UNIVERSITY OF CALGARY

What are the proven utility scale applications for Solar Steam systems in Alberta?

by

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CERTIFICATE OF COMPLETION OF PROJECT

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The undersigned certifies that he has read, and recommends to the Sustainable Energy Development Program (SEDV) for acceptance, the Project Report entitled "What are the proven utility scale applications for Solar Steam systems in Alberta?" submitted by Apostol Radev, in partial fulfilment of the requirements for the degree of Master of Science in Sustainable Energy Development.

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Date: August 21, 2017

Abstract

This paper will assess *What are the proven utility scale applications for Solar Steam systems in Alberta?* Although Alberta does not have adequate sunshine to generate year-round electricity through solar technology, there is suitable irradiance to economically produce high-quality steam for use in industrial processes. Solar steam systems will empower Alberta oil industry meet its environmental commitments while providing revenues that can help recoup capital investment. This study will integrate an economic analysis as an additional dimension to energy generation potential and environmental benefits of the technology. The financial modeling will reflect the baseline cost for solar fields within NREL's System Advisor Model. The performance-enhancing and cost-reducing model of enclosing solar mirrors in a glasshouse, proven by GlassPoint, will increase the viability of solar steam applications in Alberta. Building a solar steam generation system is seen as technically feasible, with the obstacles being mainly economic and surface right allocation.

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Apostol Radev, August 2017
Calgary, Alberta, Canada

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List of Abbreviations

AEP - Environment and Parks

ANI - Aperture Normal Irradiance

AUC - Alberta Utilities Commission

CAD - Canadian Dollars

CAPEX - Capital Expenditure

CFREF - Canada First Research Excellence Fund

CO_2 - Carbon Dioxide

COP 21 - 2015 United Nations Climate Change Conference

COSIA - Canada's Oil Sands Innovation Alliance

CSP - Concentrating Solar Power

CSS - Cyclic Steam Stimulation

DNI - Direct Normal Irradiance

DOE - Department of Energy

DSG - Direct Steam Generation

EOR - Enhanced Oil Recovery

GHG - Greenhouse Gas

GHI - Global Horizontal Irradiance

gJ - Gigajoule

hr - Hour

HTF - Heat Transfer Fluid

IRENA - International Renewable Energy Association

kg - Kilogram

km - Kilometer

km^2 - Square Kilometer

kWh/m2 - Kilowatt Hour per Square Meter

LARP - Lower Athabasca Regional Plan

LCOE - Levelized Cost of Energy

m/s – Metter per Second

m2 - Meters Square

mb/d – Million Barrels per Day

MW – Megawatt

MWhr - Megawatt Hour

MWhr/m2 - Megawatt Hour per Square Meter

MWt – Megawatt Thermal

NRCan - Natural Resources Canada

NREL - National Renewable Energy Laboratory

OPEX - Operational Expenditure

OT-HRSG - Once Through-Heat Recovery Steam Generation

OTSG - Once Through Steam Generation

PTC - Parabolic Trough Collector

PV - Photovoltaics

SAGD - Steam-Assisted Gravity Drainage

SAIT - Southern Alberta Institute of Technology

SAM - System Advisor Model

SOR – Steam to Oil Ratio

SSG - Solar Steam Generation

TES - Thermal Energy Storage

US - United States

USD - United States Dollars

Symbols

°C - Celsius

bar - 100 kilopascals

Conversion rates

Canadian Dollars to United States Dollars: CAD to USD (1 CAD = 0,8 USD)

Million British Thermal Units to Gigajoule (1,055 MMBTU = 1 gJ)

Pounds per square inch to bar: PSI to bar (1 PSI = 0,069 bar)

CHAPTER 1: Introduction and Background

With some of the largest deposits of oil, coal, and natural gas, Canada has the potential to establish itself as a global energy leader. In addition to Alberta's vast deposits of fossil fuels, hydro, wind and solar energy projects have also been a big part of Canada's energy mix. Moreover, as fluctuating oil and gas prices have led to a recession, the adage of diversifying the economy has once again been tabled. Typically, stakeholder groups that support Alberta's oil industry and the Clean Tech energy development lobbyists do not agree on what the proper strategy for Canada's renewable energy development is. Currently, there is no nationwide energy strategy, and this is a topic of debate as to whether one should or should not exist. Recent discussions over the country's sustainable energy development policy have led to the conclusion that rather than considering the oil and the renewable energy sectors as rivals, they should look into collaborating with each other.

The pledges made by 133 countries, including Canada, as part of the Paris Agreement (COP 21) have accelerated the pace of change in the global energy sector. One of the Paris Agreement's central targets is to strengthen the global response to climate change by keeping a global temperature rise below 2 degrees Celsius compared to pre-industrial levels[1] (United Nations, 2016). These are challenging times for the energy sector in Canada, but responding to this new reality should be taken as an opportunity for new beginnings. The changing policy landscape in the country is creating new drivers from a business risk management and investment perspective. Furthermore, the business case for integrating a climate dimension on a corporate level is a lot stronger than it used to be. There are great entrepreneurship and innovation in Alberta's energy industry, and the local spirit and skill set can help build the bridge to a sustainable energy sector (Delphi Group, 2016).

1.1 The Research Question

Alberta has taken the position of Canada's sign-off on COP 21 as a long-term opportunity to reduce oil-sands emissions by looking into investing in next-generation de-carbonization technologies (Frangoul, 2017). Alberta's oil sands have faced a widespread support in being a critical

[1] Pre-industrial levels refer to a period just before the beginning of 19th century. (Hawkins, 2017)

part of the global energy mix, and it is important that the local energy industry demonstrates that the oil sands are being developed in a holistic manner in line with domestic and global requirements. Considering the steam dependent oil operations in Alberta, the local producers have an ideal opportunity for a low-carbon solar steam generation due to the high Direct Normal Irradiance (DNI) that the province has to offer. Even if there is validity to the suggestion that climate change is not caused by the release of carbon emissions, this study proposes a novel technology that offers attractive economic benefits to Canada's oil industry. Considering Alberta's steam assisted Enhanced Oil Recovery (EOR) needs, and the unlimited solar potential that could be used for an economical and carbon-free production of steam, the research question of this study is *What are the proven utility scale applications for Solar Steam systems in Alberta?*

1.2 The Purpose of the Study

According to the World Energy Outlook 2016, energy development is set to increase regardless if nations meet their pledges to COP 21. Power demand is projected to increase by 30 percent by 2040, and natural gas demand is expected to grow by 50 percent, overtaking coal in the global energy mix. Oil demand from passenger cars is anticipated to decline even as the number of vehicles doubles in the next quarter century, mainly due to improvements in efficiency and the uptake of electric vehicles. However, oil demand will continue to increase, mostly because of a lack of viable alternatives to oil in road freight, aviation, and petrochemicals. As a result, the global oil consumption is expected to increase by 15 percent to 103.5 mb/d in 2040, from 92.5 mb/d in 2015 (International Energy Agency, 2016). Despite the increased number of renewable energy projects developed in the past 20 years, a global energy shift towards 100 percent renewable power generation will continue to be a long-term process. Achieving local and global sustainability goals will not be accomplished without the use of conventional power generation and fuels. The purpose of this study is to propose a solution for R*educing the high cost and high carbon emission of Canada's oil industry.*

1.3 Alberta Oil Industry

Oil, as it occurs in the ground, comes in various types and different viscosities. Some oil is very thin (conventional oil) some is very thick (unconventional oil). Primary production in all of the world's major conventional oil reservoirs is now in decline and at the same time demand is still increasing. The gap opening between existing supply of oil and demand for oil can be made up by exploiting unconventional resources, such as Alberta's Oil Sands.

The Oil Sands of Alberta are reservoirs containing oil in the form of bitumen. The bitumen is mixed with sand, water and clay. Bitumen has a high viscosity, making it difficult to extract from the reservoir. To get bitumen out of the ground, oil producers use the principle of heating the oil up and reducing its viscosity. The challenging part is that the oil is thousands of feet underground and it can't be heated directly. The technology that producers use to heat the ground up is thermal Enhanced Oil Recovery (EOR) which is becoming the leading method of producing oil in Alberta. Thermal EOR is heating up a cubic mile of rock by injecting high-pressure steam produced in natural gas-fired boilers. These EOR methods include Steam-Assisted Gravity Drainage (SAGD) and Cyclic Steam Stimulation (CSS). Both methods involve the production of heat in the form of steam that is injected into the reservoir in order to lower the viscosity of the oil, thus making it more easily extractable.

The opportunity for solar systems is to use solar energy rather than fuel to deliver heat at a competitive price to fuel. The process of using the sun to heat water into steam reduces the need for natural gas in the oil extraction process. It is friendly to the environment and friendly to the bottom line of the oil producers due to the natural gas and carbon tax revenues that the technology offers. With more than half of Alberta oil produced by steam injection, supplying 10% of that steam demand with solar instead of burning natural gas can result in a lot of high paying jobs created and billions of revenue added to oil province's energy industry.

1.4 Energy, Environment and Economics

This study will use a three-dimensional approach focusing on: (1) meeting Alberta oil industry energy demands, (2) while complying with domestic and international environmental commitments by (3) using an economically feasible solution that doesn't affect the bottom line of producers. The solar steam technology that this study proposes will not only enhance oil production with solar energy but it will also reduce carbon emissions and costs. The financial and economic benefits of the system can establish the Alberta oil industry as the next big market for solar in

Canada. Reflected in the following two chapters are the research literature review and methodologies used, which include validation of previous academic and professional work on the topic along with financial modeling and business plan development for solar steam systems.

CHAPTER 2: Literature Review

Most of the information on solar steam technology available focuses on electrical generation (Concentrated Solar Power, CSP) rather than steam generation alone. Research is limited regarding its application and success in northern, high-latitude regions.

This literature review has focused on research outlining potential to utilize concentrated solar technology in cold northern climates. Research indicates that, although Alberta is not ideal for electrical generation through current concentrated solar power technology, there is enough solar potential to economically produce high-quality steam for process heat applications such as thermal EOR. The market for EOR in Alberta is vast, especially when applied to in place (in-situ) bitumen operations. Hybrid plants could be integrated into existing natural gas steam generation facilities and provide constant steam supply while saving on operational costs and reducing the environmental impact as a result of solar steam energy contribution.

2.1 Previous Professional and Academic Work Related

The three primary sources of qualitative and quantitative information used were:

1. California based GlassPoint and the data available from their operations in California and Oman;
2. The thesis on *Solar Concentrating Steam Generation in Alberta, Canada* developed by two graduate students from KTH School of Industrial Engineering and Management in Sweden, and;
3. SAIT Polytechnic's study on *Concentrated Solar Steam Plant Feasibility* developed by a team of two SAIT research analyst, a firs class power engineer from SAIT and myself.

2.1.1 GlassPoint

GlassPoint Concentrated Solar system has shown rapid deployment for steam production in the oil industry in the recent years. GlassPoint's 0.3 MWt parabolic trough proof of concept plant in McKittrick, California that was built to demonstrate their system has been providing thermal energy to an adjacent Berry Petroleum EOR facility since 2011. After successfully demonstrating their model, GlassPoint went on to construct a 7 MWt direct steam generation plant for Petroleum Development in Amal, Oman that has been providing 50 tons of steam per day since 2013. The scalability of the GlassPoint system has been proven with the construction of a 1,000 MWt plant in Miraah, Oman that is scheduled to start generating steam in 2017 (GlassPoint, 2017).

GlassPoint's system of enclosing the solar mirrors in a glasshouse along with the other performance-enhancing and cost reducing features potentially increases the viability of solar steam applications in Alberta, particularly when contrasted with earlier concentrated solar designs such as the system installed in Medicine Hat.

2.1.2 School of Industrial Engineering and Management | KTH

Another reference to my topic is a study from KTH School of Industrial Engineering and Management in Sweden investigating the viability of producing industrial steam from concentrating solar technology in Alberta. The paper provides an in-depth description of the technical feasibility of the technology, but the research falls short of detailing a financial feasibility and cost structure associated with development and operation (Ambrosson & Selin, 2016).

2.1.3 SAIT Polytechnic

The Southern Alberta Institute of Technology (SAIT) Green Building Technologies research group and SAIT MacPhail School of Energy partnered to conduct a research project on the feasibility of utilizing utility-scale concentrated solar power for steam production in cold climates.

The authors recommend installing a 1.5 MWt proof of concept steam generating CSP facility on the SAIT or University of Calgary campus for training that would also be tied into the district heating system and provide a portion of the campus heating energy. The core values of this project could be realized from data gathered from this pilot plant that would give input for winter design and operation considerations for future CSP projects in Canada. The study showcases how renewable energy production can be used in conjunction with the oil industry to improve efficiency and reduce GHG emissions (Jackman et al., 2017).

2.2 The Intellectual Gap in the Past Research

My study will leverage the available literature as a foundation when addressing the technical feasibility and the environmental benefits of implementing Concentrated Solar Power technology principles in northern climates. Building upon past work, this study will develop a business plan for implementation of Solar Steam systems in Alberta. The previous work on the topic has a gap on financial feasibility that will be addressed in this research.

CHAPTER 3: Methodology

Considering Alberta's Enhanced Oil Recovery (EOR) needs, and the unlimited solar potential that could be used for an economical and low-carbon production of steam, this study will assess the technical and financial viability of implementing utility scale Solar Steam systems in Alberta.

3.1 Objective

The objective of this study is to develop a feasibility analysis for a cost-effective solar energy technology for Alberta's oil sector and all other industrial and district heating processes in the province. SolarSteam generation will provide not only environmental benefits, but it will also help reduce natural gas and carbon tax cost.

3.2 Material and Methodology

First and foremost an extensive literature review was conducted, and many people with experience in the industry were consulted in order to obtain necessary knowledge and information on the subject. The current markets for concentrating solar technologies have been investigated as well as what has previously been done in the area of concentrating solar steam generation.

As mentioned above the objective of this research is to conduct a feasibility study analyzing on the viability of solar steam generation technology for utility scale implementation in the Alberta Oil Sands. A feasibility study typically includes five areas: technical, economic, legal, operational and schedule feasibility. Due to the system being at a proof of concept and business development stage, the emphasis of this study is on the energy generation technical feasibility, the economic aspects of the system and the environmental benefits it offers.

3.2.1 Energy Generation Feasibility

An important part of energy generation technical feasibility was to validate weather data collected. The weather data included direct normal irradiance (DNI), wind speed and ambient temperature. All aforementioned parameters are necessary for the calculation of the potential steam output from the system.

After validating the weather data, components for the system were chosen and designed to maximize overall output. Calculations were made on an hourly basis using weather data dating back eight years to give an overview of how the steam output changed over time. The software used for the calculation model was Microsoft Office Excel which is a software that offers a good overview of calculations that are using many input parameters.

The glasshouse enclosed parabolic mirror technology pioneered by California-based GlassPoint was chosen as the baseline concept considered for this study. Their design keeps the mirrors within a glasshouse structure to help overcome challenges with the winter and windy conditions typical for Alberta. Depending on whether the rate of steam injection from the solar steam system is held constant or increased during the hours with most sunshine available, gas consumption could be reduced between twenty-five and eighty percent by injecting more steam during the day and less at night. Unlike gas-fired units, solar steam produces zero-emissions making it easier for operators to comply with increasingly tight environmental regulations (Glass Point, 2017).

3.2.2 Economic Feasibility

This study included an estimation of possible Capital Expenditure cost (CAPEX) and Operational Expenditure cost (OPEX) along with projected savings from using solar energy to create steam in oil production as opposed to burning natural gas. The projections were conducted through calculating the cost of steam from conventional EOR and Solar EOR production methods. The site for this investigation was Cold Lake located in the Alberta Oil Sands, at which EOR methods are used to increase oil production rates.

The economic modeling reflected the baseline cost for parabolic trough solar fields within NREL's System Advisor Model (SAM). SAM is the primary tool used by NREL and the U.S. Department of Energy (DOE) for estimating the performance and cost of Concentrating Solar Power (CSP) technologies and projects. The budgeted cost of GlassPoint's 1,000 MWt Miraah plant was also used as a cross-reference and indicated similar estimate to the costs shown in the economic models developed in this study.

This study will also develop a business plan to support building the business case for solar steam systems utility scale implementation as a renewable energy solution to Alberta's oil sector. The business plan build will determine Net Present Value (NPV), Capital Efficiency, Breakeven (BE) and CAPEX & OPEX for 500MWt 33,000 barrels per day Solar EOR operation in the Lower Athabasca Region of Alberta.

3.2.3 Environmental Benefits

The primary environmental benefit from implementing solar steam systems in Alberta would be the reduction of carbon dioxide (CO_2) produced in natural gas consumption for steam generation. Decreasing the natural gas required for process steam production would result in significant CO_2 emissions savings that would help Alberta and Canada meet its environmental commitments. If 10% of the current steam for thermal extraction in Alberta were produced by solar steam at an average steam to oil ratio (SOR) of 4, the resulting annual emission reductions would be over 2,760,000 tons/year.

3.3 Assumptions

Assumptions made in this research project are as follows:

- The weather data (including direct normal irradiance) from 1998 to 2005 that was used in this study will accurately describes future weather conditions;
- Climate Leadership and energy policies in Canada will be followed for the coming years;
- Provincial and federal governments will be supportive with making amendments to current surface rights approved applications to allow for solar steam systems development;
- Appropriate Aboriginals people's consultation resulting in social license;
- The demand for Thermal EOR development in Alberta will continue to grow;
- USD to CAD exchange rate at 1 to 1.25.

3.4 Scope and Boundaries of the Study

The analysis of this study will be primarily focused on the feasibility of implementing two pilot plants, one in Calgary and one in Cold Lake, and a 500MWt utility scale solar steam system to support 33,000 bpd EOR operation in the Lower Athabasca Region of Alberta, Canada. Existing information on the technological feasibility for solar steam generation will be used when presenting the technical and engineering aspect of the proposed technology. Due to the complexities of changing nature of Canada's position towards first nations consultation is currently out of scope. We are looking at pure play financial feasibility study for the purposes of this research project.

3.4.1 In Scope

- Technical feasibility of using renewable solar steam technology to meet increasing thermal EOR demand in the Alberta Oil Sands.
- Financial feasibility of solar steam technology in Alberta.
- Develop a business plan that will determine the NPV, Capital Efficiency, BE and CAPEX & OPEX for 500MWt 33,000 barrels per day Solar EOR operation in Alberta
- Assess the carbon dioxide reductions that solar steam technology can offer to Alberta Oil Sands industry.

3.4.2 Out of Scope

- International markets.
- Aboriginal people's consultation.
- Unforeseen externalities.
- Surface rights application.
- Methane and Carbon Monoxide emissions reduction.
- Changing the image of Alberta Oil Sands.

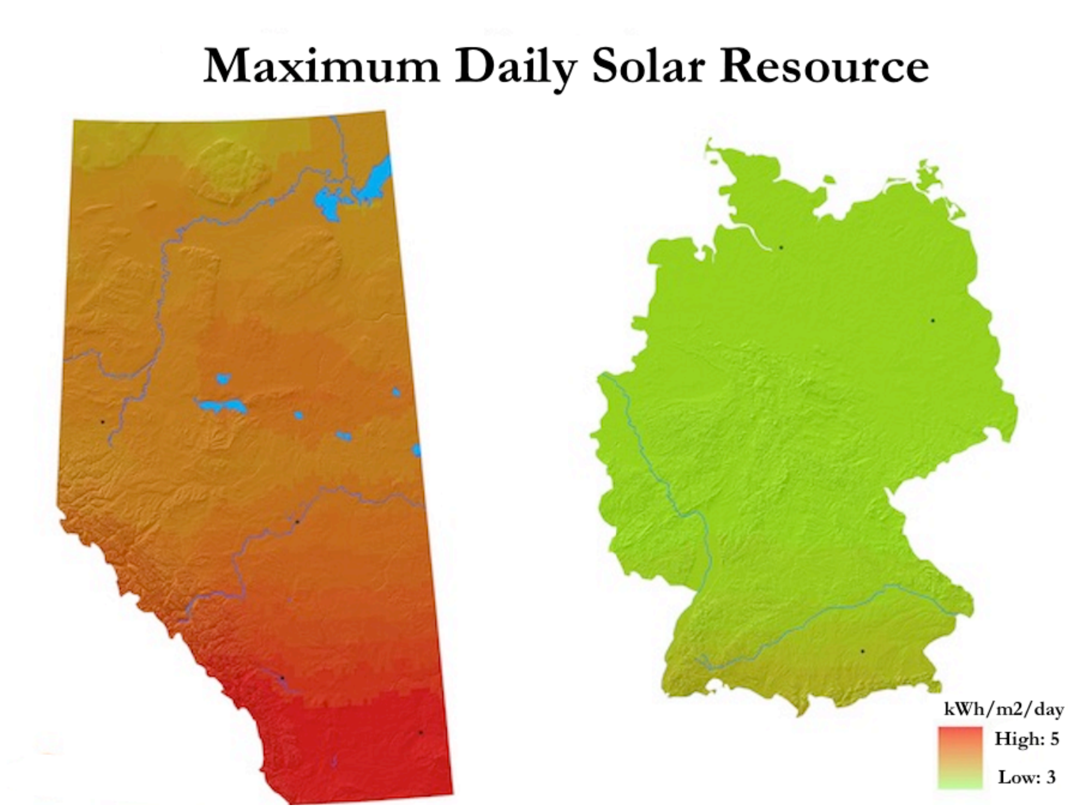
3.4.3 Major Risk

Although surface rights are out of scope for the purposes of this research paper, land allocation is a key restriction to the viability of this project. Given the need for surface areas of over a square kilometer near existing SAGD operations and the challenges of receiving approval for development, this study addresses allocation to surface rights from a risk mitigation standpoint in Chapter 9.

CHAPTER 4: Alberta Solar Irradiance and Weather Potential

With a solar resource, 25 percent better than Ontario's and 30 percent better than Germany's (KPMG, 2014) Alberta has enough solar irradiance to economically produce high-quality solar steam using the principles of Concentrated Solar Power (CSP) technology.

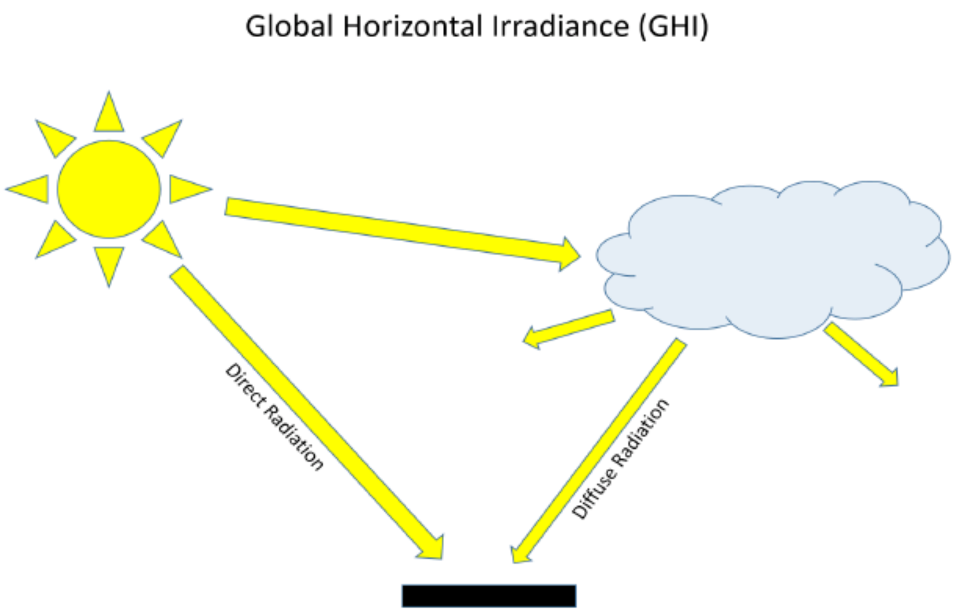
Figure 1 Alberta vs Germany Maximum Daily Solar Resource.



(Alberta Innovates , 2013)

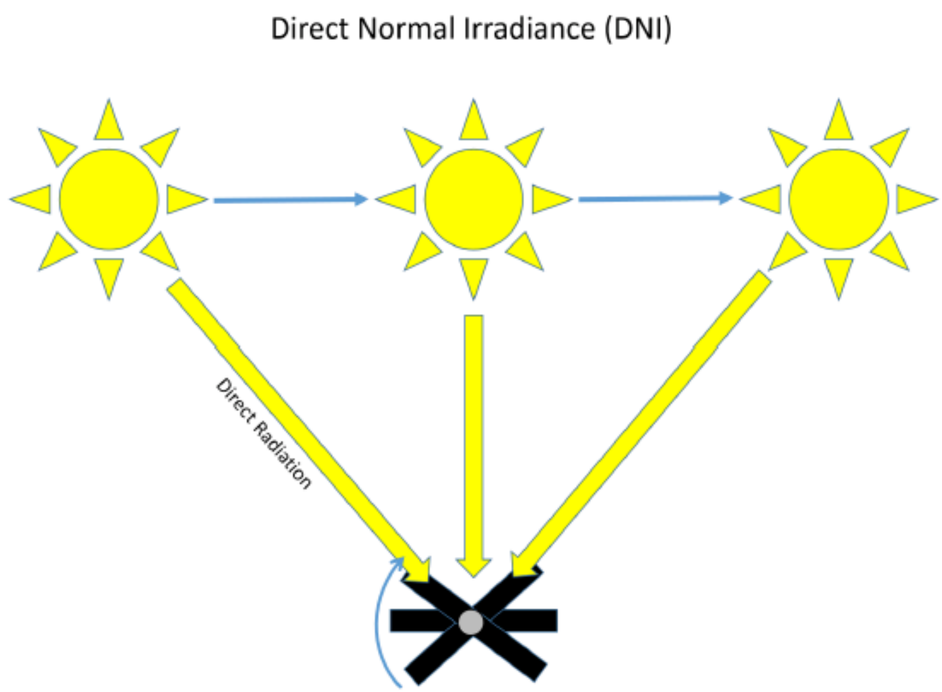
Calgary and Cold Lake are among the cities receiving the most sunlight hours per year in Canada, with an average between 310 and 330 sunny days per year (Current Results, 2010). In order to thoroughly evaluate the potential for solar steam generation at Calgary and Cold Lake areas, a large quantity of weather data was needed. This data was gathered from sources collecting weather data hourly and included direct normal irradiance (DNI), global horizontal irradiance (GHI), ambient temperature and wind speed and wind direction. Figures 2 and 3 below show schematic pictures demonstrating global horizontal irradiance and direct normal irradiance respectively (Ambrosson & Selin, 2016, p. 5).

Figure 2 Global Horizontal Irradiance on a surface - direct radiation and diffused radiation.



(Ambrosson & Selin, 2016)

Figure3 Direct Normal Irradiance at three different time of the day.



(Ambrosson & Selin, 2016)

DNI is the amount of solar irradiance that hits a surface normally oriented to the direction of the solar rays (Vaisala Energy, 2017). When measuring DNI, a tracking device must be used to follow the sun's position in order to keep the plane with the measuring device normal to the solar rays. The device most commonly used is a pyrheliometer coupled with a tracking device (Kipp & Zonen, n.d.). Figure 4 shows the pyrheliometer used for DNI measurements at Hat Smart in Medicine Hat. DNI only accounts for direct irradiance and no diffuse irradiance is included in the DNI value. In Figure 3 above, the black lines represent the normal plane to the direct radiation from the sun at three different moments in time. DNI is measured as the amount of energy per surface area, using W/m2 units.

Figure 4 Weather station at Hat Smart CSP Plant in Medicine Hat, Alberta.

(Ambrosson & Selin, 2016)

4.1 Solar Irradiance Potential and Validation

Weather data was collected for the city of Calgary for a proposed demonstration proof-of-concept pilot plant. The solar irradiance was validated using accessible solar data on an hourly basis. Direct normal irradiance (DNI) data and Global Horizontal Irradiance (GHI) data was acquired from the Calgary International Airport. However, data from the airport was only available until 2005. In order to validate usage of solar irradiance data from the airport an average year of 1998-

2005 was created. This average year was then compared to an average year at SAIT Polytechnic, composed of data from the Green Building Technology group. Hourly data from the Green Building Technology group was available from September 19, 2012, to June 14, 2014, and an average year of irradiance was calculated using this data (Ambrosson & Selin, 2016, p. 7).

Solar irradiance data and ambient temperature data used for Calgary was collected from the Calgary International Airport and SAIT Polytechnic weather stations. Airport weather data was available for the period 1953-2005 and from this data, a sample 8-year period of 1998-2005 was chosen for this review. It is assumed that the weather conditions observed from 1998 to 2005 are representative of the weather conditions occurring after 2005.

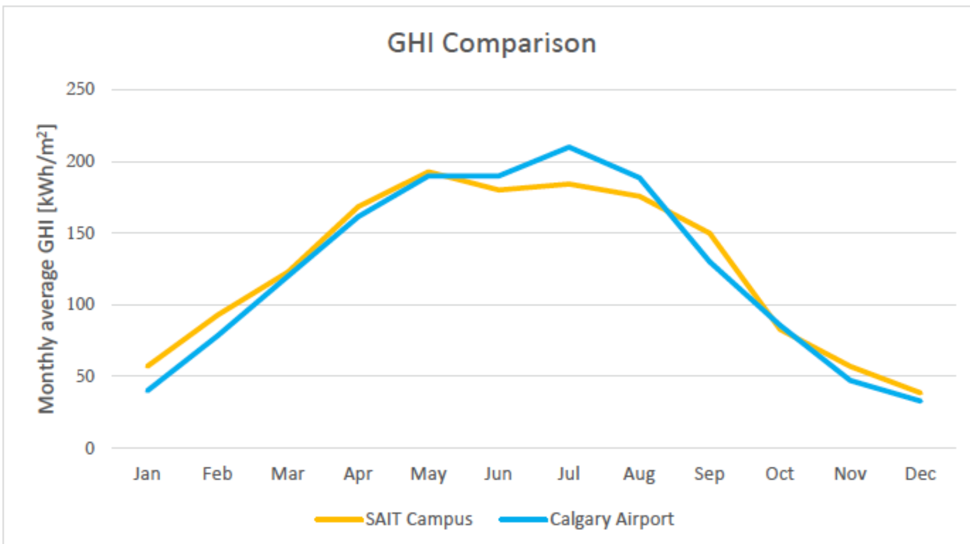
The GHI average over the eight years available from the Calgary Airport was 1485 kWh/m2 yearly, and the average year of the weather station at SAIT campus was 1486 kWh/m2. The data from the airport is measured horizontally, however the pyranometer used for measuring GHI at SAIT Polytechnic was placed on a south-facing surface with a slope of approximately 22 degrees. The south-facing pyranometer will therefore likely show a slightly higher value for GHI than a horizontally oriented pyranometer (Ambrosson & Selin, 2016, p. 7).

Figure 5 Solar irradiance measurement station using tilted pyranometer at SAIT Polytechnic.

(Ambrosson & Selin, 2016)

The figure below shows a comparison of the GHI measured on SAIT Polytechnic campus and the values measured at the Calgary International Airport.

Figure 6 Global Horizontal Irradiance (GHI) measurements of Calgary International Airport and SAIT Polytechnic Campus.

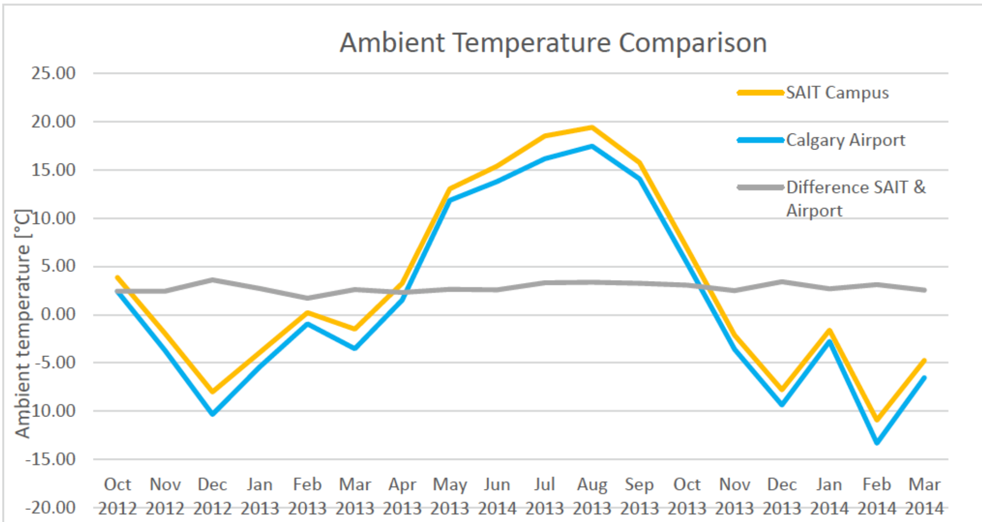


(Ambrosson & Selin, 2016)

4.2 Ambient Temperature Comparison

In order to validate the temperature data from the Calgary International Airport, temperature data taken from the Green Building Technology group at SAIT Polytechnic was also used. The Green Building Technology group uses a dry bulb thermometer that logs the ambient temperature on the northwest part of SAIT campus hourly. This data was compared to the hourly ambient temperature data from the Calgary International Airport. The comparison is shown in Figure 7, where the gray line shows the temperature difference between the SAIT measurements and the airport measurements. Temperature data from SAIT is available from October 2012 to March 2014 on an hourly basis and was compared to corresponding temperature data from the airport (Ambrosson & Selin, 2016, p. 9).

Figure 7 Ambient temperature measured at SAIT campus and at the Calgary International Airport and the difference between the two measurements.



(Ambrosson & Selin, 2016)

It is seen that the temperature measurements of both measuring stations follow the same curve, thus validating the usage of temperature data from the Calgary International Airport. On average, the difference in measuring was between two to three degrees with the measurements taken at SAIT showing a slightly higher temperature. The effects of changes in ambient temperature are shown in section 6.4 and are considered minor.

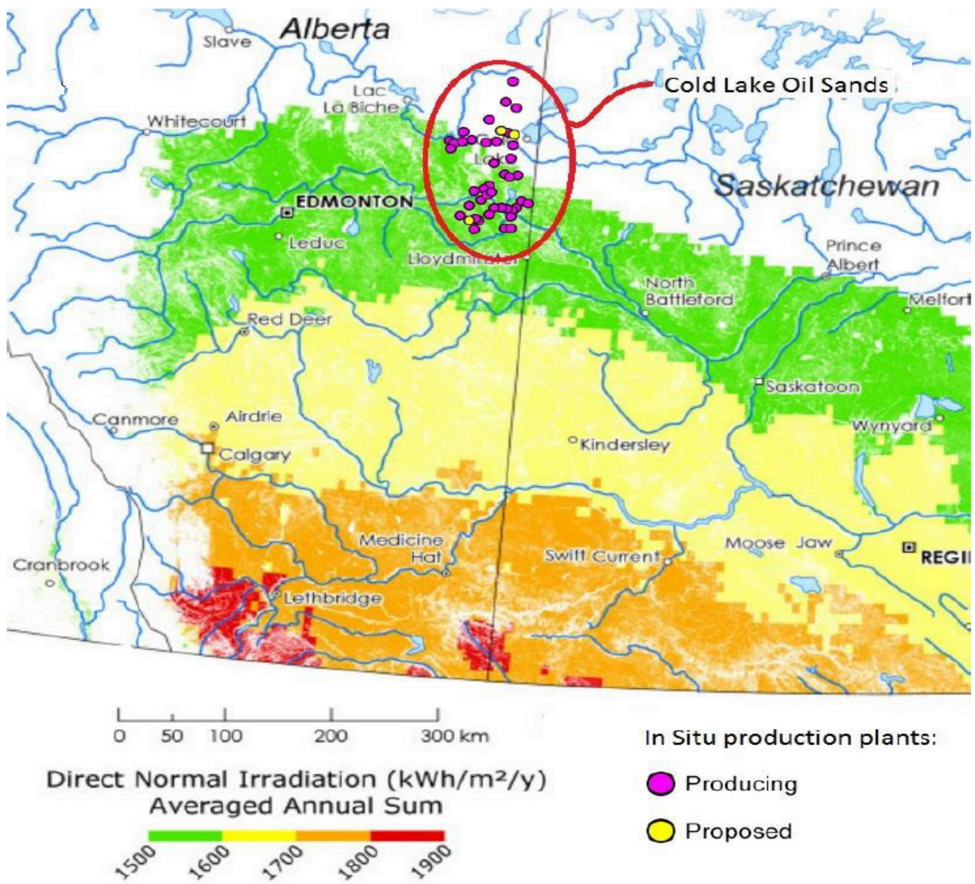
4.3 Potential Sites for SolarSteam Systems in Alberta

International Renewable Energy Association (IRENA) reports indicates that a minimum DNI of 2.0 MWhr/m2 per year is required for the economical operation of a CSP plant that is to produce electricity. However, past research has shown that solar steam production could be viable with as little as 1 MWhr/m2 per year.

The results from the weather data gathered for the city of Calgary have helped verify that central Alberta reaches irradiance levels of over to 2.0 MWhr/m2 per year. Even though the oil producing northern parts of Alberta do not experience the highest solar irradiance in the province, areas of the Cold Lake area of Alberta have between 1.1 and 1.6 MWhr/m2 per year as the following Direct Normal Irradiation map show.

Furthermore, Figure 19 in Chapter 6 shows that the lowest rates of DNI in Cold Lake are in the months of November, December, January and February with DNI of less than 1 MWh/m2. This suggests that there is sufficient solar resource to generate steam using solar energy for at least eight months out of the year along with potentially being able to use the system for boiler feed hot water generation in the winter.

Figure 8 Cold Lake Oil Sands DNI values and in-situ producing plants.



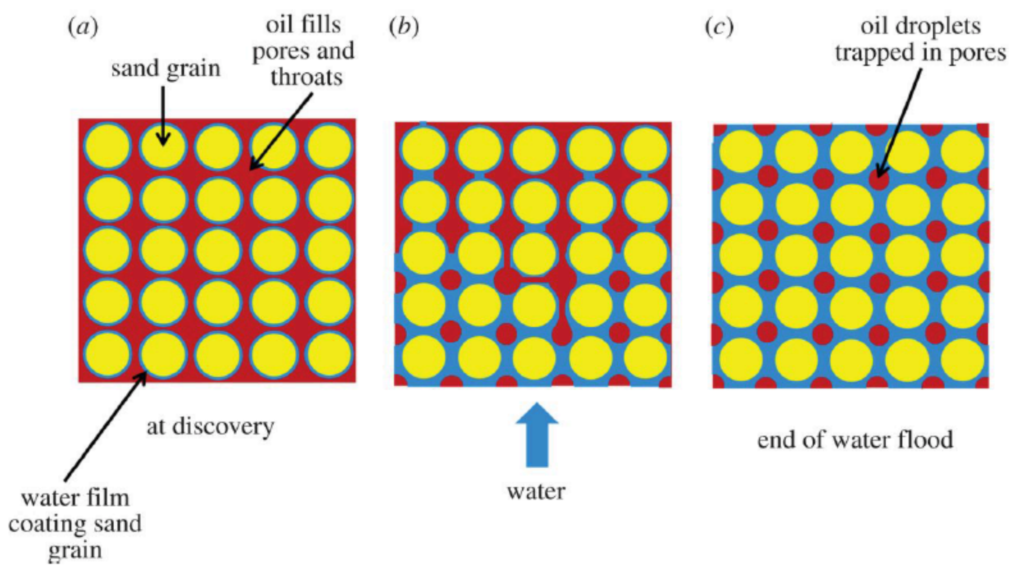
(Djebbar et al., 2014)

The the most likely part of the Alberta Oil Sands to have the ability to utilize solar steam generation is the southernmost part of Cold Lake, which receives the highest annual DNI. In the Cold Lake area most of the oil reservoir is situated 400-600 m below ground and currently Cyclic Steam Stimulation (CSS) is commonly incorporated on the production sites. However, in the northern part of Alberta the oil reservoirs are only situated approximately 250 meters below the surface and in these areas Steam Assisted Gravity Drainage (SAGD) is also implemented. These implementation methods to recover bitumen are called in situ (in place) methods (Muggeridge et al., 2013). A picture of the DNI and the Oil Sands of Cold Lake as well as in-situ production plants are shown in Figure 8.

CHAPTER 5: Lower Athabasca Region Oil

In the Cold Lake area of the Lower Athabasca Region, as opposed to some other parts of the Oil Sands, the oil reservoirs in the rocks are so-called water wet. This means that the oil is trapped in wet grains of sand which enables the usage of steam injection to enhance the extraction of oil.

Figure 9 Picture showing oil trapped by water wet sand grains.



(Muggeridge et al., 2013)

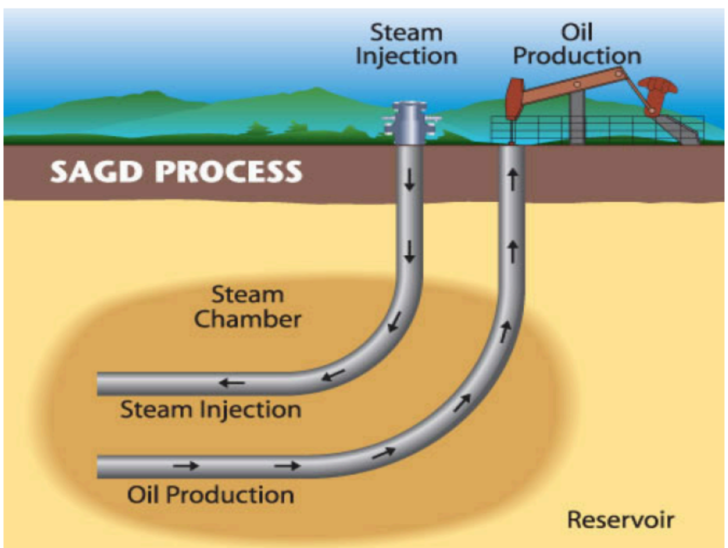
5.1 Steam-Assisted Gravity Drainage (SAGD)

SAGD is a technique used within the field of enhanced oil recovery to maximize the output of an oil reservoir. SAGD is the process of injecting hot steam together with a solvent into the oil reservoir making it easier to pump (due to a lower viscosity) and consequently increasing the production of the oil reservoir. This process is widely used in oil reservoirs that have a highly viscous oil-content in the form of bitumen or heavy crude oil.

To implement SAGD (as shown in Figure 10), two parallel horizontal holes are drilled approximately 4-6 meters apart into the reservoir. Hot steam is injected into the upper of the two wells, lowering the viscosity of the bitumen. Once the bitumen is heated sufficiently, gravitational forces will make the bitumen flow downwards to the lower horizontal well where the oil extraction occurs. SAGD usually enables a higher degree of oil recovery than CSS, at around a recovery rate of 50 percent compared to 20 percent, however, CSS has a higher degree of recovery of water and solvents (Donnelly, 2000).

In Cold Lake applications, SAGD steam is injected at a pressure of 10-40 bar, with a steam temperature varying between 180 °C and 260 °C and the steam quality is maximized up to qualities close to 100 percent vapor (Mohammad et al., 2017).

Figure 10 Schematic showing the concept of Steam-Assisted Gravity Drainage.



(Hislop, 2014)

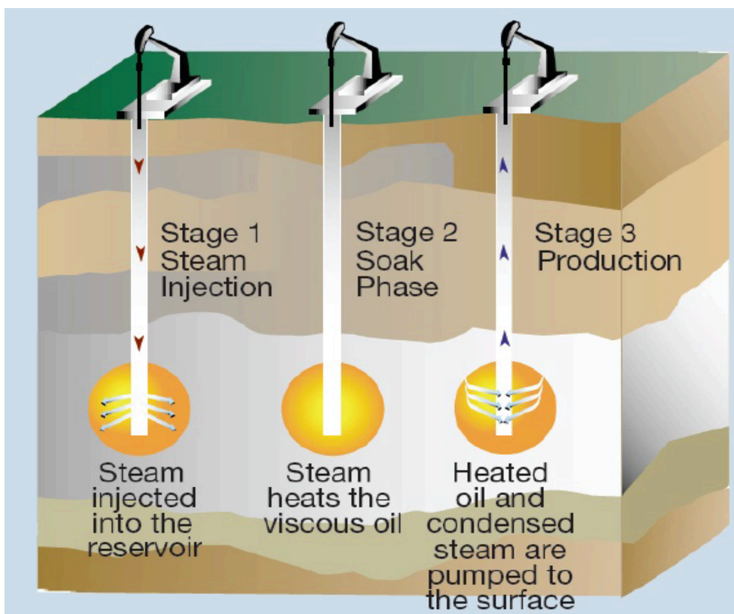
5.2 Cyclic Steam Stimulation (CSS)

Cyclic steam stimulation (CSS) is a technology that uses the injection of steam together with a solvent on a cyclical basis as opposed to SAGD, which injects steam continuously for a longer period of time. In the CSS process, steam is injected into a vertical borehole to decrease the viscosity of the bitumen or heavy crude oil, enabling it to flow into a production well from where it is then pumped up (RAMP, 2017).

As shown in Figure 11, there are essentially three steps to CSS: the first step is the injection of steam into the reservoir, the second step is soaking which allows the heat to soak into the reservoir making it extractable, and the third step is production whereby the oil is pumped up to the surface.

CSS used in the Cold Lake area of the Oil Sands uses steam generated at 140-170 bar flashed to an injection pressure of 100-140 bar. The temperature of the steam is approximately 310 °C to 320 °C and the quality is about 60 percent vapor (RAMP , 2017).

Figure 11 Schematic picture demonstrating how CSS works.



(CAPP, 2015)

One of the drawbacks of SAGD, CSS and other steam injecting oil recovery processes is that it consumes more energy per produced barrel of oil than conventional oil production. When this energy is coming from conventional fuel sources, it imposes an additional cost on the cost of extraction. However, using solar energy in enhanced oil recovery methods eliminates some of the fuel associated cost.

CHAPTER 6: Solar Steam System

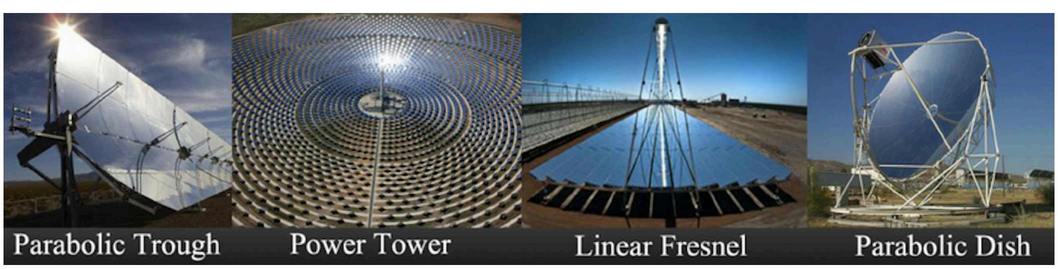
Concentrated Solar Power (CSP) is an innovative renewable technology that has already been utilized on industrial scale. The technology and its use are very different from solar photovoltaic (PV) systems which create electricity directly from sunlight, and from solar thermal systems that heat fluid to maximum 80°C for domestic water, space or pool heating applications.

CSP technologies use mirrors to concentrate and collect the sun's thermal energy onto a receiver. The received energy is used to directly heat water or a Heat Transfer Fluid which is used to produce steam that can be utilized for industrial purposes or to power a steam turbine. Many CSP plants are in operation around the world, most notably in warm and sunny climates. These plants use the steam to power a steam turbine that drives an electrical generator. Recently Solar Once-Through-Steam-Generators (OTSG) have been incorporated to create steam directly from water for Enhanced Oil Recovery applications, thus eliminating the heat transfer fluid, heat exchanger as well as the related pumps and controls. Although utilizing CSP for electricity in Canada is not yet ideal due to the country's high-latitude and long winters, steam generation solar technology is feasible for use in areas such as EOR, industrial processes and district heating (Jackman et al., 2017, p. 9).

6.1 Solar Collectors

Within the field of CSP technologies, there are four major solar receivers that are used with the mirrors concentrating the solar irradiance to either a single point or onto a line. The objective of the solar collectors is to concentrate the solar thermal energy with as few losses as possible and to transfer it to a fluid. All four concentrating solar technologies can be seen in the figure below.

Figure 12 Different types of concentrating solar collectors.



(Google Image, 2015)

6.1.1 Parabolic Trough

The parabolic trough technology is a line focusing solar technology using mirrors with a parabolic shape that are reflectively coated. The mirrors reflect the sunlight to an absorber pipe at the focal point of the mirror. The absorber pipe usually consists of an outer glass tube and an inner-coated steel pipe with a vacuum in-between in order to minimize convective losses. Inside the absorber pipe, the heat transfer fluid flows with a turbulent flow in order to maximize heat transfer with the walls of the steel pipe and gain as much energy as possible. Rows of the collectors or troughs can be mounted in series or in parallel. The rows can have an east-west or a north-south orientation. A north-south orientation is more efficient, whereas the east-west orientation provides a more even output throughout the year. Parabolic trough collectors are coupled with tracking devices that track the sun in one axis to increase the amount of irradiance reaching the surface. Parabolic troughs typically reach temperatures ranging from 200°C to 500°C depending on what heat transfer medium is used. The technology can be coupled with thermal storage, which increases its dispatchability. Parabolic trough technology is currently the most commercially used CSP technology (Skyfuel, 2016).

6.1.2 Power Tower

The power tower technology is a point concentrating technology using flat mirrors, called heliostats that focus the sunlight onto a receiver collector tower situated high over the arrays of mirrors. The tower may be over 100 meters high with heat transfer fluids reaching temperatures of up to 1000°C. The heliostat field may be situated on the north or south side of the tower or all around depending on whether the system is placed on the north or south side of the equator. Solar towers are typically an expensive technology requiring huge investments since all mirrors on the field have to track the sun in two axes. It is possible to increase the capacity factor of a central tower power plant by adding thermal storage and due to the high temperatures reached the storage can be more attractive for electric power production than that of a parabolic trough system (Simbolotti, 2013).

6.1.3 Linear Fresnel

Linear Fresnel technology is a line concentrating solar technology that uses flat mirrors, which can be seen as a parabolic trough divided into parts. The mirrors concentrate the solar irradiance towards an absorber pipe situated a few meters above the rows of plates. The temperature range of a linear Fresnel system is usually from 200°C to 300°C. The orientation of the rows is generally north-south, and tracking is done on an east-west orientation. The absorber pipe may look like the absorber of a parabolic trough and it contains heat transfer fluid that harnesses the solar irradiance. In some systems, a secondary receiver might be used which is situated over the absorber tube in order to account for astigmatism of the mirrors. Linear Fresnel systems are typically less expensive than parabolic trough systems since the mirrors are a lot cheaper. However the concentration ratio is typically lower and presently there are no storage options coupled with linear Fresnel technology (Simbolotti, 2013).

6.1.4 Parabolic Dish

The parabolic dish technology is a point focusing solar technology that utilizes a parabolic dish as it's concentrating component. In concentrating solar power, it is usually called a Stirling dish since the heat produced from concentrating the solar irradiance is usually coupled with a Stirling engine. Parabolic dish technology can reach temperatures as high as 1500°C. The technology uses two-axis tracking to follow the sun's position. Parabolic dish technology has the highest efficiency of all concentrating solar technologies due to having the highest concentration ratio. Parabolic dishes can easily be placed on inclined ground, unlike other concentrating solar technologies. However, the major disadvantage of a parabolic dish is its significantly higher capital cost as compared with the other collector technologies (Ambrosson & Selin, 2016, p. 20).

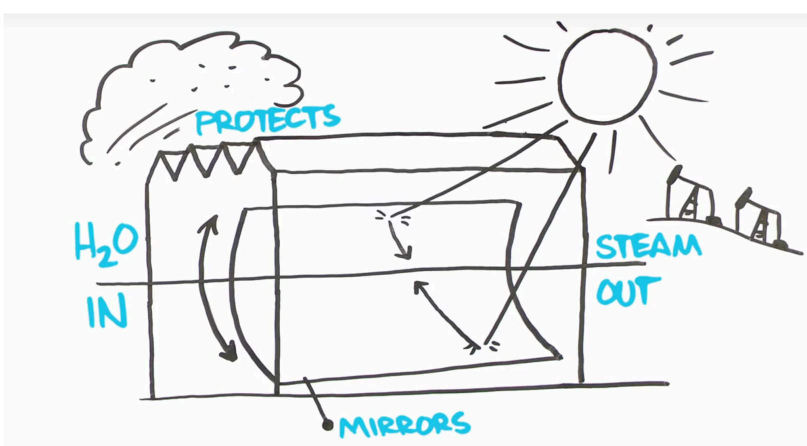
6.2 Receiver Chosen for Utility Scale Implementation

Since temperatures above 500°C are not necessary for enhanced oil recovery but only for electricity generation, both solar tower and parabolic dish technologies have been rejected for utility scale steam production implementation. Both of these technologies also carry a significantly higher capital investment cost than the line concentrating technologies, making them less attractive for utility scale use. Linear Fresnel is an immature technology and the price of the system is uncertain. Parabolic trough technology is the more proven alternative and has more certainty regarding pricing and therefore was chosen for utility scale implementation. In order for oil production companies to invest in either technology, they need to be able to make an economic assessment of the system cost and therefore it is more feasible to choose parabolic trough over linear Fresnel (Ambrosson & Selin, 2016, p. 23).

6.3 Baseline Technology

The glasshouse sheltered parabolic mirror technology Enclosed Trough, pioneered by GlassPoint, is the baseline concept considered for this study (Figure 13). This new design that keeps the mirrors within an enclosed structure helps overcome challenges with the winter, windy and dusty conditions common in the oil-producing regions of Alberta. Delicate mirrors can become very dirty, very quickly if they are put outside. You can expect, roughly 2 percent degradation in performance a day if the collectors are not cleaned regularly, which is very dramatic drop in performance. Essentially solar systems could stop working without an adequate cleaning solution. Enclosure means the mirrors inside stay super clean. In fact, the air inside the glass house could be filtered, dehumidified and injected under pressure, so if there are any little cracks in the structure air is coming out, so dust is not coming in (Glass Point, 2017). What this means is that the mirrors stay clean all of the time.

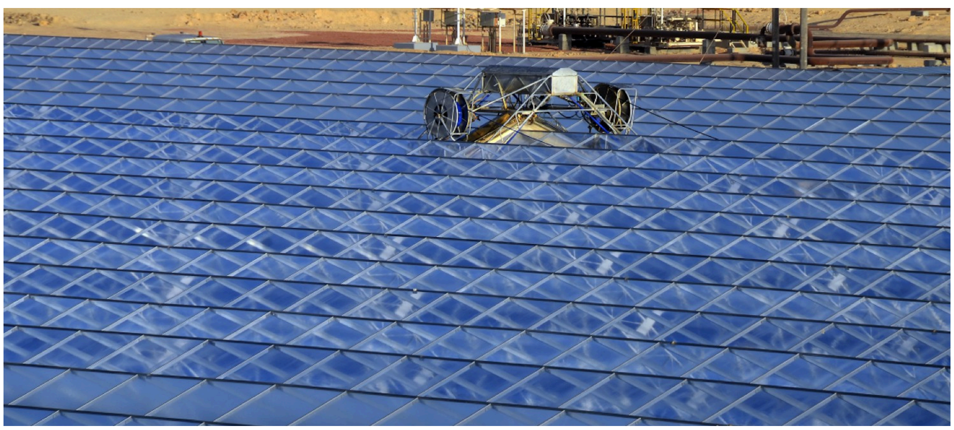
Figure 13 Enclosed Trough technology schematic.



(GlassPoint, 2017)

The structure itself still accumulates dust and dirt especially on the roof of the glass house. The agricultural industry has had this problem all along and as a result, it developed an automated cleaning solution that looks a lot like upside-down car washes (Figure 14). The washers drive along the peak of the roof with brushes that spin cleaning as they go and when they get to the end they move over one roof and start the cleaning again. The water used is captured and recycled. The system allows cleaning the entire roof of the glass house every night, so there's no performance degradation as there would be if the system was outside. In addition, because the system is fully automated there is no need to employ people and machinery to clean the mirrors.

Figure 14 Glass house automated cleaning system.

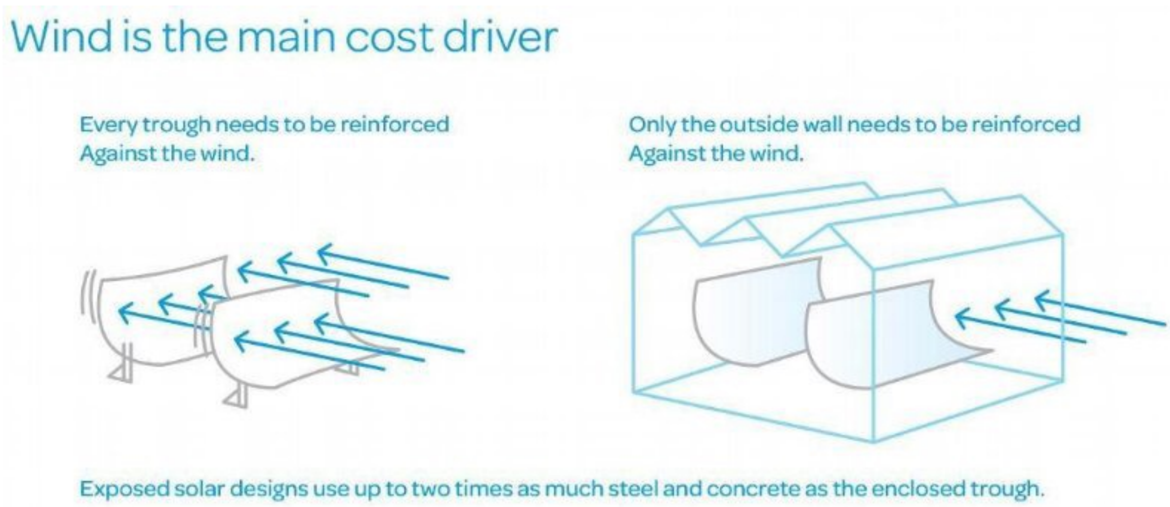


(GlassPoint, 2017)

A key aspect of Enhanced Oil Recovery is water. The enclosed Solar EOR systems are designed to operate with what's called produced water. Produce water is water which comes out the oil well along with oil and is typically eighty percent water and twenty percent oil (product). Solar steam systems are designed just like an oilfield boiler to accept the produced water and make steam out of it. Oil field water compatibility allows developers and operators to use the same pumps, the same controls and the same boiler tubes as conventional oil field boilers.

A big advantage of the glass house structure is that it is cheaper to have the mirrors inside than outside. The main cost driver for solar systems is wind loading (Figure 15). Outdoor six-meter-tall solar thermal mirror constructions are kept rigid by reinforcing them with a lot of steel along with concrete to keep onto the ground. In the case of glass enclosed structure, the mirrors are indoors and they never see wind. As a result, the mirrors are made of a material which is slightly thicker than tin foil and slightly thinner than a soda can, which makes them incredibly lightweight and inexpensive.

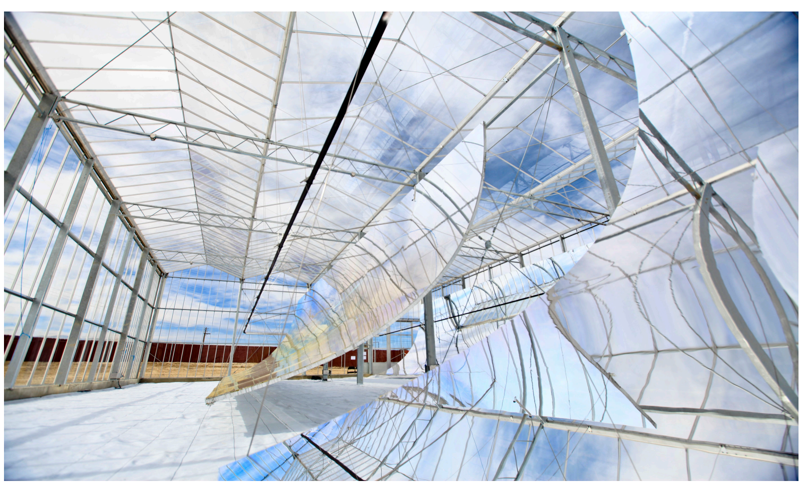
Figure 15 Glass House Enclosure Protects the Mirrors from Wind.



(GlassPoint, 2017)

Another advantage is that the positioning system which aims the mirrors can be very small, as opposed to the giant hydraulic systems that you need if the collectors were outside (Figure 16).

Figure 16 Commercial greenhouse structure of the type normally used for agriculture.

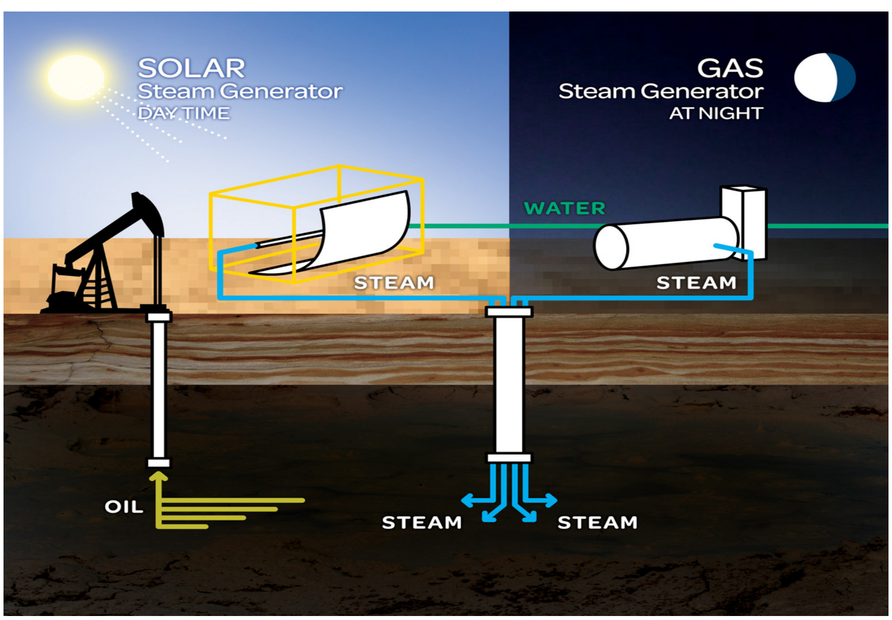


(GlassPoint, 2017)

Additionally, because they're very lightweight, they are only a tiny fraction of the cost of mirrors which had to survive wind outside. As a result, instead of having to reinforce every single mirror in the entire array the system only needs to have the structure of the building reinforced. There's about half as much metal, steel and aluminum in an enclosed trough than there is in an outdoor system. Having half as much material is having half as much construction cost. There are some performance loses from having the system inside, from reflection of the glass and some shading, but that is miniscule compared to the huge reduction in cost. When developing a novel technology is important to focus on dollar efficiency such as cost per ton of steam, not optical efficiency, because at the end is the dollar efficiency that is the key driver. The glass structure gives the system a lower CAPEX because of the wind loading issue and a lower OPEX because of the automatic cleaning.

In a typical Solar EOR operation the solar steam is injected during the day and fuel fired steam is injected at night (Figure 17). If the rate of steam in kept constant a thermal oil field can get about 20 to 25 percent of its energy from solar. However, if the steam injection rate during the day is increased and then reduce at night, a field can produce up to 80 percent of its steam needs with solar energy. What matters in EOR is the weekly total injection, not whether steam is injected at noon or at night like delivering power into the grid.

Figure 17 Solar Steam Generation Day/Night Time



(GlassPoint, 2017)

6.4 Operational Months

Oil production sites need steam for oil recovery year-round, twenty-four hours a day making solar produced steam not viable as the only steam production method on a production site due to variations in solar irradiance. Nevertheless, solar energy could be advantageously used as a supplement provider of steam alongside a gas fueled steam boiler or as a preheater of the feed water which is to be converted into steam in a gas fueled burner. Both alternatives would reduce the overall need for natural gas in the production of steam.

Due to the varying weather conditions of Alberta throughout the year, an assessment has been made as to which months the system should be operational. If the solar energy during the winter months is too low, it might be favorable to use the system for preheating boiler feed water rather than for steam generation during these months. Therefore, the monthly DNI average has been calculated for each month. The average is calculated using the weather data available from 1998-2005. A minimum of 120 kWh/m2 was set in order for the system to be operational and assessments have been made for both Calgary and Cold Lake.

Ambient temperature[2], sky temperature[3] and wind speed which all could affect the thermal efficiency of the solar collectors are also taken into consideration when assessing the viability of the solar steam system for Alberta. However, after calculating the effects of these parameters, a report by the U.S. National Renewable Energy Laboratory (NREL) has shown that the overall efficiency is barely impacted by changes in weather parameters (Kutscher et al., 2010, p. 12). As a result, DNI variation over the year will be the deciding factor for when to have the system operational for steam production and when for feed water production.

[2] Ambient temperature is the dry bulb temperature of the surrounding air.
[3] The sky temperature is the apparent temperature of the sky on which a surface can radiate heat to (NASA, 2016)

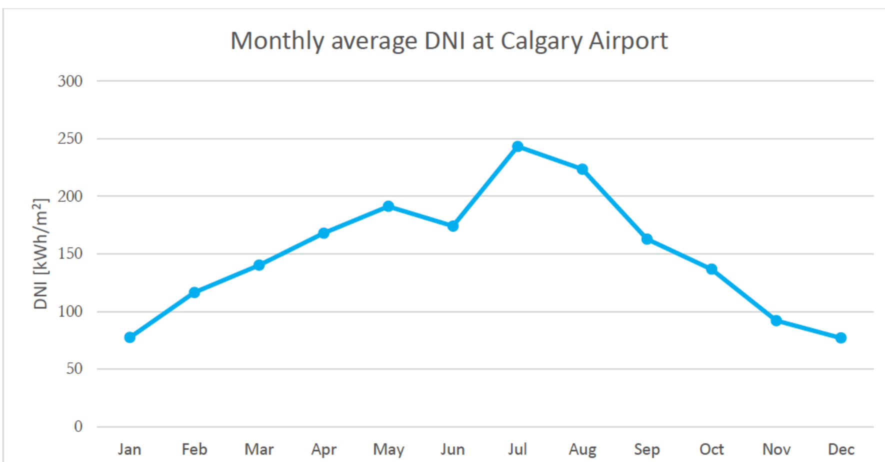
Table 1 Thermal efficiency impact of variation of weather parameters

Parameter	Parameter variation	Change in thermal efficiency
Ambient temperature	0C - 40C	0,1%
Sky temperature	-40C - 20C	0,1%
Wind speed	0 m/s - 20 m/s	0,3%

(Kutscher et al., 2010).

In Figure 18 the monthly DNI average from 1998 to 2005 in Calgary is shown. It is seen that the lowest DNI-values are reached in the months of November, December, January, and February.

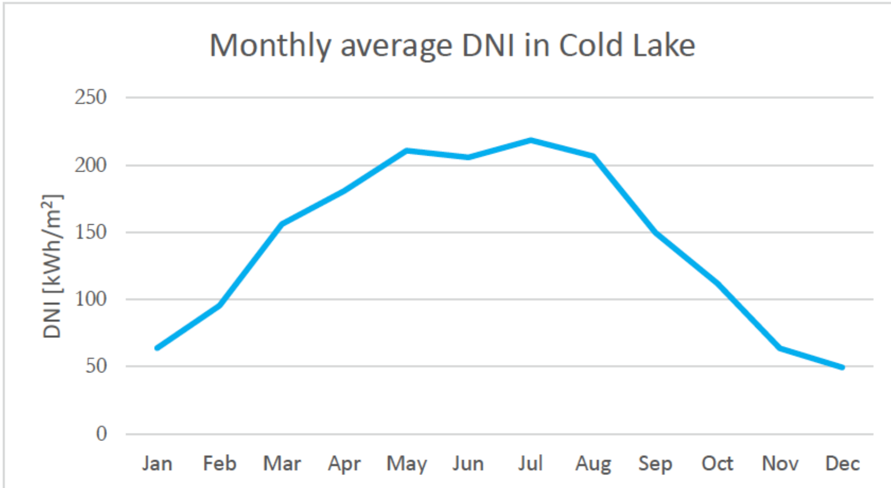
Figure 18 Average monthly DNI from the Calgary International Airport from 1998 to 2005 in kWh/m2.



(Ambrosson & Selin, 2016)

In the following Figure 19, the monthly average DNI from 1998 to 2005 in Cold Lake is also shown. Similarly, to Calgary, the lowest rates of DNI are in the months of November, December, January and February with DNI of less than 100 kWh/m2.

Figure 19 Average monthly DNI from Cold Lake from 1998 to 2005 in kWh/m2.



(Ambrosson & Selin, 2016)

With most of the solar energy being available during the summer months, it is proposed that solar steam facilities in Alberta be operated for part of the year until efficiencies, Thermal Energy Storage (TES) and economies of scale justify year round operation. Depending on the latitude, solar steam plant operation would be between eight months of the year in central and northern Alberta and up to ten months of the year in southern areas of the province. It is anticipated that the most effective operating months of the solar steam plant will take place in the eight months March through October providing solar resource totaling 1,896 operating hours per year as shown below.

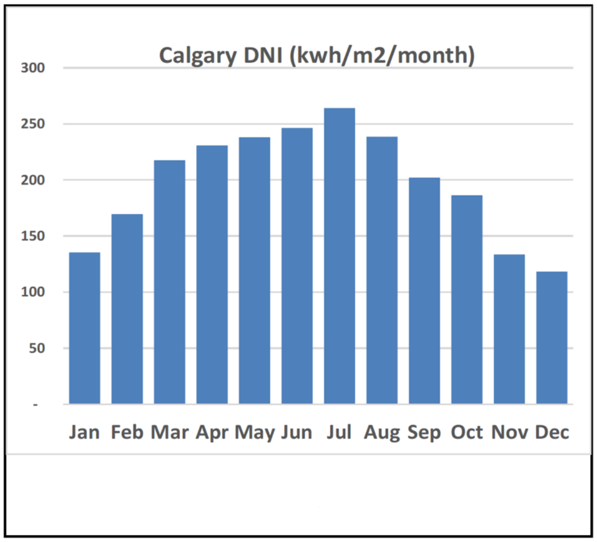
Table 2 Monthly Hours of Sunshine in Calgary.

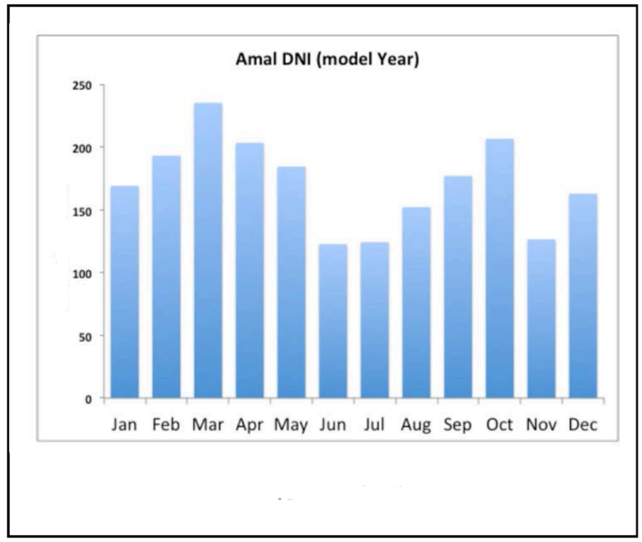
March	April	May	June	July	August	September	October	Total
177	220	249	270	314	284	207	175	1,896

(NRCan, Single-Axis Tracker)

Of interest when considering solar thermal potential is that research has revealed that dust storms in Oman, where solar steam has been proven success, significantly reduce the DNI available to levels similar to DNI in Calgary as can be seen in Figure 20 below.

Figure 20 Calgary vs Amal (Oman) DNI (kwh/m2/month).



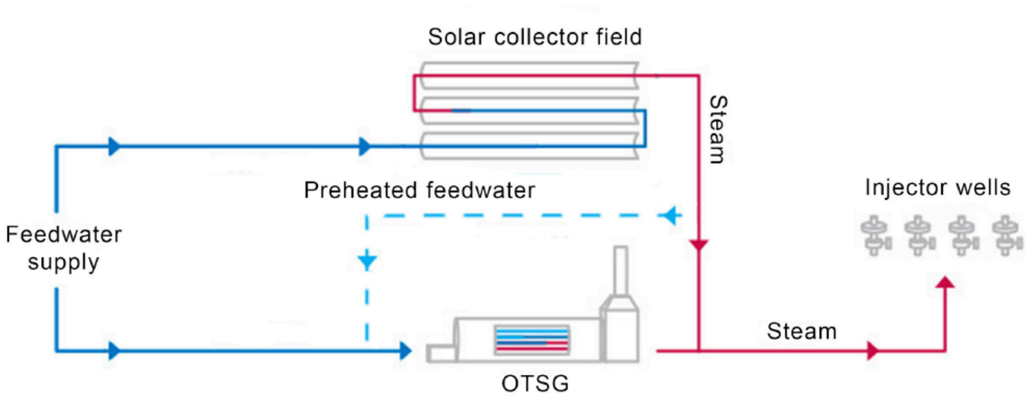


(Jackman et al., 2017)

6.5 SolarSteam System Layout

Due to the above-mentioned operational months for solar steam technologies in Alberta, it is reasonable to see the system as an addition to an existing Enhanced Oil Recovery facility. EOR facilities need to keep the steam injection into the reservoir steady and due to the intermittency of solar energy, it is not possible to see Solar EOR as an isolated facility. The layout below suggests that the solar steam field can also be used as a preheater for boiler feed water if an insufficient amount of heat is available to create solar steam during the winter.

Figure 21 Possible layout of a Solar EOR facility using a solar system as an add-on.



(Jackman et al., 2017)

CHAPTER 7: Financial Feasibility of SolarSteam Systems

Focusing Concentrated Solar Power technology on the production of steam (Solar Steam), rather than on its electrical generation capabilities, has proven to be cost effective. What makes steam generation affordable compared to electricity generation through CSP is that there is no power block required. Solar Steam generation does not require any turbines, heat exchangers or thermal storage, but only mirrors to focus the sunlight onto pipes and carry water to generate steam. Although concentrated solar steam plant systems will only have hot water output in the winter months, the long summer days in the high latitudes will give ample energy during the day to reduce the demands of the natural gas boilers currently use.

Given that the first plants for solar steam generation are to operate in parallel with existing steam generating systems (brownfield operations), capital costs will be lower than if an entire new greenfield plant was to be built, thus assisting with lower costs of steam production. The parallel operation of solar and conventional steam plants may offer an operating cost advantage as personnel from the existing plant may be available to assist with the operation of the solar steam plant (Jackman et al., 2017, p. 13).

7.1 Energy Demands for Alberta Oil Industry

According to the Alberta Oil Sands Industry 2017 report, the Alberta Oil Sands produced on average 1,000,000 barrels per day with thermal in-situ extraction through Cyclic Steam Stimulation (CSS) and Steam-Assisted Gravity Drainage (SAGD). The amount of steam injected is measured against the oil produced to determine the steam-oil ratio (SOR), which can range between 3 - 8 and for CSS and 2 - 5 for SAGD, for each barrel of oil produced (Government of Alberta , 2017). Table 3 below summarizes the energy demands of the Alberta oil industry.

Table 3 Energy Demands for Alberta Oil Industry.

Daily Oil production (barrels)	1,000,000	
Daily Steam Required (barrels)	4,000,000	Steam -to-Oil Ratio = 4
Daily Steam Required (tonnes)	636,000	159 liters (kg) per barrel
Daily energy to produce steam (gJ)	1,691,760	2.66 gJ energy per tonne of steam
Daily energy to produce steam (MWh)	470,309	
Annual steam required (tonnes)	232,140,000	365 days per year
Steam production / year / MWt	2,462	see Appendix C
MWt required to meet oil production	94,289	

(Jackman et al., 2017)

For a perspective of the potential of Solar EOR in Alberta, if 10 percent (100,000 barrels per day) of the current steam for thermal extraction in Alberta was produced by solar at an average SOR of 4, this would require 9,400 MW of solar steam systems. Given the scale of energy use in the Oil Sands, this study has assessed the economics of a 500 MWt SolarSteam system in addition to a 1.5 MWt and a 7.0 MWt proof of concept plants.

7.2 SolarSteam System Cost Estimates

The estimated cost is shown in Table 4 and totaled CAD 341 million for a 500 MWt SolarSteam system. The estimated cost is validated by benchmarking to the GlassPoint Miraah plant currently under construction which provided a projected cost of CAD 360 million (Table 5).

Nineteen 500 MWt plants would be required, at a expected cost of CAD 6.5 Billion, to provide 10 percent of the current oil extraction energy.

Table 4 Breakdown of SolarSteam System Cost Estimates.

CAPEX	**Rate (CAD)**	**Cost (CAD)**	**Cost (CAD)**	**Cost (CAD)**
Solar System Size:	-	**1.5MWt** (3,700 m2)	**7.0MWt** (17,280 m2)	**500MWt** (1,000,000 m2)
Site Improvements ($/m2)	$30 - $90	$333,000	$1,036,800	$30,000,000
Solar Field ($/m2)	$55	$203,500	$950,400	$55,000,000
Glass House ($/m2)	$40	$148,000	$691,200	$40,000,000
Piping and Controls ($/m2)	$35	$129,500	$604,800	$35,000,000
EPC ($/m2)	$40 - $120	$444,000	$1,382,400	$40,000,000
Balance of Plant ($/kWe)	$120 - $180	$270,000	$1,050,000	$60,000,000
Trough Assembly Equipment	$270,000	$270,000	$270,00	$270,000
Automated Washing System	$100,000	$100,000	$100,000	$1,800,000
Total Cost	-	$1,898,000	$5,815,600	$262,070,000
+ 30 percent overhead	-	**$2,467,400**	**$7,560,280**	**$340,691,000**
per m2	$200 - $340	$513 - $667	$336 - $437	$262 - $341

(Author, 2017)

The cost breakdown report reflected the baseline cost for parabolic trough solar fields within NREL's System Advisor Model (SAM). SAM is the primary tool used by NREL and the U.S. Department of Energy (DOE) for estimating the performance and cost of Concentrating Solar Power (CSP) technologies and projects. This cost analysis provides a bottom-up build and cost estimate for the SkyTrough parabolic trough design (Appendix A) combined with a glasshouse enclosure (Kurup & Turchi, 2015).

As a cross-reference the budgeted cost of the 1,000 MWt Miraah plant is reported to be USD 600 million (Kreamer, 2015). Using this benchmark, a similar cost estimate of CAD 360 million has been developed below.

Table 5 Breakdown of SolarSteam System Cost Estimates.

500 MWt SolarSteam system based on Mirah benchmark		
1,000 MWt Mirah CSSP plant by GlassPoint	600	million USD
CAD exchange at 1.2	720	million CAD
50% reduction to 500 MWT Alberta CSSP	360	million CAD

(Jackman et al., 2017)

7.3 Economic Benefits from SolarSteam systems

A basic economic analysis for a 500 MWt SolarSteam plant has been prepared and is shown in the tables below. The two operational cost savings, natural gas and carbon levy, will recover the capital investment in 11 years using $5.00 per gJ for natural gas cost and $30 per tonne for the carbon levy. Increasing these cost inputs to $8.00 per gJ for natural gas and $50 per tonne for carbon levy reduces the simple payback to 7 years.

Table 6 Revenue streams for Natural Gas Savings and Carbon Levy Savings.

Energy Required to produce steam:			**SolarSteam output in steam:**		
Feed water temperature (C)	25		Plant rating (500 MWt)	500,000	kw
Saturated Steam temperature (C)	180		Plant rating (278 kw/gJ/hr)	1,799	gJ/h
Delta T (C)	155		Energy required per tonne of steam	2.66	gJ
Heat Capacitance of water	4.2	kJ/kg	Plant output per hour	675	tonnes
Heat energy required/kg	649	kJ	Annual operating time (8 months)	1,823	hours
Enthalpy of Vaporization energy	2,014	kJ/kg	Annual steam output	1,231,026	tonnes
Total Energy to produce steam	2,663	kJ/kg	Natural Gas cost	$19.02	tonne
Total Energy to produce steam	2.66	gJ/tonne	Annual Natural Gas Cost savings	**$23,419,836**	
Natural Gas required to produce steam:			**Natural Gas Offset:**		
Total Energy to produce steam	2,663	kJ/kg	Annual SolarSteam output	1,231,026	tonnes
70% efficient boiler	3,805	kJ/kg	Natural gas to produce steam	3.80	gJ/tonne
Natural Gas required	0.004	gJ/kg	Natural gas saved per year	4,683,967	gJ
Natural Gas required	3.80	gJ/tonne	GHG's offset at .056 tonnes/gJ	262,302	tonnes
Natural Gas cost at $5/gJ	**$19.02**	tonne	Carbon levy saved at $30/tonne	**$7,869,065**	

(Author, 2017)

Table 7 Payback Steady Scenario (Natural Gas = \$5.00/gJ & Carbon Levy = \$30/tonne).

Economic Summary - 500 MWt (CAD \$ millions)		
Natural Gas = \$5.00/gJ Carbon Levy = \$30/tonne		
CAPEX		341
Operating Costs:		
4 additional Power Engineers (\$150,000)	0.6	
Maintenance (\$300/hr x 1823 hours)	0.5	
Natural Gas Savings	(23.4)	
Carbon Levy Savings	(7.9)	
OPEX revenues		(30.2)
Simple Payback (years)		**11.3**

(Author, 2017)

Table 8 Payback Progressive Scenario (Natural Gas = \$8.00/gJ & Carbon Levy = \$50/tonne).

Economic Summary - 500 MWt (CAD \$ millions)		
Natural Gas = \$8.00/gJ Carbon Levy = \$50/tonne		
CAPEX		341
Operating Costs:		
4 additional Power Engineers (\$150,000)	0.6	
Maintenance (\$300/hr x 1823 hours)	0.5	
Natural Gas Savings	(37.5)	
Carbon Levy Savings	(13.1)	
OPEX revenues		(49.5)
Simple Payback (years)		**6.9**

(Author, 2017)

Economic assessments show that although the initial capital investment of solar steam generation is high as compared to conventional steam generation, operating costs are lower due to fuel savings and maintenance cost. As a result, a 500 MWt SolarSteam system break-even would occur at 11.3 years under the Steady Scenario and at 6.9 years under the Progressive Scenario. While this simple model does not factor cost of capital, it also does not provide for boiler feed water savings, water treatment savings and 'green' reputation benefits (Jackman et al., 2017, p. 37).

7.4 Funding for Clean Tech/Renewable Energy

Clean Tech and Oil Sands de-carbonization funding opportunities would have a considerable impact on building the business case for Solar Steam utility scale implementation. Federal and provincial government incentives along with industry funding can help with the development of proof-of-concept systems to be built in Calgary and Cold Lake. Carbon reducing projects, like Solar Steam, add value to Alberta's economy and represent the potential for billions of dollars of economic impact and the reduction of millions of tonnes of GHG emissions once they reach commercialization. As Federal Minister of Natural Resources Jim Carr said "The revenues generated from Clean Tech projects will help us finance the transition to a low-carbon economy, which we know will take quite some time" (Stephenson, 2017).

7.4.1 Federal Funding

Partnering up with the University of Calgary would allow access to funding through CFREF (Canada First Research Excellence Fund) that can be used for building a 1.5 MWt proof of concept facility at university campus that can also be used for teaching purposes. CFREF helps Canadian universities, colleges and polytechnics compete with the best in the world for talent and partnership opportunities, to make breakthrough discoveries, and to excel globally in research areas that will create long-term economic advantages for Canada. CFREF invests approximately $200 million per year in supporting Canada's postsecondary institutions in their efforts to become global research leaders (Government of Canada, 2017).

7.4.2 CRIN Supercluster Initiative

The $950-million "Supercluster" initiative announced by the Trudeau government will focus on growing innovation and employment in key sectors of the Canadian Economy. Alberta is at the heart of country's energy sector and Calgary is in a unique position to benefit from superclusters in de-carbonization technology funding. The model encourages collaboration and partnership between large and emerging companies. The applications must include large industrial player (an Oil Sands company) and small and medium sized enterprises (a Solar Steam developer). An alliance with an academic institution is also required (such as the University of Calgary) (Yedlin, 2017).

7.4.3 Provincial Funding

Solar Steam development can take advantage of Alberta Innovates teaming up with Natural Resources (NRCan) and industry partners in effort to take three clean oil and gas technologies to commercial demonstration. NRCan is contributing $21 million and Alberta Innovates is investing $5.2 million, for a total of $26.2 million over two-years to support clean oil and gas technologies to help develop Canada's hydrocarbon resources in sustainable ways. "Alberta Innovates and NRCan believe that accelerating these technologies will be a key component to making Alberta's oil and gas economy more competitive, creating jobs and supporting Alberta's transition toward a low-carbon economy" (Alberta Innovates, 2017). Three industry partners, Cenovus Energy, Field Upgrading, and MEG Energy are also investing $43.3 million in commercial demonstration (Alberta Innovates, 2017).

7.4.4 COSIA Natural Gas Decarbonization Challenge

Canada's Oil Sands Innovation Alliance (COSIA) Members are committed to identifying emerging technologies and funding the development of the technologies to the point of commercialization, while protecting the Intellectual Property rights of the owner of the technology. Successful proposals can receive funding from COSIA members to develop and demonstrate the technology in an oil sands application. Multiple technologies may be funded, at the discretion of the Members (COSIA, 2014).

The COSIA GHG Environmental Priority Area Steering Committee has identified natural gas de-carbonization as an opportunity area in which to explore for technologies that will materially reduce oil sands GHG emissions. These technologies will partially or completely remove the carbon content of natural gas. The emissions associated with producing the decarbonized gas, plus the emissions from combusting the decarbonized gas, will have to be less than the emissions from combusting natural gas. Evaluation metrics include GHG emission intensity and CO_2 avoidance cost. GHG intensity will include any change in combustion efficiency that may result from the decarbonized gas. The second metric will account for the costs required to achieve GHG reduction including CO_2 or carbon sequestration (COSIA, 2014).

7.5 Business Plan

The following presents the Project Financing / Offering and Cash Flow Summary sections of a SolarSteam LCC proposed business plan.

Project Financing / Offering

SolarSteam will require funding for incorporation, legal expenses, website development and validation of the technology in a lab environment. Further operational funding will be required for engineering and suppliers' contracts for validation, development and commissioning of a 1.5MWt pilot plant in Calgary.

Lab Environment Validation	$50,000
Relevant Environment Validation	$250,000
Pilot Plant Development and Commissioning	$2,700,000
Total required	**$3,000,000**

Cash Flow Summary

Table 9 Cash-Flow Table.

YEAR	Annual Cash Flow	Net Cash Flow	
0	($2,467,400)	($2,467,400)	
1	($246,700)	($2,714,100)	
2	($241,000)	($2,955,100)	
3	$1,841,680	($1,113,420)	**< - PROFITABILITY**
4	$6,249,000	$5,135,580	**< - BREAK EVEN**
5	$29,580,000	$34,715,580	**< - SUSTAINED GROWTH**

(Author, 2017)

Find the full Business Plan in the additional PDF file.

CHAPTER 8: Environmental Benefits

Reducing greenhouse gas (GHG) emissions is an important global issue. Specifically, for the Alberta oil and gas industry, the challenge is to reduce GHG emissions while the demand for energy and the amount of energy the world is consuming is growing. Work is in progress on a variety of new technologies to lower GHG emissions and capture and store CO_2.

8.1 Oil Sands and GHG's

Canada, with 0.5 percent of the world's population, produces about two percent of global CO_2 emissions. Oil sands account for 9.3 percent of Canada's GHG emissions and about 0.13 percent of global GHG emissions (Appendix E). Life cycle analysis, sometimes called wells-to wheels, estimates the amount of GHG emissions associated with the entire life of a product. For petroleum fuels, this includes crude oil production, transport, refining, refined product transport and ultimately combusting the fuel in a vehicle. When GHG emissions are viewed on a wells-to-wheels basis, emissions released during the combustion of fuel (such as gasoline or diesel) make up 70 to 80 percent of total emissions. In EOR oil sands extraction energy is required to generate the steam that gets injected in drilling recovery methods. Other energy-intensive processes include producing the hydrogen needed to upgrade heavy crude. All these steps release GHGs into the atmosphere which is a contributing factor to climate change (CAPP, 2017).

8.2 Climate Policy

Action on climate change can be achieved through the creation of emissions-reducing innovation and technology, and effective government policy across Canada. Alongside the provinces of Ontario, Quebec and British Columbia, Alberta's provincial policy will build on the province's oil and natural gas industry's ongoing commitment to environmental performance and emissions reductions. Oil producing companies in Alberta are investing more than $1.33 billion collectively into developing new technologies to improve environmental performance through Canada's Oil Sands Innovation Alliance (CAPP, 2017).

8.3 Environmental Benefits from SolarSteam Technology

The primary environmental benefit from implementing Solar Steam in Alberta would be the reduction of CO_2 produced in natural gas consumption for steam generation. Decreasing the natural gas required for process steam production would result in CO_2 emissions savings that would help Alberta and Canada meet its environmental commitments. If 10 percent of the current steam for thermal extraction in Alberta were produced by concentrated solar at an average steam to oil ratio (SOR) of 4, this would require approximately 9,400 MW thermal of Solar Steam energy. The proposed 500 MW thermal project in Cold Lake is expected to reduce 262,302 tons CO_2 emissions per year (Table 6). If similar assumptions for potential CO_2 savings are made for nineteen plants of that size, the resulting annual emission reductions will be close to 5 megatons[4]/year which is the equivalent of removing all 1 million registered vehicles in Calgary off the road (Alberta, 2016) or 3.5 percent reduction to current Oil Sands emissions levels (Government of Canada, 2016).

[4] one megaton = one million tones

CHAPTER 9: Major Challenges and Limitations - Surface Rights

An important consideration for the development of Solar Steam is land footprint. The proposed utility scale 500MWt field will be comprised of 20 solar steam system modules (Appendix B) occupying an area of 260 acres or 1km^2. The land required for the construction of the glasshouse enclosed solar field could be Crown land, Aboriginal people's land or private land. In addition, both Federal and Provincial regulatory compliance and legislation will have to be followed. In order to assess the viability of using such an area for the development of a solar steam field, the following sections will look into the Alberta Utilities Commission regulations and Land-use Planning in Alberta. Assessing the proper jurisdiction that this project might fall under will help clarify which are the parties that hold the surface rights for the development of solar project in the Lower Athabasca region of Alberta.

9.1 Alberta Utilities Commission

Any power plant expected to generate more than 10 megawatts requires approval from the independent, quasi-judicial agency the Alberta Utilities Commission (AUC). For all power plant applications, a local Alberta Environment and Parks (AEP) wildlife biologist must be consulted unless the project is located within an urban area with no nearby wildlife habitat. The Commission requires a sign-off from AEP prior to processing any new solar or wind power applications. Applicants are also required to conduct public consultation with anyone directly affected. The company has to include information on objections when it files its proposal with the Alberta Utilities Commission and must indicate whether those objections have been resolved or not. If not, a public hearing may be triggered and held in the community affected (Glen, 2017). AUC utility scale approval process is shown in Appendix C (Alberta Utilities Commission, 2017).

9.2 Land-use Planning in Alberta

Land planning and decision-making in Alberta are carried out under various provincial legislation and policies. These are applied by a range of decision-makers, including Alberta government departments, boards and agencies, and municipal governments, responsible for making decisions about activities in the region. The Lower Athabasca Regional Plan (LARP) applies to Crown and private lands in the region.

LARP, which took effect on September 1, 2012, sets the stage for the next 50 years, concentrating on environmental, economic and social actions. This includes establishing six new conservation areas, moving Dillon River Conservation Area from a Public Land-use Zone to a Wildland Provincial Park, and creating nine new provincial recreational areas as identified in the Lower Athabasca Regional Plan 2012-2022 Schedule G Map shown in Appendix D (Environment and Parks Alberta, 2012).

9.3 Private Lands

Planning on private lands is primarily governed by the *Municipal Government Act* and instruments made under its authority. Private landowners make decisions about how to use and manage their land consistent with existing provincial and municipal legislation. The LARP does not change this or alter private property rights. Métis Settlements, likewise maintain their responsibility and authority for local land-use planning and development on settlement patented land.

The LARP, including sub-regional plans, does not rescind land title or freehold mineral rights. Any decisions that may affect private landowners or freehold owners will occur through existing legislation and processes, and private landowners and freehold owners remain entitled to due process. Private landowners may be entitled to compensation under those laws (Government of Alberta, 2012).

However, negotiating with solar project developers on private lands is not the same as negotiating for oil and gas development. Among the differences:

- Alberta's Surface Rights Act does not apply to wind or solar leases;
- There is no right of entry or expropriation process;
- The renewable energy sector does not have to use licensed land agents for negotiations;
- The policies on decommissioning and reclaiming solar and wind projects have yet to be written. (Glen, 2017)

Renewable energy companies do not have to use licensed land agents, as the oil and gas sector does, so negotiators won't have to follow the professional codes of ethics that govern licensed agents. Participation in any solar projects is voluntary on the part of the landowners. If a landowner says no when a solar project is proposed for development on their land, that's the end of negotiations. The energy company or the mediator cannot force themselves onto the land. Nevertheless, the project might be developed on neighbor's land and even if there are any alleged effects on the surrounding land, there is nothing that non-land owners can do to stop the project. The Farmers Advocate Office advises that "Since there is no surface rights board to set the rate for compensation if right of entry is ordered, it's best for you to be talking with your neighbors." (Government of Alberta, 2017).

9.4 Crown Lands

Crown lands include lands that are administered as public lands under the *Public Lands Act*, parks under the *Provincial Parks Act* and highways under the *Highways Development and Protection Act*. Crown lands are owned by the Crown and managed for the benefit of all Albertans. The Alberta government often allows individuals and businesses to use public lands through statutory consents that grant permission to do certain activities on public land – such as livestock grazing, tree harvesting, energy development or recreational use. In addition, the Alberta government grants statutory consents related to the use of, or impacts on, public resources (like water) to allow or support specific development, industrial activity, conservation or other activities (Government of Alberta, 2012).

On public lands, direction under the LARP will be delivered through existing legislation such as the *Public Lands Act*, the *Forests Act* and the *Provincial Parks Act* and through existing tools such as integrated resource plans, access management plans and forest management planning. These further define access to and use of provincial Crown land, and focus on operational activities that reflect the regional priorities and direction (Government of Alberta, 2012).

While documentation is scant, it appears that the Government of Alberta has had a moratorium on the development of wind and solar projects on provincial Crown lands since 2005 (renewable development does not fall under the Environmental Protection Enhancement Act). This moratorium was to remain in place until a comprehensive energy strategy had been developed for the province, and has been the subject of stakeholder consultations at both the AESO and the Alberta Utilities Commission. In particular, stakeholders that participated in the AESO's Renewable Electricity Program consultation process in 2016 suggested that "exploring whether there may be options to build renewable electricity energy projects on public land" was warranted to remove a potential constraint on renewable energy development in Alberta (Harper et al., 2016).

9.5 Aboriginal People's Lands

Alberta recognizes that those First Nations and Métis communities that hold constitutionally protected rights are uniquely positioned to inform land-use planning. Consulting aboriginal communities on regional planning, particularly those aspects that have the potential to adversely impact their constitutionally protected rights, and reconciling interests are essential to achieving the regional vision. In accordance with applicable government policy as it may be from time to time, the Government of Alberta will continue to consult with aboriginal peoples when government decisions may adversely affect the continued exercise of their constitutionally protected rights, and the input from such consultations continues to be considered prior to the decision (Government of Alberta, 2012). Due to the complexities of changing nature of Canada's position towards first nations consultation is currently out this study's scope.

9.6 Other Jurisdictions and Regions

Co-ordination with other jurisdictions such as the federal government, provinces and territories, and other Land-use Framework regions, will be required to ensure alignment of regional outcomes, and that objectives and strategies are achieved (Government of Alberta, 2012).

CHAPTER 10: Discussion

In this chapter the results presented in the previous chapters will be discussed. The aim of this study was to assess what are the proven utility scale applications of Solar Steam systems in Alberta. Building on the research available on engineering and technological feasibility this study demonstrates that while it is feasible to produce steam from concentrating solar technologies, there might be economic and surface rights allocation obstacles to its implementation.

The proposed Enclosed Trough Solar Steam system uses components currently available on the market. However, the components must be customized for the conditions present in Alberta. The best way to make Solar Steam work in Alberta is by developing a demonstration plant (1.5 MWt) in Calgary that can prove the technical viability of the system and attract investment. A second pilot plant at a larger scale (7MWt), developed upon partnering with a producer in the Cold Lake area, will further help accurately evaluate the technical and financial feasibility of Solar Steam systems. The proposed proof-of-concept demonstration facilities will be used to assess the system for withstanding hail storms and cold weather condition.

The feasibility of adding solar energy to EOR facilities can vary greatly due to the many different factors at play when evaluating a long-term investment for an oil production company. Firstly, there needs to be significant amount of land available where the collector field can be placed in order to produce steam at an economically viable rate. The operator must be willing to make a long-term commitment to solar energy, which may be difficult with the variance in oil prices even over a short time span. The potential for carbon credits and future carbon tax may play a major part in the decision-making process for the implementation of Solar EOR facilities in the future.

Another significant factor is whether the facility has natural gas provided internally for steam production in the EOR-process, or if the fuel needs to be purchased from an external source. If the site is producing natural gas itself, it is difficult to determine a specific price for this natural gas since it is not determined by the market. However, if natural gas must be purchased the incentive for implementing solar energy to the facility will increase. In this case, the price of natural gas will be higher and provides an uncertainty in the company's budget since the gas market is constantly changing. A sudden increase in the price of natural gas would increase the overall oil extraction cost to the company. This effect could be partially eliminated by having some of the facility's steam production come from solar steam generation where the cost of steam production is constant with time and independent of the price of fuel.

Currently, Solar Steam systems are only seen as viable for operation during the months with the highest irradiance of the year (the eight months from March to October). This is partly due to the irradiance being low and not able to provide a significant amount of steam during the winter months and also partly due to the problems arising from snow formation during the winter months. Unlike previous research considerations, this study proposes facilitating the system for boiler feed water preheating, when solar irradiance for steam generation is insufficient. If the current trend of improving efficiencies for concentrating solar technologies coupled with decreasing prices of components continues, it may become economically feasible to have the solar steam system running year-round.

Solar energy technologies can play a major part in reducing global greenhouse gas emissions. The oil industry in Alberta is a large emitter of CO_2, especially since the majority of oil reservoirs in Alberta consist of oil that is difficult to recover, requiring more energy to extract. By incorporating steam generated through concentrating solar technologies the emissions per amount of oil extracted can be decreased significantly. The implementation of carbon tax in Alberta provides another incentive for the use of Solar EOR facilities.

An increase in the amount of gas available for LNG export and power generation, due to coal fired power generation phase-out, will in turn allow for more investments in industry and subsequent job creation in different sectors. When you see start seeing the potential of offsetting gas consumption in the oil field from that level, solar is starting to become very economical.

In order to truly investigate the renewability of a solar steam generation system, the lifetime emissions of the different components of the system have to be evaluated as well as the emissions for operation and maintenance of the system.

CHAPTER 11: Conclusions and Recommendations

The following section presents a summary of the conclusions drawn from this research:

- Building a solar steam generation system at is seen as technically feasible, with the obstacles being mainly economic and surface right allocation;
- Three million dollars in initial funding required to develop a Solar Steam pilot system in Calgary to help assess best practices of making the system economically viable;
- The utility scale system proposed offers a great potential for reduction of GHG emissions and a 500 MW thermal plant added onto an existing EOR plant would enable a reduction of 262 000 tonnes of CO2 equivalents;
- Solar EOR should be seen as an addition to existing EOR facilities due to its intermittency and inability to provide a steady amount of steam;
- On a utility scale, the deciding factor for Solar EOR implementation is its economic viability. Currently, the natural gas price is too low for this to happen, thus heavier taxation of natural gas or further incentivizing of solar energy is needed for Solar EOR to become an economically viable option. The carbon tax of $30 per ton of CO2 introduced by the Alberta Government at the beginning of 2017 has helped with building the business case for the technology, but in order for solar steam generation to be economically feasible, the delivery price of natural gas in the EOR facility has to be around 7 CAD/GJ.

11.1 Future Work

- Initiating discussions with Alberta Economic Development and Trade, and Environment and Parks as well as federal government representatives to appraise them of the potential for Solar Steam projects in Alberta and Canada is another necessary step to be taken along with continuing business plan development.
- Develop a framework for Aboriginal people’s consultation in developing Solar Steam systems.
- Collaborate with the Alberta Energy Regulator and Alberta Environmental and Parks on surface rights allocation for Solar Steam systems development.
- Seek government and oil industry support in pursuing further development of business plan.
- Attract initial investments to prove Technological Readiness Level of Solar Steam.

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APPENDIX A – Installed Cost Breakdown of a SkyTrough Collector (1500 SCAs)

4.3 Installed Cost ($\$/m^2$) for 1500 SCAs

The NREL analysis on the manufacturing, assembly, installation equipment, and construction activities assumed a production volume of 1500 SCAs, which is representative of a 100-MW_e plant with TES. For an aperture width of 6 m with a net aperture area of 656 m^2, it is estimated that the overall installed cost for the SkyTrough 115-m design is approximately \$170/m^2. This figure includes a manufacturing investment to purchase tooling for specific SF components. By design, specific assembly tooling and jigs are unnecessary—the SkyTrough has been designed to be assembled onsite without special equipment. The \$270,000 manufacturing investment is included for subsystems such as the stamping machine for the parabolic ribs and the specifically shaped casting dies needed for the aluminum extrusions (e.g., the connectors in the spaceframe). When the manufacturing tooling investment is amortized over 1500 SCAs, it adds less than \$1/m^2 to the installed cost. The breakdown of the subsystems as a proportion of the total installed cost is shown in Figure 10. This cost includes the SF assembly into the subsystems.

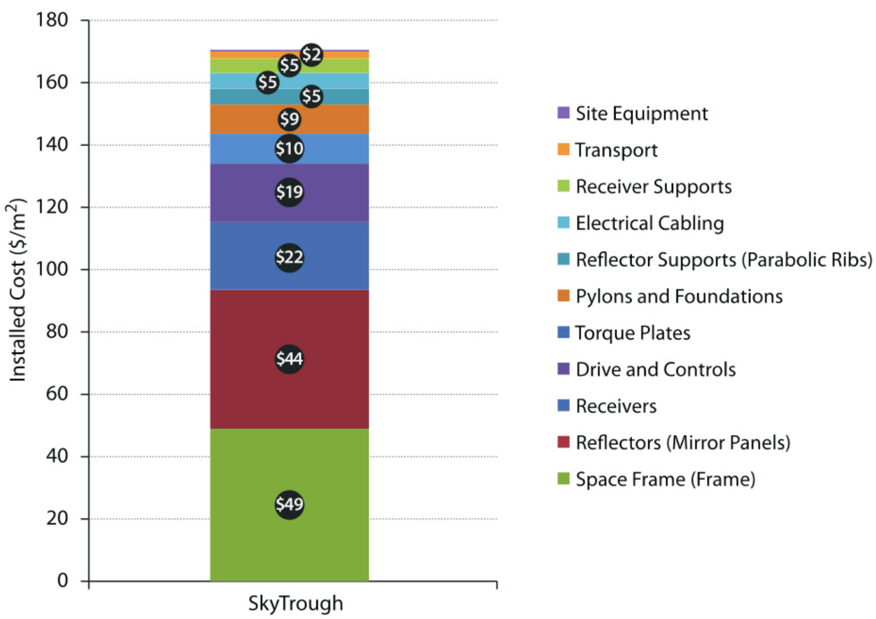

Figure 10. Installed cost for the SkyTrough assuming 1500 SCAs. Total installed cost is estimated at \$170/m^2.

(Illustration by Al Hicks, NREL)

As can be seen in the chart, it was found that the space frame and reflector panels each contributed a little less than 30% of the installed cost. The next largest cost contributors are the receivers (13%) and the drive and control system (11%).

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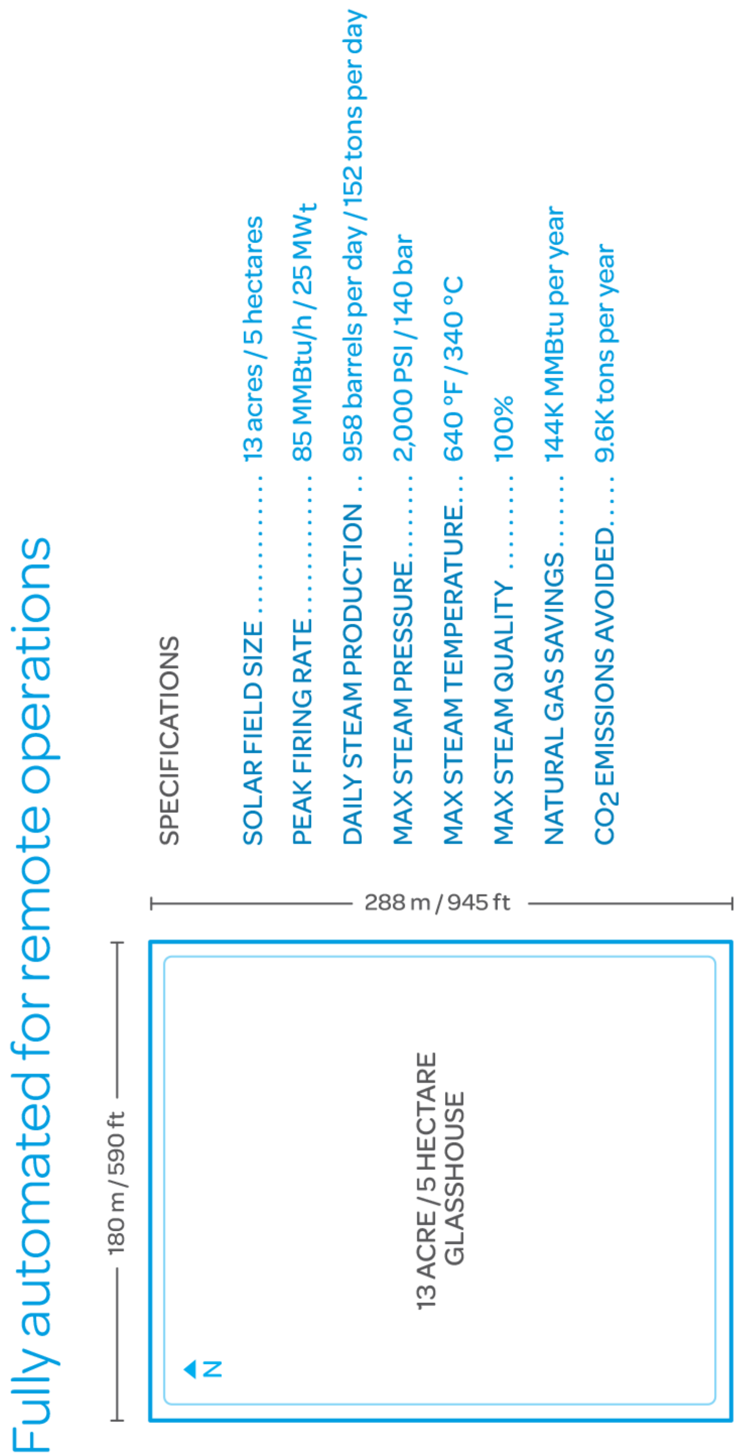
This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.

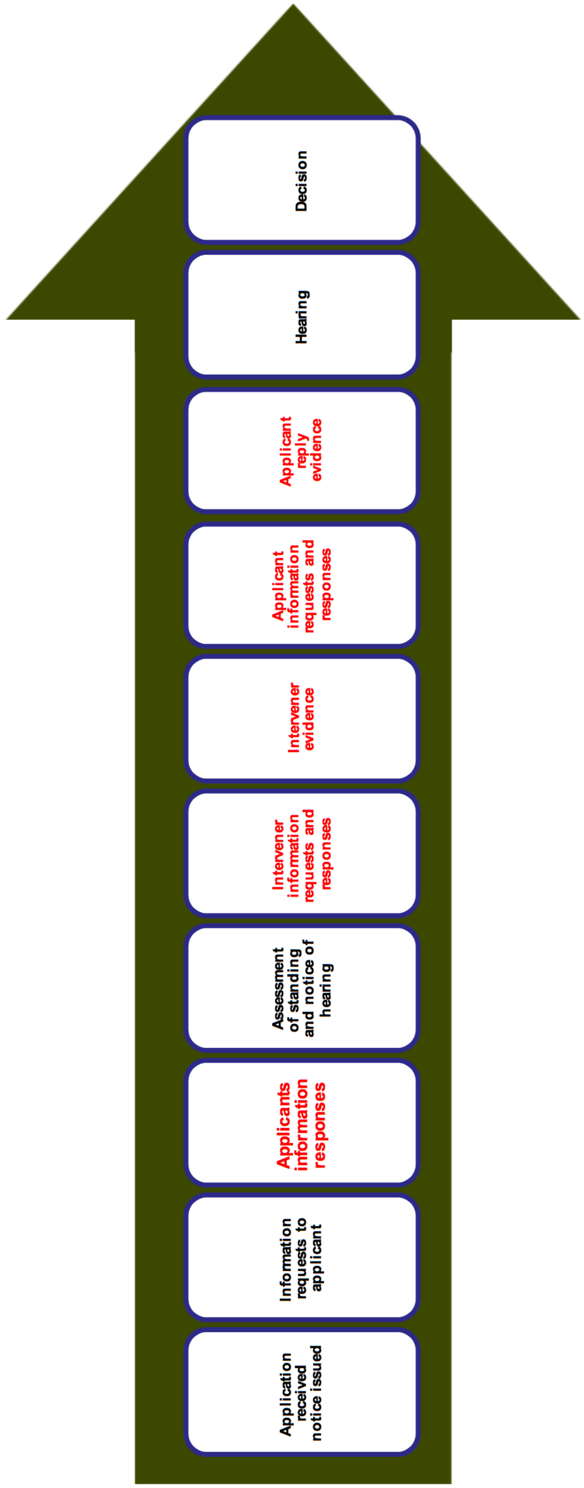
(Kurup & Turchi, 2015)

APPENDIX B – SolarSteam System Standard 25MWt Module



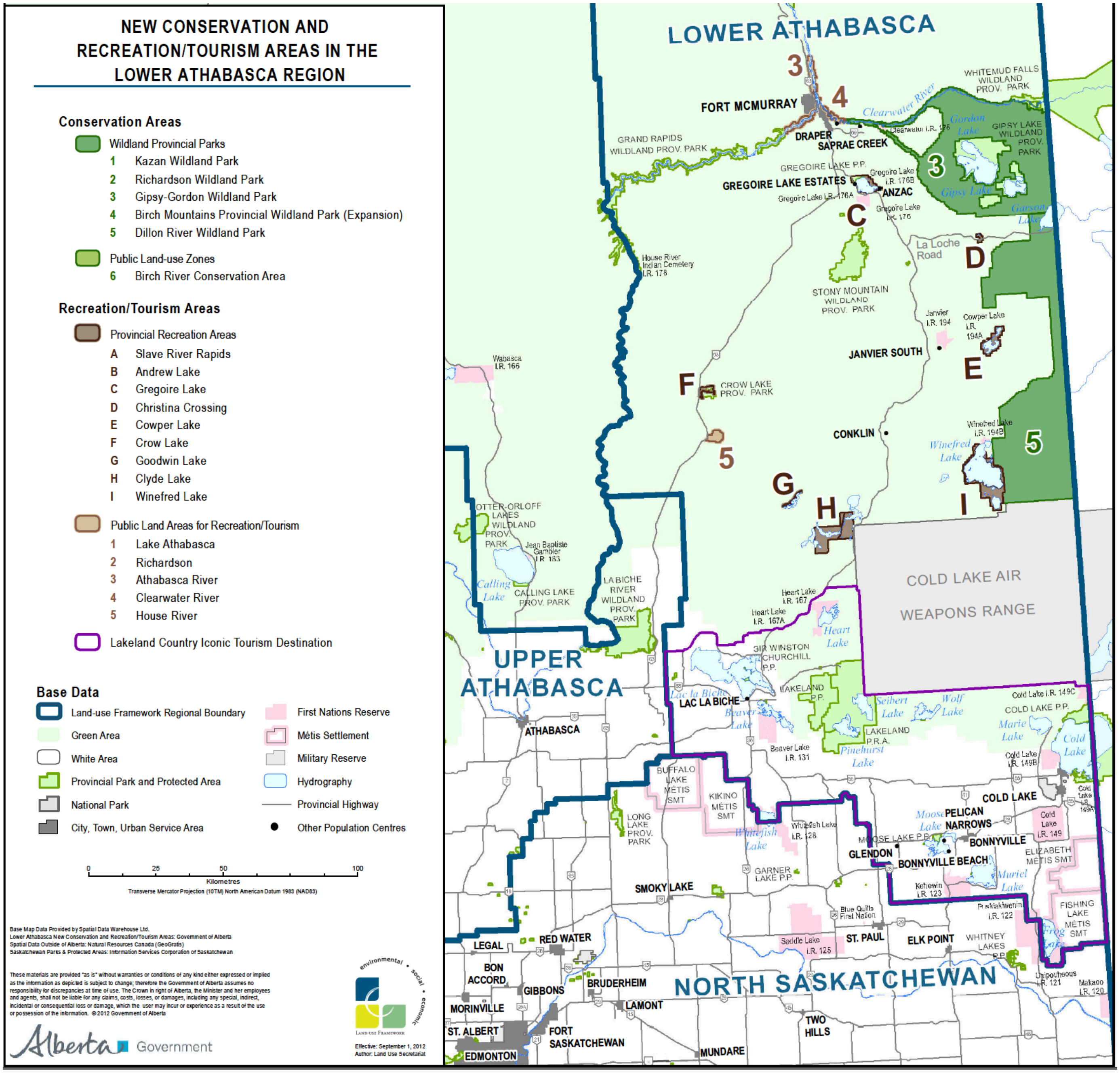
(Glass Point, 2017)

APPENDIX C – Alberta Utilities Commission Utility Scale Approval Process



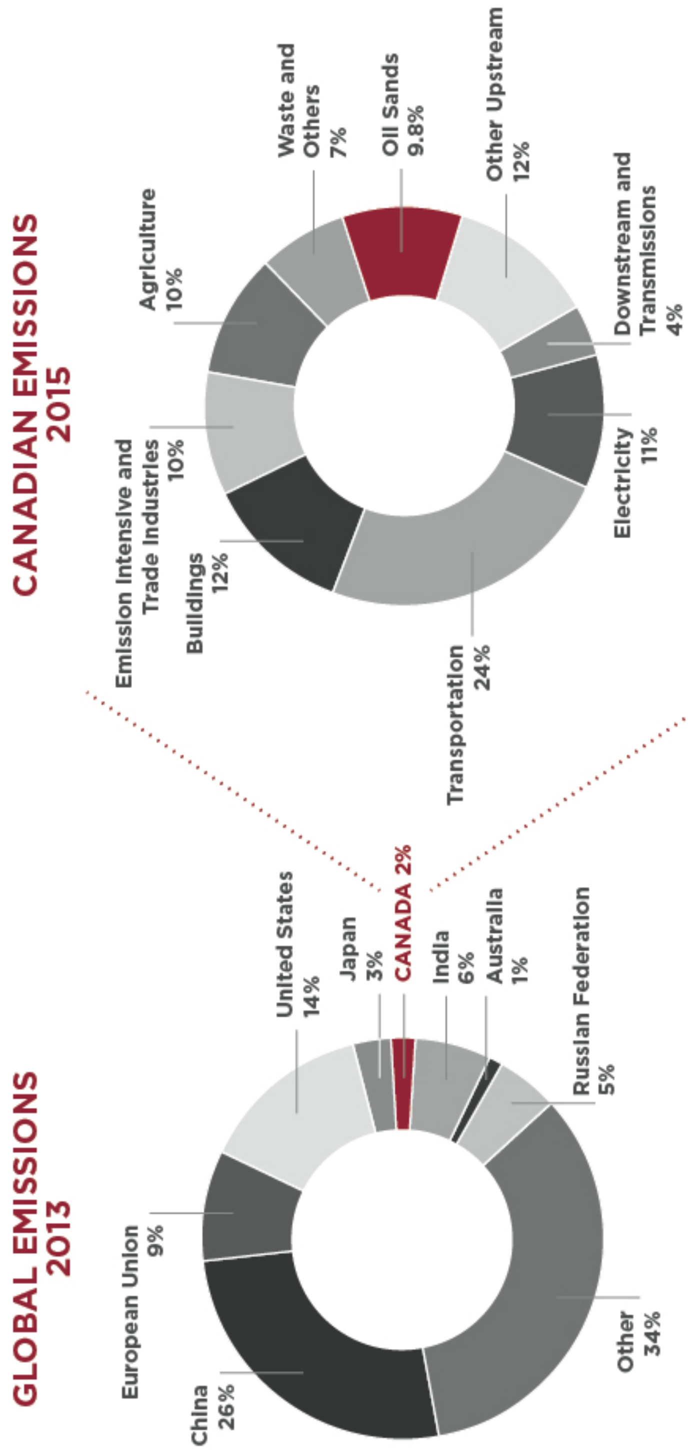
(Alberta Utilities Commission, 2017)

APPENDIX D – Lower Athabasca Regional Plan 2012-2022 Schedule G Map



(Environment and Parks Alberta, 2012)

APPENDIX E – Oil Sands and GHGs



(CAPP, 2017)