. Geotherm Energy Sci 2015; 3:13–7.

Shafeen, A., Croiset, E., Douglas, P. and Chatzis, I. 2004a, CO2 sequestration in Ontario, Canada. Part I: Storage evaluation of potential reservoirs. Energy Conversion and Management 45: 2645-2659.

Sanyal SK. Future of Geothermal Energy, Proceedings the Thirty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, 2010, SGP-TR-188.

Sorey, M.L., Nathenson, M., and Smith, C 1982. "Methods for Assessing Low-Temperature Geothermal Resources." in Reed, M.J., ed., Assessment of Low-temperature Geothermal Resources of the United States -1982: U.S. Geological Survey Circular 892, p. 17-29.

Tester, J.W., et al (2006). The Future of Geothermal Energy: The Impact of Enhanced Geothermal Systems on the United States in the 21st Century (Cambridge, MA: MIT Press)

Vaught, T.L., (1980). TEMPERATURE GRADIENTS IN A PORTION OF MICHIGAN: A REVIEW OF THE USEFULNESS OF DATA FROM THE AAPG GEOTHERMAL SURVEY OF NORTH AMERICA

Vugrinovich, R., (1989). Subsurface temperatures and surface heat flow in the Michigan Basin and their relationships to regional subsurface fluid movement

Williams C. Updated methods for estimating recovery factors for geothermal resources. In: Proceedings of the thirty-second workshop on geothermal reservoir engineering 2007, Stanford University, Stanford, California, USA; 2007.