Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Direct Utilization of Geothermal Energy from Coast to Coast: a Review of Current Applications and Research in Canada

Jasmin Raymond[1,a], Michel Malo[1], Denis Tanguay[2], Stephen Grasby[3] and Faisal Bakhteyar[4]

1- Institut national de la recherche scientifique, Centre Eau Terre Environnement, 490 de la Couronne, Québec (QC), G1K 9A9, Canada

2- Canadian GeoExchange Coalition, 1030 Cherrier, Suite 304, Montreal (QC), H2L 1H9, Canada

3- Geological Survey of Canada, 3303 33rd Street, N.W., Calgary (AB), T2L 2A7, Canada

4- Canadian Geothermal Energy Association, PO Box 1462 Station M, Calgary (AB), T2P 2L6, Canada

a- jasmin.raymond@inrs.ca

Keywords: Direct Use, Canada, Heat Pump, Hot Springs, Thermal Water

ABSTRACT

Geothermal energy in Canada is mostly used for two applications; heating and cooling buildings with geothermal heat pumps, and hot water source for bathing. The current status and state of the art related to both applications has been reviewed to provide an overview of geothermal energy utilization in Canada. Geothermal heat pump systems have been installed across the country with a total capacity estimated to 1, 458 MW_t and annual geothermal energy use of 11,338 TJ. The largest markets are in the provinces of Ontario, Quebec and British-Columbia. In the residential sector, which accounts for about 60% of the installed capacity, approximately 56% of the systems are horizontal closed-loops and 24% are vertical closed-loops. The industry has experienced a growth rate on the order of 40% during 2006 to 2008 and has severely decreased in 2010. Installations in 2013 were roughly half those recorded during the peak of 2009. More than 140 hot springs of temperature higher than 10°C have been inventoried in the Western Canadian Cordillera. Commercial exploitation of hot springs and thermal waters pumped from a deep aquifer, for bathing and heating pools, is taking place at thirteen locations in the provinces of Saskatchewan, Alberta and British-Columbia as well as Yukon Territory. The total capacity and the annual geothermal energy use of the commercial bathing facilities are approximately 8.8 MW_t and 277 TJ. Flow rates and temperatures ranging from 1 to 30 $L\ s^{-1}$ and 40 to 57°C have been inventoried for those commercial hot springs. Research has been carried out to support the growth of the geothermal industry, which has a high potential to reduce greenhouse gas emissions. A total of 765 scientific publications related to geothermal topics and having one or more Canadian affiliation(s) have been inventoried from 1990 to 2013. The generally increasing number of Canadian geothermal publications since 2001 indicates growing interest in this field. The use of heat pumps makes geothermal utilization in Canada a nationwide economic activity while hot springs, exploited in western Canada and marginally contributing to the Canadian geothermal energy budget, remain a feature of strong interest.

1. INTRODUCTION

Canada is the world's second largest country with a total area of 9,984,670 km^2 and population of 35,344,962 (Statistics Canada, 2014a). The gross domestic product is approximately 1.9 G$ (Statistics Canada, 2014b), which places Canada among the top fifteen global economies. Energy consumption for the Canadian residential and commercial sectors is 2,883 $PJ\ yr^{-1}$ (National Energy Board, 2013), a high consumption for a small population affected by the cold climate. Among all the energy sources fulfilling the needs of the Canadian population is geothermal energy, which is mostly used for heating and cooling buildings with geothermal heat pumps across the country and for bathing at hot springs in Western Canada. Early direct utilization of geothermal energy in Canada was made by the First Nations that used the hot springs before the 1800's. Workers of the Canadian Pacific Railways discovered the Cave and Basin Hot Springs of Alberta in 1882, which led to the creation of Banff National Park and the commercial exploitation of the hot springs with the construction of a hotel in 1886. Geothermal heat pumps have been commercially used in Canada since the 1970's. The geothermal heat pump industry has significantly grown since the last decade and makes Canada a leading country for direct utilization of geothermal energy, particularly when considering Canada's small population. Hot springs now provide only a small portion of the geothermal energy used in Canada although they are of historic significance.

Data related to the direct utilization of geothermal energy in Canada presented at past World Geothermal Congresses was unfortunately incomplete, as reviews were mostly concerned with the development of geothermal power generation (Allen et al., 2000; Ghomshei et al., 2005; Thompson, 2010). In an effort to illustrate the positive contribution of Canada to the geothermal industry, a literature review was performed to evaluate Canada's geothermal energy budget. The objective of the work was to estimate the total capacity and annual energy use related to the direct utilization of geothermal resources. Geothermal heat pump sales statistics were examined to determine the approximate number of systems currently operating in Canada. This estimate was used as a starting point to calculate the total capacity of heat pumps and geothermal energy use. Temperature and flow rate data of most hot springs and a thermal water well system commercially exploited in Canada were found in the literature to calculate the hot springs capacity and energy use. A review of major research related to geothermal resources and systems conducted by Canadian based researchers, or with Canadian collaborations, was also conducted to demonstrate efforts achieved over the past years to improve geothermal knowledge and technologies.

2. GEOTHERMAL HEAT PUMPS

Geothermal technologies represent a small proportion of the global heating and cooling market in Canada. The size of the geothermal market segment is consequently difficult to estimate. Nevertheless, the Canadian GeoExchange Coalition (CGC) has produced industry surveys and market analysis (CGC, 2010a, 2012; Tanguay, 2014), allowing an estimate of the number of installed systems. Data presented in those reports is based on an industry survey conducted in 2008 and 2009 that covered 25 to 30% of the Canadian geothermal heat pump market, additional smaller industry surveys completed in 2006, 2011 and 2012 that provided qualitative results, databases of 500 businesses certified by the CGC and 18,000 systems installed under the ecoENERGY Retrofit program of Natural Resources Canada as well as data provided by the Energy Information Administration of the United States, Department of Energy, knowing that about 90% of heat pumps installed in Canada are manufactured in the United States.

Cross-validation of the data sources allowed an estimate of the number of geothermal heat pump units installed in Canada from 1990 to 2013 (Figure 1). The number of units installed is for both the residential and commercial sectors and units of the commercial sector have been expressed in equivalent residential units, taking into account the heat pumps capacity. The industry experienced a growth rate of about 40% during 2006 to 2008 and severely decreased from 2010 to 2012. Peak installation of 15,913 units occurred in 2009. At the time of writing, the most recent data obtained for 2013 suggested that installations were roughly half of those reported for 2009. High growth rates before 2009 is explained by the increase of oil prices, the relatively high prices of natural gas with peaks in 2005 and 2008, financial incentives offered at many government levels, and a well-structured industry supported by quality programs of the CGC as well as emerging Canadian heat pump manufacturers. The 2010 downturn is thought to be due to the 2009-2010 financial crisis, the decrease in oil and gas prices, the end of many government incentive programs, the increase of electricity prices and the loss of Canadian heat pump manufacturers.

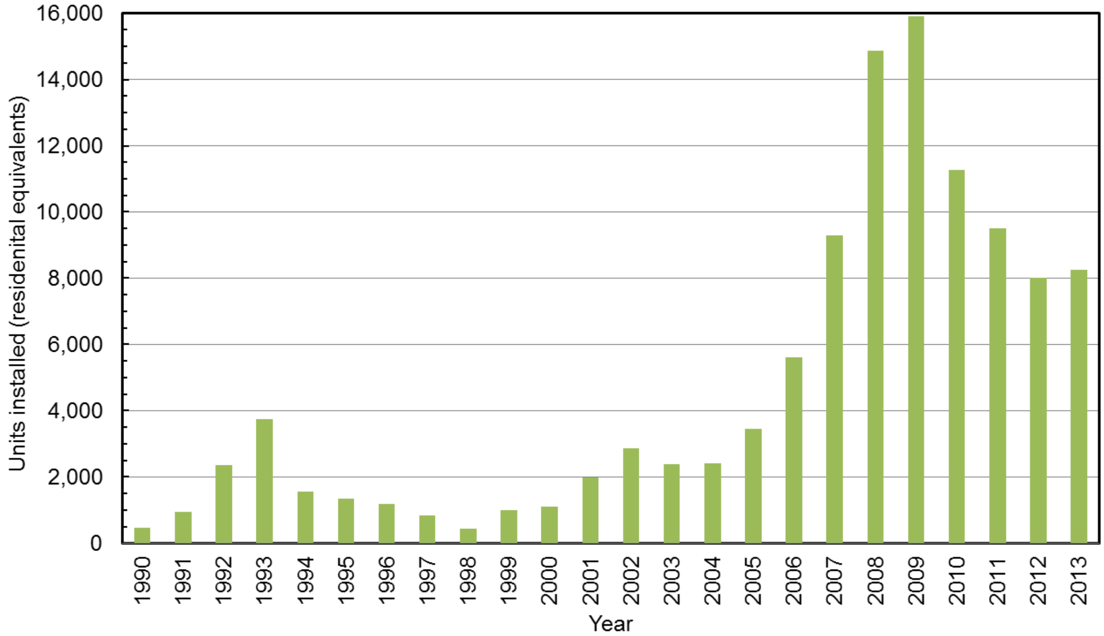

Figure 1. Geothermal heat pump units installed in Canada from 1990 to 2013 (Tanguay, 2014).

The initial industry survey released by the CGC (2010a) contains most data giving a global picture of the market until 2009. The residential sector accounted for about 60% of the unit capacity, although this proportion may have been between 40 to 60% in different years. In 2009, residential units were installed in existing homes to replace conventional heating systems (57%) or existing geothermal systems that reached the end of their life (13%) and in new homes (30%). The sum of units installed was used to estimate the number of operating geothermal units after subtracting installations that were possibly geothermal retrofits (Table 1). This amount of geothermal system replacements was assumed equal to 2% of installations in 1990 and then increased by 1% every four years until 2005. Starting in 2006, the amount of geothermal retrofits was estimated assuming a heat pump life of seventeen years and that 50% of heat pumps installed seventeen years before were replaced. This assumption yield 12% of geothermal retrofits for 2009, which is fairly close to the 13% geothermal retrofits reported in 2009 by the CGC (2010a). The average heat pump capacity was assumed equal to 14 kW_t from previous industry surveys (CGC, 2010a, 2012) and has been multiplied by the cumulative number of systems in operation, since commercial units are expressed in equivalent residential units, and revealed a total geothermal heat pump capacity equal to 1,449°MW_t for the end of 2013. The system coefficient of performance and heating hours at full load was assumed equal to 3.5 and 3,000°hr yr^{-1}, respectively, to keep consistency with previous world estimates of geothermal direct energy use (Lund et al., 2010). The heating hours at full load are a gross estimate that remains conservative for a high latitude country such as Canada. The calculation indicates an annual geothermal energy used related to heating with geothermal heat pumps equal to 11,111 TJ°yr^{-1} for the end of 2013. This exploitation of shallow geothermal resources is concentrated in southern Ontario and Quebec but present throughout the country, as evidenced by the map of geothermal heat pump systems certified by the CGC (Figure 2).

The types of geothermal heat pump systems installed in the residential sector are dominantly horizontal and vertical closed-loops followed by groundwater heat pumps (Figure 3a; CGC, 2012). This distribution of system type reflects the Canadian province with the strongest geothermal market, which is Ontario. About 65% of residential systems installed in Ontario are horizontal closed-loops. The second and third provinces having the largest geothermal market are Quebec and British Columbia, where installations in these provinces are dominantly vertical (83%) and horizontal (46%) closed-loops, respectively. At the national level, geothermal heat pumps installed in existing homes dominantly replace fuel oil and electricity heating systems by an equal proportion of about 39% of total energy sources replaced by heat pumps (Figure 3b; CGC, 2012).

Table 1. Geothermal heat pump systems installed in Canada, estimated capacity and energy used

Year	Units installed	Replacements* (%)	New installations	Cumulative new installations	Total capacity** (MW_t)	Energy use*** (TJ yr^{-1})
1990	450	2	441	441	6	46
1991	950	2	931	1,372	19	146
1992	2350	2	2,303	3,675	51	391
1993	3750	2	3,675	7,350	103	790
1994	1550	3	1,504	8,854	124	951
1995	1350	3	1,310	10,164	142	1,089
1996	1181	3	1,146	11,310	158	1,212
1997	826	3	801	12,111	170	1,304
1998	442	4	424	12,535	175	1,342
1999	1,007	4	967	13,502	189	1,449
2000	1,094	4	1,050	14,552	204	1,564
2001	1,985	4	1,906	16,458	230	1,764
2002	2,861	5	2,718	19,176	268	2,055
2003	2,388	5	2,269	21,445	300	2,300
2004	2,417	5	2,296	23,741	332	2,546
2005	3,488	5	3,276	27,017	378	2,899
2006	5,620	4	5,395	32,412	454	3,481
2007	9,284	5	8,809	41,221	577	4,424
2008	14,879	8	13,704	54,925	769	5,897
2009	15,913	12	14,038	68,963	965	7,400
2010	11,263	7	10,488	79,451	1,112	8,527
2011	9,500	7	8,825	88,276	1,236	9,478
2012	8,000	7	7,410	95,686	1,340	10,275
2013	8,250	5	7,837	103,523	1,449	11,111

*Assuming 50% of systems installed 17 years before were replaced in 2006 and after, ** Average system capacity was estimated to 14 kW_t, *** Average coefficient of performance and heating hours at full load were assumed to 3.5 and 3,000 hr yr^{-1}

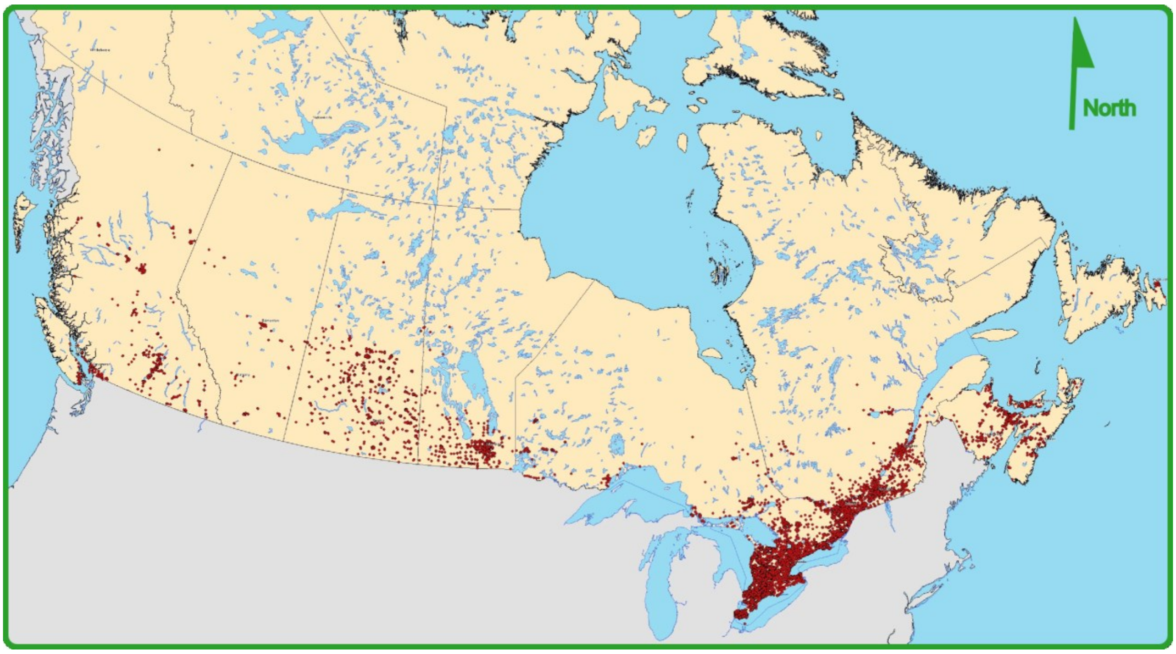

Figure 2. Distribution of geothermal heat pump systems certified by the CGC (Canadian GeoExchange Coalition).

A country update manuscript submitted for Canada at a previous World Geothermal Congress (Ghomshei et al., 2005) and a publication by Jessop et al. (1995) described a geothermal heating and cooling project at Springhill, Nova Scotia, that used flooded mine water and seems to have inspired similar developments at new locations. A recent closed-loop system installed in a flooded mining shaft and open pond loops installed in a flooded quarry have been reported in the province of Quebec (Raymond, 2011). Feasibilities studies for major district heating systems using mine water has been disclosed for Murdochville, Quebec (Raymond and Therrien, 2008, 2014), Timmins, Ontario (Hall et al., 2011), Con Mine, Northwest Territories (Ghomshei, 2007) and Britannia Mine, British Columbia (Ghomshei and Meech, 2003). An inventory of closed mines in the provinces of Nova Scotia, Quebec, Saskatchewan, Alberta and British Columbia indicated that they are at least 2,262 abandoned mines that can host geothermal resources of 18,642°TJ (Grasby et al., 2011). It is currently difficult to estimate the number of operating geothermal systems at flooded mines, since small projects may have not been reported in the literature. However, most projects envisioned for flooded mines were planning to use heat pumps fed by mine water, such that the capacity estimate performed according to geothermal heat pump sale statistics should include the contribution of the mine water projects.

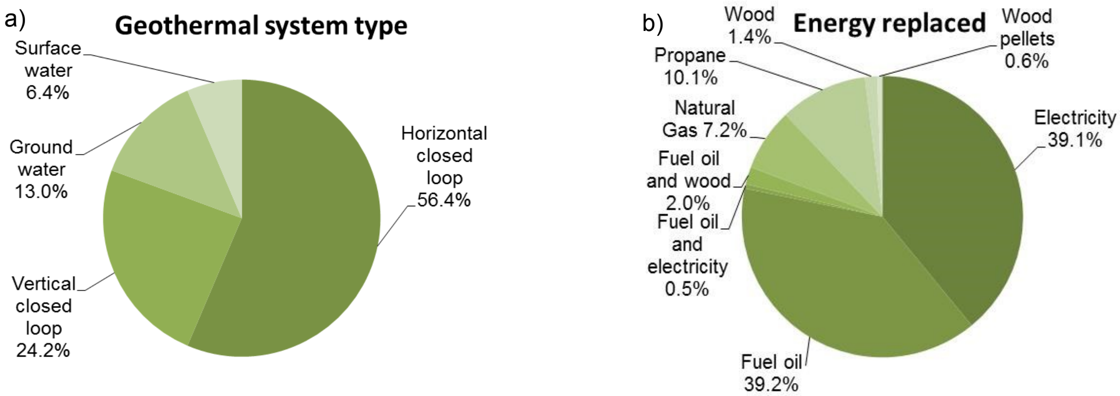

Figure 3. a) Type of geothermal systems and b) energy sources replaced by residential geothermal heat pumps in Canada (CGC, 2012).

3. HOT SPRINGS

More than 140 thermal springs of temperature higher than 10°C have been identified in the Western Canadian Cordillera (Grasby et al., 2009). Commercial exploitation of those natural hot springs in the provinces of Alberta, British Colombia and Yukon as well as thermal water pumped from deep aquifers in Saskatchewan is taking place at fourteen locations to heat pools for bathing purposes (Figure 4). The hot springs have played an important role for the early development of tourism in the Canadian Rockies. The creation of Banff National Park in 1885, the first national park in Canada, is the result of a dispute about the right to develop the hot springs. The history of hot springs utilization for popular sites can be found on Parks Canada web site (www.pc.gc.ca/eng/voyage-travel/sources-springs/index.aspx). Commercial exploitation of the hot springs began in the 1880's, although First Nations people had used them for generations prior. Europeans initially visited Banff Hot Springs in 1882 and the first recorded visit at Radium Hot Spring, made by Sir George Simpson, the governor of the Hudson's Bay Company, was in 1841. Construction of bathhouses and hotels at Banff, Miette and Radium Hot Springs respectively began in 1886, 1913 and 1914. Original bathhouses have been modified, restored or reconstructed and the hot springs pools are still operated today.

The Canadian Geothermal Energy Association (CanGEA) has recently inventoried hot springs that are commercially exploited in Canada (Table 2; CanGEA, 2013). A previous inventory of commercial hot springs was reported by Ghomshei et al. (2005), which identified twelve sites. Among those, the Cave and Basin Hot Springs in Banff are no longer used for bathing but remain a historic site to visit in Banff National Park. Water at the Canyon Hot Springs is heated after piped at a temperature of about 26°C (Souther, 1976) to feed a pool, which has not been taken into account to estimate the capacity of the commercial hot springs. Three additional sites have been described in the recent inventory of the CanGEA revealing the use of hot groundwater naturally resurging at the surface with a temperature between 40 and 57°C and a flow rate of 1 to 30°L/s to heat pools of thirteen bathhouses or hotels. The size of the installations vary greatly, ranging from small bath tubs to large pools that attract important tourism, for example, more than 270,000 people annually visit Radium Hot Springs. The Liard site is located in a natural area at Liard River Hot Springs Provincial Park of British Colombia and has minor infrastructures to accommodate the park visitors, which were considered to estimate the capacity of the commercial hot springs. The outlet temperature for this site was assumed equal to 30°C since water flows in swamps and using the discharge temperature of the river would have revealed and unreasonably high capacity. In addition to the commercial springs, groundwater at a temperature of 45°C is pumped at a depth of 1,350°m to supply pools of Temple Garden Mineral Spa Resort in Saskatchewan. Water is tapped about 1 km from the facility and carried on site with an insulated pipeline. Undeveloped hot springs have also been found in the wilderness, particularly in British Columbia and Northwest Territories, and are locally used for bathing in natural pools in scenic areas often reached only by hiking. Those remote locations have not been examined for the calculation of the commercial hot springs capacity.

Pool temperatures were used to determine the outlet temperature and calculate the hot springs capacity by multiplying the temperature difference between the springs and the pool outlet, the water flow rate and the specific heat capacity assumed for water (4.2°J m^{-3} K^{-1}). The hot springs average capacity was 676°kW_t and the total capacity of the thirteen sites inventoried was about 8.8°MW_t (Table 2). Assuming that water flows from the springs at the same rate all year long to maintain the pools temperature, the springs total capacity was multiplied by the amount of time in a year to determine their annual energy use that is equal to 277 TJ. This number is a rough approximation as springs flow rate and pools occupancy can vary throughout the year.

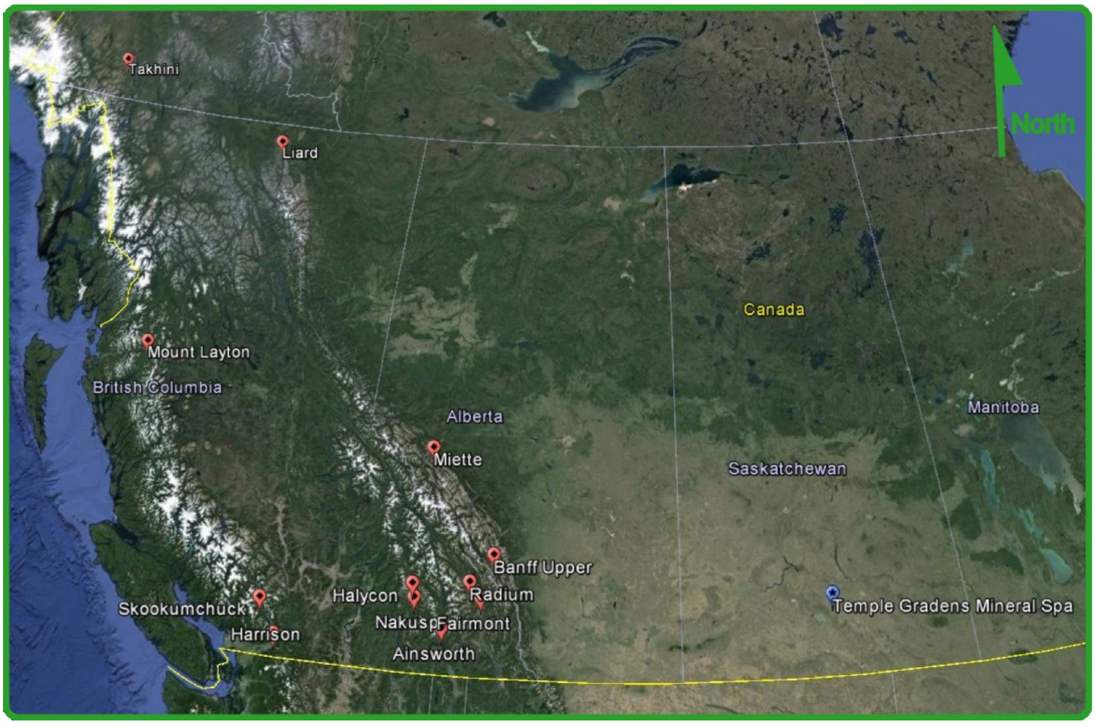

Figure 4. Goolge Earth image showing the location of the commercially exploited hot springs (diamond) and thermal water (star) in Canada.

Table 2. Hot springs and thermal water commercially exploited in Canada

Name	Province	Flow rate (L/s)	Springs temperature (°C)	Pool outlet temperature (°C)	Capacity (kW_t)
Banff Upper	AB	14.9	47	38	563
Miette	AB	15.3	54	37	1092
Ainsworth	BC	6.9	47	32	435
Fairmont	BC	20.9	46	44	176
Halycon	BC	3.5	54	32	323
Harrison	BC	26.1	40	28	1,315
Liard	BC	30.0	52	30*	2,772
Nakusp	BC	1.2	57	30	136
Mount Layton (Lakelse)	BC	9.9	41	30	457
Radium	BC	28	40	32	941
Skookumchuck (St. Agnes)	BC	3.2	35	30	67
Takhini	YT	5.7	40	35	120
Temple Gardens Mineral Spa	SK	5.7	46	30	383
				Total capacity (kW_t)	8,780
				Energy use (TJ yr^{-1})	277

Abbreviations: AB, Alberta; BC, British Columbia; SK, Saskatchewan; YT, Yukon. *Assumed temperature as water flows in swamps.

4. RESEARCH CONTRIBUTIONS

Canadian researchers have been actively doing research on all kind of geothermal resources and systems in their homeland and overseas. A Scopus search (www.scopus.com) with “geothermal” in title, abstract or keywords from 1990 to 2013 revealed 18,616 scientific publications, most of them being published by researchers with affiliations in the United States (4,928), China (1,766) and Germany (1,166). Canada’s rank was seven and had 765 publications, a fair position when taking into account that Canada contributes to about 2.5 % of word gross domestic product and has approximately 0.5% of the world population. The search performed captured publications with subjects that are not strictly related to geothermal resources, like oil thermal maturation, gas hydrate, hydrothermal mineralization or paleoclimate, but highlighted contributions that generally helped to improve geothermal related knowledge.

Additional information was retrieved from Scopus to determine the yearly number of contributions made by Canadian based researchers or with Canadian collaborations during 1990 to 2013 (Figure 5). The number of publications has been increasing in recent years, with an average growth of 12% from 2003 to 2013. Among the publications found, important studies directly related to the Canadian geothermal resource potential (Majorowicz and Jessop, 1981; Majorowicz and Grasby, 2010a, 2010b; Majorowicz et al., 2009), and other highly cited work belonged to the study of hydrothermal systems to understand early life forms (Beatty et al., 2005; Jones et al., 1997; Op den Camp et al., 2009; Vincent, 2000) or as analogues to mineralization processes (Cathles et al., 1997; Groves et al., 1998; Williams-Jones and Heinrich, 2005; Yang and Scott, 1996). The fifteen affiliations, source titles and authors that have the most publications are given in Table 3, highlighting the diversity of institutions located in six different provinces across the country and publishing in different periodicals whose audiences are mostly concerned with earth sciences and engineering. Note that affiliations and authors listed are not necessarily Canadian based, for example New Zealand and Turkey, and in such cases has collaborated with Canadian based researchers for the given number of publications. The search performed may not reveal all geothermal researches, as the word geothermal is not always used in geothermal related publications, particularly for heat pumps, but gives a reasonable overview of geothermal research trends in Canada.

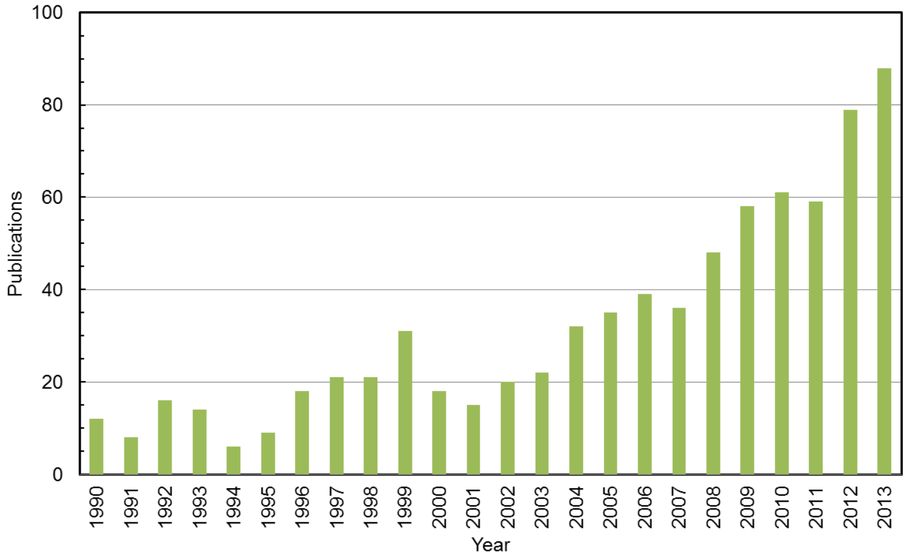

Figure 5. Publications with "geothermal" in title, abstract or keywords having one or more Canadian affiliations according to Scopus.

Table 3. Number of publications for the fifteen affiliations, source titles and authors having the most publications with Canadian affiliations and covering geothermal topics from 1990 to 2013

Rank	Affiliation	Source title	Author
1	University of Alberta, AB (97)	Geothermal Resources Council Transactions (57)	Dincer, I. (59)
2	Geological Survey of Canada, various provinces (78)	Geothermics (21)	Jones, B. (30)
3	University of Ontario Institute of Technology, ON (77)	Canadian Journal of Earth Sciences (20)	Majorowicz, J. A. (30)
4	University of Calgary, AB (41)	Economic Geology (19)	Renaut, R.W. (27)
5	McGill University, QC (41)	Journal of Volcanology and Geothermal Research (17)	Rosen, M.A. (20)
6	University of Saskatchewan, SK (37)	ASHRAE Journal (13)	Hepbasli, A. (18)
7	University of Toronto, ON (33)	Applied Thermal Engineering (12)	Bernier, M. (15)
8	University of British Colombia, BC (27)	Bulletin of Canadian Petroleum Geology (12)	Beltrami, H. (13)
9	École polytechnique de Montréal, QC (22)	Geophysical Research Letters (11)	Ferguson, G. (13)
10	GNS Science, New Zealand (20)	Lithos (11)	Ozgener, L. (12)
11	Carleton University, ON (18)	ASHRAE Transactions (11)	Oktay, Z. (12)
12	Simon Fraser University, BC (17)	Tectonophysics (11)	Rosen, M.R. (10)
13	Saint Francis Xavier University, NS (17)	Energy and Buildings (10)	Raymond, J. (9)
14	Ege University Faculty of Engineering, Turkey (15)	Earth and Planetary Science Letters (9)	Grasby, S.E. (9)
15	Dalhousie University, NS (15)	Ore Geology Reviews (9)	Ranalli, G. (9)

Affiliation, source title and author columns are independent of each other. The entries have been ranked according to the number of publications given in parenthesis. Abbreviations: AB, Alberta; BC, British Columbia; NS, Nova Scotia; ON, Ontario; QC, Quebec, SK, Saskatchewan.

Publications made by Canadian researchers or with Canadian collaborations that most impacted the direct use of geothermal resources, i.e. which belong to heat pumps or hot springs utilization and that have been the most cited, concern the development of analytical solutions to simulate ground heat exchangers (Lamarche and Beauchamp, 2007a; 85 citations) hourly simulation procedures for geothermal heat pumps (Bernier, 2001; 65 citations) and the evaluation of the borehole thermal resistance with in situ thermal conductivity tests (Marcotte and Pasquier, 2008b; 57 citations). Hot springs research had less impact than heat pump research and work to determine the chemical nature of the Canadian hot springs (Grasby et al., 2000; 48 citations) has been used in further studies to better understand their origin. The large research contributions of Canadians and their collaborators to the direct use of geothermal energy are difficult to summarize. An overview of publications obtained by limiting the above Scopus search with direct use keywords and that helped to identify publications with significant impact, typically more than ten citations but not strictly restricted to this criterion, is nevertheless given below. Some publications may have not been highlighted by this Scopus search and the authors apologize for important work that could have been overlooked.

A subject that has attracted important attention to the Canadian research community is the design and simulation of geothermal heat pump systems, which have a large potential to reduce greenhouse gas emissions (Hanova and Dowlatabadi, 2007; Self et al., 2013; Younis et al., 2010). Ground heat exchangers are the most expensive part of those systems and research has been performed to improve the design and simulation methods to better evaluate ground heat exchanger length and potentially reduce installation cost. New analytical solutions offering greater flexibility to simulate the systems has been proposed (Lamarche and Beauchamp, 2007a, 2007b). Algorithms to improve the rapidity of simulations taking into account building hourly loads were developed (Lamarche, 2009; Marcotte and Pasquier, 2008a). The validity of different solutions available for geothermal heat pump simulations and their effect on heat transfer was studied (Marcotte and Pasquier, 2009; Marcotte et al., 2010; Philippe et al., 2009). Different methods to evaluate the borehole thermal resistance of ground heat exchangers were compared (Lamarche et al., 2010). Designing a geothermal heat pump system requires knowledge of the thermal state and properties of the subsurface, which is generally obtained by performing thermal response tests in ground heat exchangers (Raymond et al., 2011b). Methods related to the analysis of thermal response tests were developed to improve evaluation of the average water temperature of the ground heat exchanger (Marcotte and Pasquier, 2008b), to use recovery measurements following heat injection to better assess the subsurface thermal conductivity and borehole thermal resistance (Raymond et al., 2011a) and to use numerical models taking into account subsurface heterogeneities (Raymond et al., 2011c).

Studies of geothermal district systems, having important complexity because of large scale installations, have been carried out to improve their performances with energy and exergy analysis (Ozgener et al., 2004, 2005a, 2005b, 2006, 2007). Research performed for district or large scale geothermal heat pump systems operated with mine water have evidenced the important geothermal potential of flooded mines, acting as permeable reservoirs to supply such systems (Hall et al., 2011; Jessop et al., 1995; Raymond and Therrien, 2008). The urban island heat effect was further shown to have an impact on increasing subsurface temperature to the benefit of shallow geothermal resources (Ferguson and Woodbury, 2004; Zhu et al., 2010).

Recent research about hot springs in Canada concerned water chemistry and temperature to determine their origin and controls. Stable oxygen and hydrogen isotope analysis revealed that the springs water is of meteoric origin (Grasby et al., 2000). Most springs are associated with high heat flow regions of volcanic belts in the cordillera, except at some locations, like Banff which sits in a low heat flow area, where hot resurging groundwater is due to deep circulation along high permeability faults (Grasby and Hutcheon, 2001). Thermal springs are located along six major thrust fault systems that formed during the Eocene or later and their temperature is influenced by the local geothermal gradient, the depth of groundwater circulation and the flow rate. Selected springs that were sampled and analyzed to determine the formation equilibrium temperature with chemical geothermometers indicated circulation depths of 0.6 to 4.8 km (Allen et al., 2006; Grasby and Hutcheon, 2001). However, numerical modeling of convective heat transfer along conceptual fault systems for the Western Canadian Cordillera showed that circulation depths is likely to be under estimated by 30 % due to fluid mixing that can occur along fault zones (Ferguson et al., 2009).

5. TOTAL GEOTHERMAL BUDGET AND CONTRIBUTIONS

The installed capacity of all types of geothermal systems operated in Canada, their geothermal energy use and the number of publications related to geothermal topics with Canadian affiliations have been evaluated as a function of population, gross domestic product or total energy demand to determine, where appropriate, the geothermal performance of Canada (Table 4). The installed geothermal capacity per capita and the fraction of geothermal energy use with respect to the total energy demand in the residential and commercial sectors, shows evidence that geothermal energy provides a very small proportion of the population energy needs. Geothermal energy use has recently grown due to increasing heat pump utilization and the hot springs energy contribution, which was assumed constant since 1990, is becoming less important when compare to heat pumps although it had an historic significance (Figure 6). There is room for geothermal technologies to reach a greater market penetration as research can help to reduce installation cost of geothermal systems. The currently fair research production should keep growing to attain such a goal.

Table 4. Canada's geothermal energy budget and performance indicators

Geothermal installed capacity (combined heat pumps and hot springs)	1,458 MW_t
Geothermal energy used (combined heat pumps and hot springs)	11,388 TJ yr^{-1}
Number of geothermal publications with Canadian affiliations	765
Geothermal installed capacity per capita	41 MW_t / M people
Geothermal installed capacity per gross domestic product	767 MW_t / G$
Geothermal energy use per total energy consumption in the residential and commercial sectors	0.40 %
Geothermal publications per capita	22 / M people
Geothermal publications per gross domestic product	403 / G$

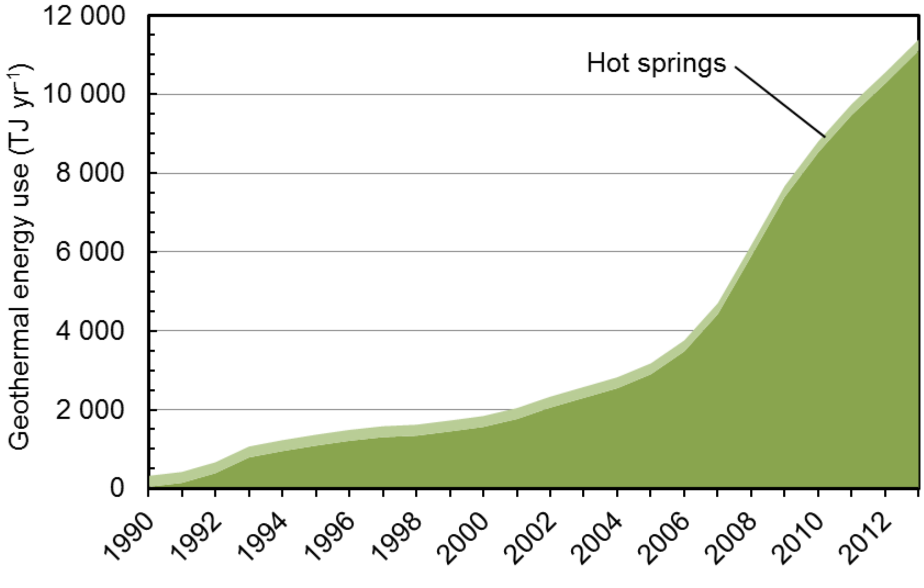

Figure 6. Annual geothermal energy used in Canada.

6. CONCLUDING REMARKS

Although there is no geothermal power plant operated in Canada, direct utilization of geothermal energy has become more popular due to an increase of geothermal heat pump installations over the past ten years. Commercial exploitation of hot springs is expected to remain similar in the near future, whereas heating and cooling of buildings with geothermal heat pumps is a viable alternative for which Canadians are showing a small but growing interest. However, the rate of geothermal development in Canada has been highly influenced by energy prices, particularly oil and gas. Decreasing gas price after the 2008 peak has recently changed energy markets. In this context, geothermal technologies have difficulties competing when looking for short term investments, although geothermal heat pump systems can have local success in niche markets where gas prices remain high or when consumers can handle a longer pay back period, for example institutional buildings. Hybrid geothermal heat pump systems in the commercial building sector also had significant success because they helped to reduce the length of ground heat exchangers needed for a system to decrease installation costs. Peak loads are fulfilled by an additional energy source in a hybrid system such that the ground heat exchanger field is used more often at is full capacity, providing almost comparable energy savings that result in a shorter payback period. This use of combined energy systems is believed to be a logical approach to balance energy savings and installation costs. Further technological developments are needed for hybrid geothermal systems to be commonly used in the residential sector and keep growing geothermal utilization in a competitive energy market.

Research has played an important role in decreasing technological barriers for a broader adoption of geothermal technologies. Efforts to improve design of geothermal systems can help the industry to achieve growth objectives by providing tools to constrain system cost and illustrate potential energy savings, particularly in the geothermal heat pump sector. Valorization of geological environments having favorable characteristics to develop geothermal energy for various direct use purposes can facilitate installation of systems with appropriate design strategies to compete with other forms of energy. For example, development of geothermal systems at flooded underground mines forming high permeability reservoirs can be facilitated by characterization of this environment offering enhanced resources for heating and cooling purposes. Development of added value technologies to increase competiveness, such as ground heat exchangers with improved performances, can finally contribute to decrease geothermal system costs.

Direct utilization of geothermal energy resources of all kinds provided energy savings to Canadians, which benefits in various ways to end users. Monetary savings, diversification of energy supplies, reduced dependency of fossil fuel and reduction of air pollution and greenhouse gas emissions are the main advantages related to geothermal energy. The small proportion of the Canadian energy needs that are fulfilled with geothermal energy indicates that benefits could increase with greater market penetration. For example, the CGC (2010b) has evaluated that greenhouse gas emissions could be reduced by 0.4 to 3.0 M tons of CO_2 equivalents per year if residential geothermal heat pump systems replaced 2 to 16 % of all heating systems currently used. The greenhouse gas emissions related to energy in the residential and commercial sectors of Canada are currently 41 and 28 M tons of CO_2 equivalents per year, respectively (Environment Canada, 2014). Geothermal technologies are definitely one of the alternatives to reduce greenhouse gas emissions in those sectors as system competiveness can improve with new developments.

ACKNOWLEDGEMENTS

The Canadian GeoExchange Coalition and the Canadian Geothermal Energy Association are acknowledged for sharing information that was used in this review to evaluate the installed capacity and energy used related to direct geothermal energy utilization.

REFERENCES

Allen, D. M., Ghomshei, M. M., Sadler-Brown, T. L., Dakin, A. and Holtz, D.: The current status of geothermal exploration and development in Canada, *Proceedings*, World Geothermal Congress 2000, Kyushu, Japan, (2000).

Allen, D. M., Grasby, S. E. and Voormeij, D. A.: Determining the circulation depth of thermal springs in the southern Rocky Mountain Trench, south-eastern British Columbia, Canada using geothermometry and borehole temperature logs, *Hydrogeology Journal*, **14**, (2006), 159–172.

Beatty, J. T., Overmann, J., Lince, M. T., Manske, A. K., Lang, A. S., Blankenship, R. E., Van Dover, C. L., Martinson, T. A. and Plumley, F. G.: An obligately photosynthetic bacterial anaerobe from a deep-sea hydrothermal vent, *Proceedings of the National Academy of Sciences of the United States of America*, **102**, (205), 9306–9310.

Bernier, M.: Ground-coupled heat pump system simulation, *ASHRAE Transactions*, **107**, (2001), 605–616.

CGC: The state of the Canadian geothermal heat pump industry 2010 - Industry survey and market analysis, Internal report, Canadian GeoExchange Coalition, Montreal, Canada, Available on the Internet: www.geo-exchange.ca/en/UserAttachments/article64_Industry%20Survey%202010_FINAL_E.pdf, (2010a).

CGC: Comparative analysis of greenhouse gas emissions of various residential heating systems in the Canadian provinces, Internal report, Canadian GeoExchange Coalition, Montreal, Canada, Available on the Internet: www.geo-exchange.ca/en/UserAttachments/article63_GES_Final_EN.pdf, (2010b).

CGC: The state of the Canadian geothermal heat pump industry 2011 - Industry survey and market analysis, Internal report, Canadian GeoExchange Coalition, Montreal, Canada, Available on the Internet: www.geo-exchange.ca/en/UserAttachments/article81_Final%20Stats%20Report%202011%20-%20February%206,%202012_E.pdf, (2012).

CanGEA: Canadian geothermal projects overview 2013, Internal report, Canadian Geothermal Energy Association, Calgary, Canada, Available on the Internet: http://www.cangea.ca/wp-content/uploads/2013/01/CanGEA_CanadianGeothermalProjects2013_final.pdf, (2013).

Cathles, L. M., Erendi, A. H. J. and Barrie, T.: How long can a hydrothermal system Be sustained by a single intrusive event?, *Economic Geology*, **92**, (1997), 766–771.

Environment Canada: National inventory report 1990-2012 greenhouse gas sources and sinks in Canada executive summary, Internal report, Environment Canada, Gatineau, Canada, Available on the Internet: www.ec.gc.ca/ges-ghg/3808457C-9E9E-4AE3-8463-05EE9515D8FE/NIR2014-Exec%20Sum-Web-Final.pdf, (2014).

Ferguson, G. and Woodbury, A. D.: Subsurface heat flow in an urban environment, *Journal of Geophysical Research B: Solid Earth*, **109**, (2004), B02402 1–9.

Ghomshei, M. M.: Geothermal energy from Con Mine for heating the City of Yellowknife, NWT: A concept study. Internal report, University of British Columbia, Canada, (2007).

Ghomshei, M. M., MacLeod, K., Sadlier-Brown, T. L., Meech, J. A. and Dakin, R. A.: Canadian geothermal energy poised for takeoff, *Proceedings*, World Geothermal Congress 2005, Antalya, Turkey, (2005).

Ghomshei, M. M. and Meech, J. A.: Usable heat from mine waters: coproduction of energy and minerals from “Mother Earth,” *Proceedings,* 4th IPMM Conference,Sendai, Japan, (2003).

Grasby, S. E., Allen, D. M., Chen, Z., Ferguson, G., Jessop, A. M., Kelman, M., Ko, M., Majorowicz, J., Moore, M., Raymond, J. and Therrien, R.: Geothermal energy resource potential of Canada, Open file report 6914, Geological Survey of Canada, Calgary, Canada, (2011).

Grasby, S. E. and Hutcheon, I.: Controls on the distribution of thermal springs in the southern Canadian Cordillera, Canadian *Journal of Earth Sciences*, **38**, (2001), 427–440.

Grasby, S. E., Hutcheon, I. and Krouse, H. R.: The influence of water-rock interaction on the chemistry of thermal springs in western Canada, *Applied Geochemistry*, **15**, (2000), 439–454.

Grasby, S. E., Majorowicz, J. and Ko, M.: Geothermal Maps of Canada, Open file report 6167, Geological Survey of Canada, Ottawa, Canada, (2009).

Groves, D. I., Goldfarb, R. J., Gebre-Mariam, M., Hagemann, S. G. and Robert, F.: Orogenic gold deposits: a proposed classification in the context of their crustal distribution and relationship to other gold deposit types, *Ore Geology Reviews*, **13**, (1998), 7–27.

Hall, A., Scott, J. A. and Shang, H.: Geothermal energy recovery from underground mines, *Renewable and Sustainable Energy Reviews*, **15**, (2011), 916–924.

Hanova, J. and Dowlatabadi, H.: Strategic GHG reduction through the use of ground source heat pump technology, *Environmental Research Letters*, *2*, (2007), 8 pp.

Jessop, A. M., Macdonald, J. K. and Spence, H.: Clean energy from abandoned mines at Springhill, Nova-Scotia, *Energy Sources*, **17**, (1995), 93–106.

Jones, B., Renaut, R. W. and Rosen, M. R.: Biogenicity of silica precipitation around geysers and hot-spring vents, North Island, New Zealand, *Journal of Sedimentary Research*, **67**, (1997), 88–104.

Lamarche, L.: A fast algorithm for the hourly simulations of ground-source heat pumps using arbitrary response factors, *Renewable Energy*, **34**, (2009), 2252–2258.

Lamarche, L. and Beauchamp, B.: A new contribution to the finite line-source model for geothermal boreholes, *Energy and Buildings*, **39**, (2007a), 188–198.

Lamarche, L. and Beauchamp, B.: New solutions for the short-time analysis of geothermal vertical boreholes, *International Journal on Heat and Mass Transfer.*, **50** (2007b), 1408–1419.

Lamarche, L., Kajl, S. and Beauchamp, B.: A review of methods to evaluate borehole thermal resistances in geothermal heat-pump systems, *Geothermics*, **39,** (2010), 187–200.

Lund, J. W., Freeston, D. H. and Boyd, T. L.: Direct utilization of geothermal energy 2010 worldwide review, *Proceedings*, World Geothermal Congress 2010, Bali, Indonesia, (2010).

Majorowicz, J. A. and Jessop, A. M.: Regional heat flow patterns in the Western Canadian Sedimentary Basin, *Tectonophysics*, **74**, (1981), 209–238.

Majorowicz, J. and Grasby, S. E.: Heat flow, depth-temperature variations and stored thermal energy for enhanced geothermal systems in Canada, *Journal of Geophysics and Engineering*, **7**, (2010a), 232–241.

Majorowicz, J. and Grasby, S. E.: High potential regions for enhanced geothermal systems in Canada, *Natural Resources Research*, **19**, (2010b), 177–188.

Majorowicz, J., Grasby, S. E. and Skinner, W. C.: Estimation of shallow geothermal energy resource in Canada: heat gain and heat sink, *Natural Resources Research*, 18, (2009), 95–108.
Marcotte, D. and Pasquier, P.: Fast fluid and ground temperature computation for geothermal ground-loop heat exchanger systems, *Geothermics*, *37*, (2008a), 651–665.
Marcotte, D. and Pasquier, P.: On the estimation of thermal resistance in borehole thermal conductivity test, *Renewable Energy*, **33**, (2008b), 2407–2415.
Marcotte, D. and Pasquier, P.: The effect of borehole inclination on fluid and ground temperature for GLHE systems, *Geothermics*, 38, (2009), 392–398.
Marcotte, D., Pasquier, P., Sheriff, F. and Bernier, M.: The importance of axial effects for borehole design of geothermal heat-pump systems, *Renewable Energy*, 35, (2010), 763–770.
National Energy Board: Canadian energy overview 2012 - energy briefing note, Internal report, National Energy Board, Calgary, Canada, Available on the internet: www.neb.gc.ca/clf-nsi/rnrgynfmtn/nrgyrprt/nrgyvrvw/cndnnrgyvrvw2012/cndnnrgyvrvw2012-eng.pdf, (2013).
Op den Camp, H. J. M., Islam, T., Stott, M. B., Harhangi, H. R., Hynes, A., Schouten, S., Jetten, M. S. M., Birkeland, N.-K., Pol, A. and Dunfield, P. F.: Environmental, genomic and taxonomic perspectives on methanotrophic Verrucomicrobia, Environmental Microbiology Reports, 1(5), 293–306, 2009.
Ozgener, L., Hepbasli, A. and Dincer, I.: Thermo-mechanical exergy analysis of Balcova Geothermal District Heating System in Izmir, Turkey, *Journal of Energy Resources Technology, Transactions of the ASME*, **126**, (2004), 293–301.
Ozgener, L., Hepbasli, A. and Dincer, I.: Energy and exergy analysis of geothermal district heating systems: An application, *Building and Environment*, **40**, (2005a), 1309–1322.
Ozgener, L., Hepbasli, A. and Dincer, I.: Energy and exergy analysis of Salihli geothermal district heating system in Manisa, Turkey, *International Journal of Energy Research*, **29**, (2005b), 393–408.
Ozgener, L., Hepbasli, A. and Dincer, I.: Performance investigation of two geothermal district heating systems for building applications: Energy analysis, *Energy and Buildings*, **38**, (2006), 286–292.
Ozgener, L., Hepbasli, A. and Dincer, I.: Exergy analysis of two geothermal district heating systems for building applications, *Energy Conversion and Management*, **48**, (2007), 1185–1192.
Philippe, M., Bernier, M. and Marchio, D.: Validity ranges of three analytical solutions to heat transfer in the vicinity of single boreholes, *Geothermics*, 38, (2009), 407–413.
Raymond, J.: Overview of geothermal projects related to mine water and direct use in the province of Quebec, Presentation at the CanGEA Annual Meeting, Toronto, Canada, (2011).
Raymond, J. and Therrien, R.: Low-temperature geothermal potential of the flooded Gaspé Mines, Québec, Canada, *Geothermics*, 37, (2008), 189–210.
Raymond, J. and Therrien, R.: Optimizing the design of a geothermal district heating and cooling system located at a flooded mine in Canada, *Hydrogeology Journal*, **22**, (2014), 217–231.
Raymond, J., Therrien, R. and Gosselin, L.: Borehole temperature evolution during thermal response tests, *Geothermics*, 40, (2011a), 69–78.
Raymond, J., Therrien, R., Gosselin, L. and Lefebvre, R.: A review of thermal response test analysis using pumping test concepts, *Ground Water*, **49**, (2011b), 932–945.
Raymond, J., Therrien, R., Gosselin, L. and Lefebvre, R.: Numerical analysis of thermal response tests with a groundwater flow and heat transfer model, *Renewable Energy*, **36**, (2011c), 315–324.
Self, S. J., Reddy, B. V. and Rosen, M. A.: Geothermal heat pump systems: Status review and comparison with other heating options, *Applied Energy*, 101, (2013), 341–348.
Statistics Canada: Estimates of population, Canada, provinces and territories, Table 051-005, Available on the internet: www5.statcan.gc.ca/cansim, (2014a).
Statistics Canada: Gross domestic product, expenditure-based (quarterly), Available on the Internet: www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/gdps02a-eng.htm, (2014b).
Souther, J.G.: Geothermal potential of western Canada, *Proceedings*, 2nd U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, CA, (1976).
Tanguay, D.: The top 10 challenges of the Canadian ground source heat pump industry, Presentation at the 7th Geothermal Heat Pump Business and Policy Forum, Montreal, Canada, (2014).
Thompson, A.: Geothermal Development in Canada: Country Update, *Proceedings*, World Geothermal Congress 2010, Bali, Indonesia, (2010).
Vincent, W. F.: Evolutionary origins of Antarctic microbiota: Invasion, selection and endemism, *Antarctic Science*, **12**, (2000), 374–385.
Williams-Jones, A. E. and Heinrich, C. A.: 100th Anniversary Special Paper: Vapor transport of metals and the formation of magmatic-hydrothermal ore deposits, *Economic Geology*, **100**, (2005), 1287–1312.
Yang, K. and Scott, S. D.: Possible contribution of a metal-rich magmatic fluid to a sea-floor hydrothermal system, *Nature*, **383**, (1996), 420–423.
Younis, M., Bolisetti, T. and Ting, D. .-K.: Ground source heat pump systems: Current status, *International Journal of Environmental Studies*, **67**, (2010), 405–415.
Zhu, K., Blum, P., Ferguson, G., Balke, K.-D. and Bayer, P.: The geothermal potential of urban heat islands, *Environmental Research Letters*, **5**, (2010), 6 pp.