Medicine Hat Concentrating Solar Thermal Power Demonstration Project

Project Final Technical Progress Report Number 6
Reporting Period 2015 January 01 to 2015 December 31

Ken MacKenzie, Manager Generation Engineering (Acting)
Medicine Hat Electric Generation
Medicine Hat, Alberta
403 529 8273
kenmac@medicinehat.ca

Presented to Climate Change Emissions Management Corporation and Alberta Environment and Parks
2016 February

Medicine Hat Concentrating Solar Thermal Power Demonstration Project

Project Technical Progress Report Number 6
Final Report 2016 Jan 31
Ken MacKenzie[1]

[1] Manager, Generation Engineering (Acting), Electric Generation, City of Medicine Hat, 580 First Street SE, Medicine Hat, Alberta, Canada T1A 8E6, Phone 403 529 8273, E-mail kenmac@medicinehat.ca

Abstract

The City of Medicine Hat, acting as the project proponent, undertook a Concentrating Solar Thermal (CST) demonstration project at Medicine Hat in Southeast Alberta, Canada. Utility scale parabolic trough technology was constructed to capture the sun's energy at sufficient temperature to generate steam which was integrated into the steam cycle of the City's combined cycle electric generating facility. Since Report #5 was prepared the 1 year test / reporting period has been completed and the final outcomes determined.

Keywords: concentrating solar thermal, concentrating solar power, parabolic trough, integrated solar combined cycle, demonstration project

Table of Contents

List of Tables

List of Figures

List of Appendices

1. Introduction

This is the sixth and final Technical Progress Report prepared during the course of the multi-year demonstration project. In 2014 October the system was commissioned and the 1 year demonstration period began. Some technology issues developed with the core Solar Collector Assembly (SCA) structural and controller technology. Most of these were resolved during the demonstration period.

This report will document the observations and conclusions developed during the demonstration period with respect to the overall goals established for the project.

2. Goals Set in Previous Reporting Period

The goals set for the final reporting period in the project were:

2.1. Replace failed collector frame connections with better design,

2.2. Perform SCA Acceptance Testing,

2.3. Complete 1 year monitoring and reporting Period,

2.4. Draft Final Report.

The overall goals set for the project were:

2.5. Increase / Demonstrate support for Renewable Energy by delivering a pre-commercial scale megawatt class (750 kW minimum) demonstration solar steam generator integrated to the steam cycle of an existing gas fired power station,

2.6. Prove that it is feasible to integrate solar thermal steam generation into a combined cycle electric generating plant in SE Alberta and document the project performance and techno-economics,

2.7. Adapt or improve the technology for the local climate and as a means to attaining Greenhouse Gas (GHG) reductions in a variety of industrial applications in Alberta,

2.8. Achieve an estimated GHG emissions reduction of 600 tonnes per year, validated by a GHG verification report.

3. Goals Achieved in this Reporting Period

3.1. Replace failed collector frame connections – Achieved

During the course of the operational phase of the Project, the City of Medicine Hat (CoMH) noticed that several trough struts were beginning to crack, and some completely sheared at their end connections and fell to the ground. CoMH engaged the original equipment manufacturer (OEM) to address the problem and also began its own investigation.

The OEM revisited the trough structural design and identified five (5) different strut designs that have exhibited wind-induced high cycle fatigue failures. The OEM revised the two most problematic strut designs by increasing the diameter / thickness of the tubes (and by providing new end connection designs), to increase the associated resonant wind velocity, reduce vibration amplitude and decrease the resulting stress ranges and the number of cycles. The other three strut types were modified with cable bracing, attached at mid-span, which will increase the resonant wind velocity, reduce vibration amplitude and decrease the resulting stress ranges and the number of cycles. The OEM also indicated that it believes north-south winds create most of the cycles and therefore SCA fatigue life can be extended by implementing a 360 degree wind fence. A west and south wind fence was installed at the site; wind rose data indicated that wind and wind gusts were infrequent and not predominant from the north and east.

Refer to **Appendix A Strut Damage Reports** for further information**.**

3.2. Perform Solar Collector Assembly (SCA) Acceptance Testing – Test Achieved

The SCAs were tested on Sept. 10th and Oct. 8th for thermal power output (kWt). The SCAs underperformed by >20%, at their best point over the test periods. This is not necessarily due to optical and physical characteristics of the SCAs and most likely is a result of SCA sun tracking issues that clearly exist, and potentially alignment issues, which can both be addressed by the manufacturer.

Refer to **Appendix B SCA Short Term Performance Acceptance Test** for further information.

3.3. Complete 1 Year Monitoring and Reporting Period – Achieved

The Solar Concentrator was commissioned in2014 October and operations began. Although the Solar Concentrator was operated throughout the winter (weather permitting) no actual steam production of the quality required to generate power was achieved until 2015 March due to insufficient Direct Normal Irradiance (DNI) combined with underperforming troughs. Operations continued to 2015 Dec 31 although no actual power from steam was generated in November and December of 2015 due to insufficient DNI and the lower sun elevation angle at that time of year. The 1 year monitoring and reporting period for purposes of this report is the period 2015 Jan 01 to 2015 Dec 31.

3.4. Draft Final Report – Achieved

3.4.1. Increase / Demonstrate support for Renewable Energy by delivering a pre-commercial scale megawatt class (750 kW minimum) demonstration solar steam generator integrated to the steam cycle of an existing gas fired power station – Achieved

The Solar Collector Assemblies, heat transfer fluid system, and solar steam generator, which integrates the SCA into the Power plant steam cycle, were designed, constructed, commissioned, tested and operated for a minimum 1 year monitoring and testing period.

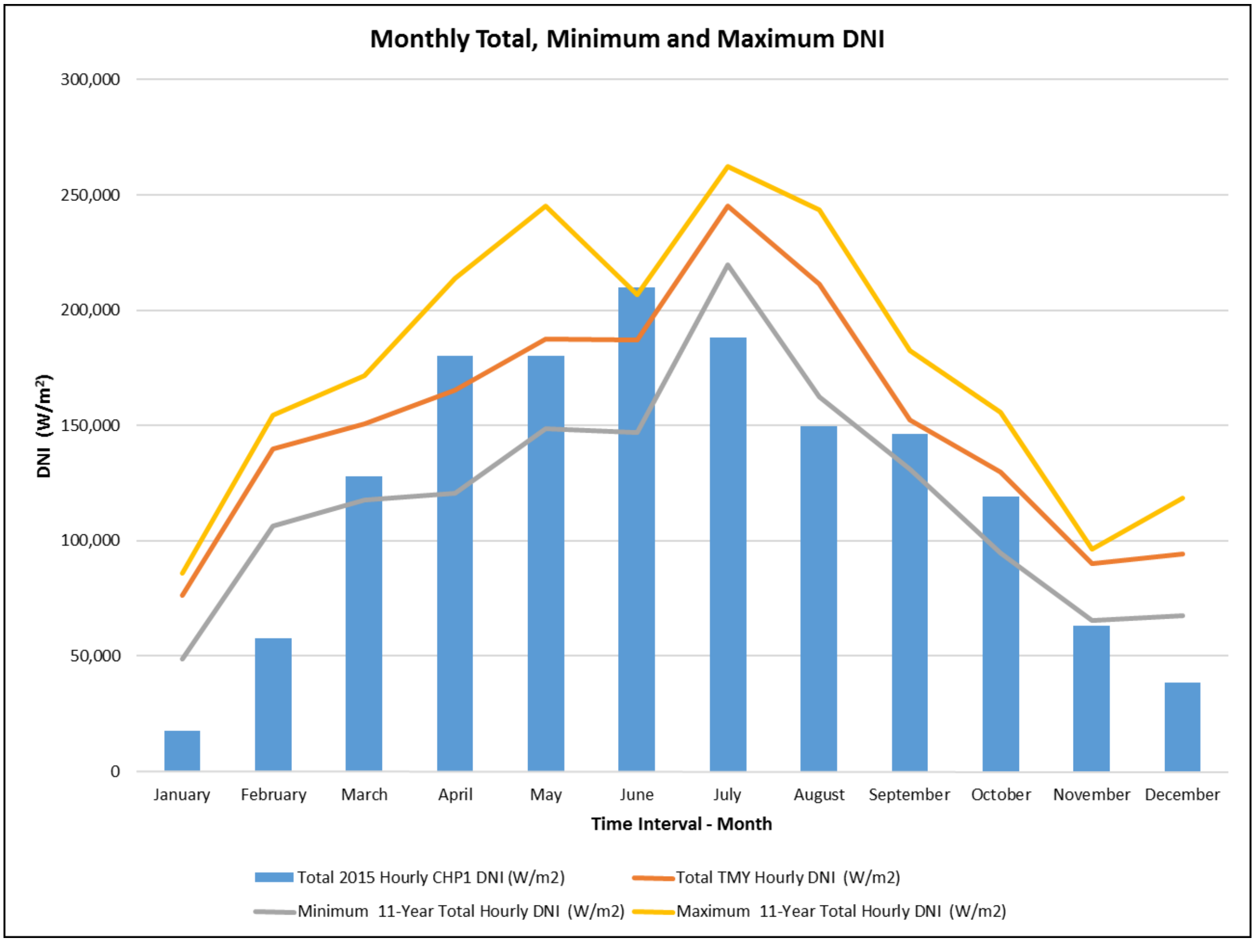
Figure 1   Aerial Photo of Solar Collector Assemblies and CoMH Power Plant

3.4.2. Solar Data Analysis.

The CoMH operated a weather station at the site during the monitoring and testing period. Measured DNI data was compiled and compared to the 11 year satellite derived data set used to generate the Typical Meteorological Year (TMY) “prediction” of solar resource at the site.

The analysis revealed that the total hourly measured DNI during the 2015 monitoring and testing period was 19 % below the TMY. Although 590 more hours of the measured data indicated zero DNI compared to the satellite derived data set, the analysis concluded that the measured data was visually reasonably placed within the TMY and maximum and minimums of the 11 year satellite derived data set. Refer to the monthly summary chart below.

Figure 2   Monthly Total, Minimum and Maximum DNI



Refer to **Appendix C Solar Analysis Measured DNI versus Typical Meteorological Year** for the analysis and conclusions.

3.4.3. Prove that it is feasible to integrate solar thermal steam generation into a combined cycle electrical generating plant in SE Alberta and document the project performance and techno-economics - Achieved

The Project met its goal of generating > 750 kWe and actually achieved a peak output of 1,148 kWe in September. A calculated total of 191 MWh of net electricity was generated by the Project in 2015; 14% of the Phase 1 estimated generation.

The 600 tonnes/year target CO_2e reduction was not met and unfortunately the estimated 2015 reduction was only 35 tonnes. The table below (Table 1 from Appendix D), provides a summary of 9 key factors why the CO_2e reduction was not achieved.

Table 1   Variables Impacting SCA Performance

#	Variable Impacting Performance	Phase 1 Estimate	Actual	Performance Reduction	Remarks
	CO_2e Tonnes Offset	**670**	**34.5**	**95%**	Phase 1 CO_2e adjusted for 2015 CO_2e/MWh factor
1	Trough Underperformance, Unoptimized Operation & Cleanliness	5%	30%	27%	5% Phase 1 assumption is trough reflectivity reduction due to cleanliness
2	DNI, W/m^2 (Jan-Oct)	1784	1400	22%	TMY vs. actual DNI (W/m^2)
3	Increased Project Parasitic Load	5%	18%	14%	Due to HTF specific heat, final design and O&M procedures
4	Trough Mechanical Outage-Monthly DNI Wghtd	2%	12%	10%	Mechanical outage of troughs during DNI
5	Trough Wind Alarm Outage-Monthly DNI Wghtd	4%	13%	9.4%	TMY high wind vs. trough strut design influenced actual wind outage
6	Solar Steam Vented to Atmosphere	0%	5%	4.7%	Captured solar energy not used to create MWh
7	Non-Trough Project Forced Outage-Monthly DNI Wghtd	0%	3%	3.4%	DNI-weighted outage time
8	Combined Cycle Unavailable-Hrly DNI Wghtd	0%	3%	3.3%	CC Unavailable and Project Available
9	No Operations in Nov, Dec	2%	0%	1.5%	Modeled Energy Fraction from Nov, Dec
	Total			**95%**	Total of #1-9

Trough underperformance of 27% is related to tracking, alignment, tuning, and cleanliness issues. When sufficient DNI is present in 2016, it is planned to have the equipment supplier return to remedy the trough tracking and alignment issues. Increased operator attention and improved main control loop tuning is expected to occur once the troughs are seen to contribute more energy to the system. An optimized trough cleaning regime, which is a tradeoff of washing costs vs. increased energy generation, will be developed in 2016 when trough alignment and tracking issues are resolved. Because the troughs were underperforming in 2015, it was not economically prudent to wash frequently.

2015 measured DNI was significantly lower than the satellite derived Typical Meteorological Year (TMY) DNI used in the performance estimate. One of the contributing factors was 2015 atmospheric conditions at the site, which were significantly affected by forest fire actively in western Canada and the USA for an unusually prolonged period from June to August.

Parasitic load is higher than predicted because of the lower HTF specific heat which increased pumping energy. This is a characteristic of the fluid and cannot be remedied without replacement. Increased parasitic load was also due to continuing operational readiness in the Nov to Feb period, when no net energy was produced but energy for heating and controls was still required. Based on this observed substantial energy draw, operational readiness will be suspended in future years during the winter period, reducing the parasitic load to a minimum during this period.

Trough strut failures and replacement activities (refer to section 3.1 and Appendix A) contributed 10% to trough unavailability during 2015. Most of these major trough structural design issues have been resolved and most of the 10% loss is not expected to reoccur in future years.

Because of the strut failures that occurred in 2015, a cautious approach to stow the field during moderate wind speeds was employed, which resulted in much greater unavailability compared to normal. When the strut repair solution was finally implemented (reference Section 3.1), the cautious approach was discontinued. This 9.4 % loss should not repeat in future years.

4.7% of the performance reduction was due to venting steam to atmosphere, some of it unnecessarily. Revised start up and operational procedures yielded up to an 80% improvement comparing late year performance to beginning of year performance during the test period. Control setting changes can yield even further improvements in 2016.

Onetime non-trough forced outages were related mostly to non-recurring commissioning issues and should not repeat in future years.

3.3% of the underperformance was due to unavailability of the steam host to accept steam when the solar steam was available. This will recur in future years to a variable extent depending on Unit 15 operation.

As described earlier, there is a net increased contribution to CO_2e emissions from the plant when the solar plant is kept ready to operate during the winter period, November to January inclusive. This operational readiness will be suspended during future years unless unusual and prolonged favorable conditions are encountered.

Refer to **Appendix D Overall System Performance Summary** for 2015 CSTD Performance Summary

3.4.4. Operational Outcomes / Production Reports

During the calendar year of 2015, the City of Medicine Hat operations group maintained an hourly log of individual Solar Collector Assembly status. The status log tracked operating hours, shutdown hours due to darkness but the SCA was available for service, shut down hours due to the steam host (unit 15 Heat Recovery Steam Generator) being out of service but the SCA was available, outage hours where the SCA was not operating due to weather conditions (further differentiated by wind and by cloud / rain / snow / hail) and outage hours where the SCA was not operating due to maintenance which was further differentiated by SCA mechanical, Heat Transfer Fluid system, or steam generating system failure. The solar field did not generate any power in the winter months due to low DNI / low sun elevation angle and few hours of sunlight. Refer to section 3.4.3 Overall System Performance Summary (and Appendix D) for a summary of the annual production and impact of the various conditions affecting the availability of the plant.

Refer to **Appendix E Solar Logsheet** Summary**.**

3.4.5. O&M Activities and Costs

During the one year operating period the plant was operated by City of Medicine Hat operating personnel. Although there was no incremental impact to the staff complement due to the addition of the demonstration project, the operations personnel tracked the time they spent each day starting, stopping, operating, and safely isolating the system whenever maintenance was required in accordance with the electric generation lock out / tag out procedures. Directly employed operating labor costs totaled around $87,000 for the year.

Emergency and repair at failure maintenance was generally undertaken by the City's directly employed maintenance staff except for major issues that required specialist expertise or where the activity was extensive requiring significant addition resources. Directly employed maintenance labor costs totaled approximately $19,000 for the year.

Prescheduled repeating maintenance activities were undertaken by contract staff. The prescheduled activities included mirror washing (anticipated) and pylon alignment (not anticipated).

Mirror washing was undertaken in May and August during the test period. The initial availability of the system was so low that washing was considered of little value until the larger problems associated with operation of the system were resolved. The initial May wash cost $34,700 and the August wash cost $21,500 for labor, equipment rental, and chemicals. Demineralizer column rental was $1320 to treat reverse osmosis treated water to acceptable dissolved solids levels.

Pylon alignment was found to be necessary prior to spring start-up and will be a recurring annual activity. The 115 meter long aluminum solar collector assemblies (SCA's) are supported on pylons and plastic bearings. They are fixed at the center point (hydraulic actuator location) and grow and shrink thermally to each end. It was discovered during the first year that the extreme minimum temperatures experienced in Medicine Hat (- 40^{o}C) caused the aluminum frames to shrink and bind with the bearing supports moving the pylons out of alignment. The design did not seem to accommodate the large longitudinal movements relative to the initial installation temperature. The re-alignment process was established in 2015 March and is repeatable for future years.

Utility costs are minor and are related to the power consumption for the Solar Collector field and weather station. Power supplies associated with the heat transfer fluid pumping system and steam generating plant is connected to the main power plant power distribution system and is not a separately billed service. These energy consumptions are measured and included in the overall performance summary in Appendix D.

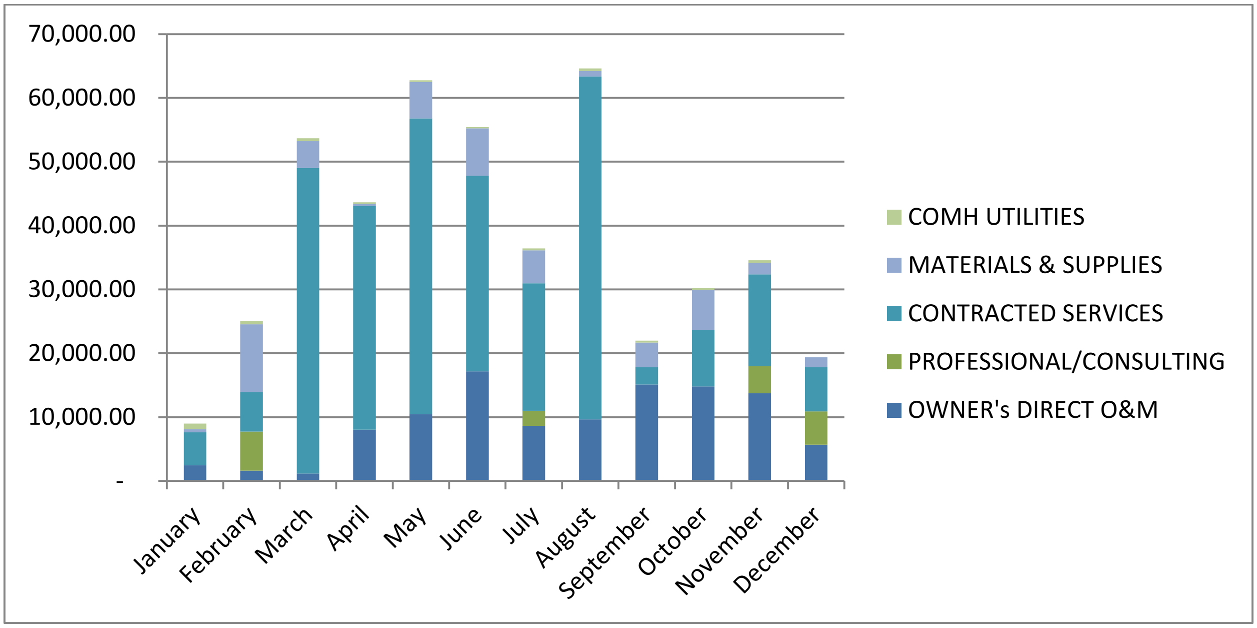
The weather station maintenance, data validation, and reporting cost is included in contracted services.

Other costs included engineering support to undertake testing and operational set up, develop operating procedures and reporting.

It was anticipated that the Heat Transfer Fluid (HTF) would deteriorate in operation. The HTF was periodically tested to determine water content, and percentages of dissolved high and low boiling point solvents. It was expected that some optimum level would be determined requiring routine blow down and replacement of fluid. During the one year test period, no significant deterioration occurred and no blow down or fluid replacement program was required mainly because the HTF was operated at a much lower temperature than design intent and was operated for a lot fewers hours than expected. Although HTF replacement costs will likely be a consideration in future years, there is insufficient data available from the first year of operation to determine when the replacement program might be initiated and what the rate of fluid replacement might be.

Below is a distribution of monthly operating costs by expenditure type during the test period.

Figure 3 Monthly Distribution of Operating Costs



The following Table 2 is a summary of the annual costs during the 2015 test period.

Table 2 2015 Operating & Maintenance Cost Summary by Expenditure Type

Expenditure Type	Annual Cost
City Directly Employed Labor	$105,950
Contracted Services	$272,680
Materials and Supplies	$47,660
Utilities	$3,510
Professional / Consulting	$17,950
Totals	**$447,750**

Opportunities for improvements in future years to reduce maintenance costs and increase availability include:

- Review of SCA actuator hydraulic pumping units and hoses – the pumps and hoses are not rated for operation below -20°C.
- Pylon bearing design – to accommodate a larger ambient temperature interval -40 ° C to + 40 ° C.
- Revise trough control design algorithms – to improve collector trough position and focus while accounting for trough sag.

Refer to **Appendix F Operations and Maintenance Costs** for a summary of monthly O&M costs.

3.4.6. Adapt or improve the technology for the local climate and as a means to attaining GHG reductions in a variety of industrial applications in Alberta – Achieved.

The best DNI in Canada falls in southern Alberta and Saskatchewan, which can be clearly seen in Appendix G, and should be the only contemplated locations for a concentrating solar power (CSP) installation. The below table shows the existing fossil fuel generators that employ a Rankine cycle, below 52.3° latitude in AB and SK. The total power from the steam turbines is about 3,180 MW. Every CSP-Hybrid project (as they are generically known, which includes the familiar ISCC) is unique and it is not possible to accurately estimate the potential CSP integration without an analysis of each steam cycle. For rough approximation purposes only, anywhere from 300 – 950 MWe of peak CSP output could be integrated with these plants, and certainly more with greenfield Integrated Solar Combined Cycle projects which have the inherent advantage of being able to optimize the steam cycle with the solar energy. The rough approximation of the annual solar electricity for these brownfield theoretical installations is 400 – 1,250 GWh.

Thermal storage, a key differentiator for CSP compared to intermittent renewable energy sources such as wind and photovoltaic (PV), can theoretically be employed to increase the capacity factor of the installations, although is not likely to be economical in Canada and with low natural gas prices.

Table 3 CSP - Hybrid Opportunities in Western Canada

Company Name	Facility Name	City	Prov	Lat	Long	Power Tech	Station Output, MW	Approx. STG, MW
Alberta Power (2000) Ltd.	Sheerness Generating Station	Hanna	AB	51.53	-111.79	Coal-Fired Boilers	780	780
Saskatchewan Power Corporation	Poplar River Power Station	Coronach	SK	49.05	-105.49	Coal-Fired Boilers	532	532
Saskatchewan Power Corporation	Boundary Dam Power Station	Estevan	SK	49.10	-103.03	Coal-Fired Boilers	813	813
Saskatchewan Power Corporation	Shand Power Station	Estevan	SK	49.09	-102.86	Coal-Fired Boiler	279	279
Saskatchewan Power Corporation	Queen Elizabeth Power Station	Saskatoon	SK	52.09	-106.71	Natural Gas Boiler	218	95
Saskatchewan Power Corporation	Queen Elizabeth Power Station	Saskatoon	SK	52.09	-106.71	NGCC	225	74
Nexen Energy ULC	Balzac Power Station	Rocky View County	AB	51.19	-113.94	NGCC	120	25
City of Medicine Hat	Electric Utility - Generation	Medicine Hat	AB	50.04	-110.72	NGCC	204	60
ENMAX Cavalier GP Inc.	Cavalier Energy Centre	Strathmore	AB	51.01	-113.19	NGCC	120	36
Calgary Energy Centre No. 2 Inc.	Calgary Energy Centre	Calgary	AB	51.18	-113.94	NGCC	320	106
ATCO Power Canada Ltd.	Cory Cogen Station	Saskatoon	SK	52.09	-106.85	NGCC +cogen	260	90
Enmax Generation Portfolio Inc	Shepard Energy Centre	Calgary	AB	50.97	-113.89	NGCC	873	288
Totals (Lat, Long are output weighted average)				**50.22**	**-107.57**		**4,744**	**3,178**

There are many other potential uses for concentrating solar thermal energy / steam, including cogeneration plants, biomass plants, and industrial processes that are heat intensive. As a generalization, the economics typically favor power generation, unless the process the solar heat is potentially being integrated with requires medium to high pressure steam and / or high temperature.

Due to the very small size of the Project, economic extrapolations to significantly larger installations cannot be made with any degree of meaningful price certainty.

Refer to **Appendix G for Natural Resources Canada paper "Potential of Concentrating Solar Power in Canada"**

3.4.7. Achieve an estimated GHG emissions reduction of 600 tonnes per year validated by a GHG verification report – Not Achieved

As stated previously, the estimated GHG reduction in 2015 was 35 tonnes (refer to Appendix D). Due to the timing of the CoMH's annual Power Plant verification report under the Large Emitter Regulation, the Verification Report will be submitted at a later date along with the report for the main Power Plant.

Future performance improvements outlined in Section 3.4.3 and described in Appendix D are expected to contribute to increased GHG reductions in 2016 and beyond compared to the 1st year monitoring period. It is also expected that much of the contracted maintenance and materials costs (outlined in Section 3.4.5 and summarized in Table 2), which combine to represent almost 72% of O&M costs, will be nonrecurring. These two factors synergistically will reduce the unit cost of emission reductions in future years. It should be noted that due to the small size of the project, relative O&M costs (both fixed and variable) will be much higher than for a commercial scale project. Any extrapolation of the demonstration project O&M costs must consider benefits of economies of scale.

4. Publications During Reporting Period

4.1. No Publications during the period.

5. Overall Conclusions.

5.1. Conclusion:

The project has definitively proven that it is possible to integrate and operate an Integrated Solar Combined Cycle plant at Canadian latitudes. Peak power output exceeded project goals. While CO_2 reductions did not meet objectives, the contributors to the shortfall are now clearly identified so that both the Proponent and future ISCC projects can address these items at early stages of the design.

6. Acknowledgements

The author would like to acknowledge the following people and organizations as major contributors to accomplishing the goals of the project:

Climate Change Emissions Management Corporation for contributing 1/3 of the original project budget,

Alberta Government for providing an EcoTrust funded grant of 1/3 of the original project budget,

Ryans Bowers, Worley Parsons

Reda Djebbar, Natural Resources Canada

Greg Baden et al, BECL and Associates

SkyFuel for providing SCA technology and equipment

And numerous local suppliers of goods and services.

7. Appendices

Appendix A:	Strut Damage Reports
Appendix B:	SCA Short Term Performance Acceptance Test
Appendix C:	Solar Analysis Measured DNI versus Typical Meteorological Year
Appendix D:	Overall System Performance Summary
Appendix E:	Solar Logsheet Summary
Appendix F:	Operations and Maintenance Costs
Appendix G:	Natural Resources Canada Paper "Potential of Concentrating Solar Power in Canada"

Appendix A: Strut Damage Reports

R. Bowers, 2-Feb-2016

SkyTrough® Original Strut Design Issue Summary

During the course of the operational phase of the Project, CoMH noticed that several SCA struts were beginning to crack, and some completely sheared at their end connections and fell to the ground. CoMH engaged SkyFuel to address the problem and also began its own investigation. This document serves to summarize CoMH's own investigation.

Acuren Group Inc. (Calgary) was engaged by CoMH to conduct a tensile test and chemical analysis on one of the failed struts and compare results to manufacturer's material specifications. The measured chemistry most closely matched Alloy 6061, although it had a slightly higher Mg weight content than the specification (1.29% vs. 0.8-1.2% allowable range). The sample exceeded the minimum tensile stength and elongation requirements, but had a ~7% lower yield strength than Alloy 6061 specification requirements.

Acuren also performed a metallurgical analysis on four cracked struts that were sent to them. A visual inspection, scanning electron microscopy examination and hardness testing were performed. Acuren concluded that all samples exhibit through-thickness brittle fractures that are indicative of high cycle low stress fatigue. The transverse orientation of the cracking is consistent with the presence of cyclic bending loads at the strut connections.

CoMH engaged WorleyParsons to perform a high-level analysis of the strut designs and offer its opinion of the situation. WorleyParsons calculated that vortex shedding at relatively low wind speeds induces cycling at the associated resonant frequencies of the struts, i.e. cyclic loading that matches the failure mechanism identified by Acuren. A detailed survey of the damage was performed by WorleyParsons and of the five types of struts that exhibited visual damage, the two most problematic had visual fatigue damage occurance rates of 73% and 54% (percent of total struts installed in the field of the associated type) as of the middle of June, 2015 (see attached damage log).

The two strut designs with the most failures have resonant velocities less than SkyFuel's published continuous operational wind speed of 40 km/h (original procurement specification requirement for continuous operation was 56 km/h). Of note is that when the SCAs are in their stow position (used for protection from wind loading and otherwise as their non-operational go-to position), the struts that are most susceptable to excitation at low wind speeds are above the height of the SkyFuel-specified wind screen. It appears that the issues with vortex shedding-induced fatigue loading on the struts with very slender tubular sections/end connections were not fully considered in the SCA design and that these struts were not meant to be shielded by the wind screens. According to American Association of State Highway and Transportation Officials (AASHTO) specifications, which are not directly related to this project but cover design of members subject to wind loading (e.g. road signs built of tubular structural members), it is not recommened to design any structural member for a finite number of cycles when the associated first modal resonant wind speed is below ~72 km/h[1]. American Society of Civil Engineers (ASCE) structural design standards also mention avoidance of vortex shedding and natural frequencies near resonant frequency.

---

[1] An excerpt from AASHTO provides some relevant guidance; *"Accurate load spectra and life prediction techniques for defining fatigue loadings are generlly not available. The assessment of stress fluctuations and the corresponding number of cycles for all wind-induced events (lifetime loading histogram) is practically impossible. With this uncertainty, the design for a finite fatigue life becomes impractical…. and an "infinite life fatigue design approach is recommended. Fatigue stress limits are based on the CAFL".*

The only way to address the problem is to increase the natural frequency of the members (by stiffening and/or reducing the unbraced span length), redesign the struts and end connections to handle infinite cycling (although the struts would still continue to resonate undesireably), reduce the number of cycles and their amplitudes, and/or prevent wind speeds from reaching the associated resonant wind speeds. The latter is not feasible given that the associated wind speeds that excite the members occur almost daily at most locations in the world. Shielding the troughs is not possible unless an incredibly tall (and impermeable) wind screen was to be erected around the site (which would block the DNI), or a glass struture was to be constructed over the field (which incidently happens to be a technology employed by another parabolic trough supplier), which is cost prohibitive.

The project was constructed with wind screens on the west and south sides of the field, although SkyFuel did recommend to install wind screens on all four sides of the field in its proposal. The wind screens are constructed of a semi-permeable polymer material, attached to a traditional chain-linked fence metal mesh, which allows some wind penetration. The semi-permeability is intentional (the wid screen is per SkyFuel's recommended height, relative location to the troughs, and permeability specifications), and is based on the NREL wind tunnel test report (NREL/SR-550-32282), used by many trough designers for structural design load analysis. The intent of the NREL wind test report is to offer parabolic trough designers insight into how to better determine peak structural design loads vs. those determined by the typical quasi-steady state building code approach. The NREL report specifically measured impacts from solid vs. semi-porous wind screens and shows that peak loads can be reduced with semi-permeable wind screens more so than with solid screens. It includes results of local reflector surface differential pressure measurements, with the intent of providing insight into the structural design considerations of reflectors. It does not address wind-induced fatigue loading. It is therefore WorleyParsons' opinion that the intent of the wind screens are predominantly to reduce the trough design wind loads associated with very high wind speeds that occur with very low statistical probability (i.e. wind speeds dictated by structural design codes) and not prevent low speed high occurance winds from reaching the troughs. Given the intent of the wind screens and the historical wind speed vs. directional data (i.e. wind rose) from an adjacent anemometer, the City decided to locate them on the west and south sides only, to save project cost, given that this is a demonstration project. There was no pattern evident in the damage assessment that would lead one to conclude that the wind screens reduced the damage on the south and west portions of the solar field, compared to the rest of the field. This further supported the conclusion by WorleyParsons and CoMH that adding a wind screen on the east and/or north sides of the solar field would not alleviate the problem.

CoMH reportedly shared WorleyParsons' investigation results with SkyFuel to consider in its own investigation of the problem. SkyFuel's solution was to revise the two most problematic strut designs by increasing the diameter/thickness of the tubes (and providing new end connection designs), which increases the associated resonant wind velocity, reduces vibration amplitude and decreases the resulting stress ranges and the number of cycles. These new replacement struts were shipped to the Project in July and were immediately installed by CoMH. The other three problematic strut types were modified by SkyFuel (with field labor from CoMH) with cable bracing, attached at strut mid-span, which also acts to increase the resonant wind velocity, reduce vibration amplitude and decrease the resulting stress ranges and the number of cycles. Evidently SkyFuel came to the same conclusion as WorleyParsons and addressed the root cause of the problem by increasing the natural frequency of the struts.

SCA Fatigue Damage Status as of 6/19/2015

R. Bowers

SCA	Field Summary				2D				2C				2B				2A				1D				1C				1B				1A			
SkyFuel Strut Part No.	**End Qty**	**%**	**Strut Qty**	**%**	End Qty	%	Strut Qty	%	End Qty	%	Strut Qty	%	End Qty	%	Strut Qty	%	End Qty	%	Strut Qty	%	End Qty	%	Strut Qty	%	End Qty	%	Strut Qty	%	End Qty	%	Strut Qty	%	End Qty	%	Strut Qty	%
197-22 (OTD1)-TO BE REPLACED	**255**	**50%**	**187**	**73%**	39	61%	28	88%	39	61%	26	81%	24	38%	21	66%	35	55%	25	78%	40	63%	27	84%	35	55%	25	78%	18	28%	17	53%	25	39%	18	56%
197-20 (BTV1)-TO BE REPLACED	**140**	**36%**	**104**	**54%**	18	38%	12	50%	19	40%	14	58%	12	25%	10	42%	24	50%	19	79%	18	38%	13	54%	20	42%	14	58%	14	29%	11	46%	15	31%	11	46%
197-21 (BTD2)-CABLED	**16**	**1.6%**	**15**	**2.9%**	0	0%	0	0%	1	1%	1	2%	0	0%	0	0%	4	3%	3	5%	4	3%	4	6%	4	3%	4	6%	2	2%	2	3%	1	1%	1	2%
197-11 (ITD2)-CABLED	**9**	**0.9%**	**9**	**1.8%**	0	0%	0	0%	3	2%	3	5%	0	0%	0	0%	0	0%	0	0%	1	1%	1	2%	1	1%	1	2%	1	1%	1	2%	3	2%	3	5%
0201-10 (OTD2)-CABLED	**1**	**0.1%**	**1**	**0.2%**	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	1	1%	1	2%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%

SCA Fatigue Damage Status as of 6/19/2015

R. Bowers

Loop 2 (West)

(Strut End Qty=2x Strut (Srt) Qty, RPLC = SkyFuel planned replacement strut, CBL =SkyFuel planned cabled strut)

2D N	End Qty	Srt Qty	Strut Type	Other Damage
	2	2	197-22 (OTD1)-RPLC	
			197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	3	3	197-22 (OTD1)-RPLC	
	1	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	5	3	197-22 (OTD1)-RPLC	
	3	3	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	6	4	197-22 (OTD1)-RPLC	
	5	3	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
O				
	7	4	197-22 (OTD1)-RPLC	
	5	3	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	5	4	197-22 (OTD1)-RPLC	
	2	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	5	4	197-22 (OTD1)-RPLC	
	2	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	6	4	197-22 (OTD1)-RPLC	
			197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
2D S				

2C N	End Qty	Srt Qty	Strut Type	Other Damage
	2	2	197-22 (OTD1)-RPLC	
	2	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	5	4	197-22 (OTD1)-RPLC	
	2	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	5	4	197-22 (OTD1)-RPLC	
	3	3	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	5	3	197-22 (OTD1)-RPLC	
	4	3	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
O				
	7	4	197-22 (OTD1)-RPLC	
	2	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
	1	1	197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	7	4	197-22 (OTD1)-RPLC	
	4	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	4	2	197-22 (OTD1)-RPLC	
			197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
	1	1	197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	4	3	197-22 (OTD1)-RPLC	
	2	1	197-20 (BTV1)-RPLC	
	1	1	197-21 (BTD2)-CBL	
	1	1	197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
2C S				

2B N	End Qty	Srt Qty	Strut Type	Other Damage
	3	2	197-22 (OTD1)-RPLC	
			197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	3	2	197-22 (OTD1)-RPLC	
			197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	2	2	197-22 (OTD1)-RPLC	
			197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	2	2	197-22 (OTD1)-RPLC	
	2	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
O				
	3	3	197-22 (OTD1)-RPLC	
	3	3	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	3	3	197-22 (OTD1)-RPLC	
	1	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	4	3	197-22 (OTD1)-RPLC	
	3	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	4	4	197-22 (OTD1)-RPLC	
	3	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
2B S				

2A N	End Qty	Srt Qty	Strut Type	Other Damage
	7	4	197-22 (OTD1)-RPLC	
	4	3	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	3	3	197-22 (OTD1)-RPLC	
	3	3	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	5	3	197-22 (OTD1)-RPLC	
	3	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	6	4	197-22 (OTD1)-RPLC	
	5	3	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
O				
	5	3	197-22 (OTD1)-RPLC	197-20 completely sheared off (replaced)
	1	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	4	3	197-22 (OTD1)-RPLC	
	4	3	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	2	2	197-22 (OTD1)-RPLC	
	1	1	197-20 (BTV1)-RPLC	
	3	2	197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	3	3	197-22 (OTD1)-RPLC	
	3	3	197-20 (BTV1)-RPLC	
	1	1	197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
2A S				

Loop 1 (East)

(Strut End Qty=2x Strut (Srt) Qty, RPLC = SkyFuel planned replacement strut, CBL =SkyFuel planned cabled strut)

1D N	End Qty	Srt Qty	Strut Type	Other Damage
	7	4	197-22 (OTD1)-RPLC	
	3	3	197-20 (BTV1)-RPLC	
	1	1	197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	3	2	197-22 (OTD1)-RPLC	
			197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	6	4	197-22 (OTD1)-RPLC	
	2	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	6	4	197-22 (OTD1)-RPLC	
	5	3	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
O				
	5	3	197-22 (OTD1)-RPLC	
	2	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	6	4	197-22 (OTD1)-RPLC	
			197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	3	3	197-22 (OTD1)-RPLC	
	2	1	197-20 (BTV1)-RPLC	
	1	1	197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
	1	1	0201-10 (OTD2)-CBL	
	4	3	197-22 (OTD1)-RPLC	rivet fix on ctr 197-20
	4	2	197-20 (BTV1)-RPLC	
	2	2	197-21 (BTD2)-CBL	
	1	1	197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
1D S				

1C N	End Qty	Srt Qty	Strut Type	Other Damage
	4	3	197-22 (OTD1)-RPLC	
	2	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	4	3	197-22 (OTD1)-RPLC	
	1	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	3	3	197-22 (OTD1)-RPLC	rivet fix on197-21 (s end)
	1	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
	1	1	197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	5	3	197-22 (OTD1)-RPLC	
	5	3	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
O				
	5	3	197-22 (OTD1)-RPLC	
	2	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	6	4	197-22 (OTD1)-RPLC	
	5	3	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	4	3	197-22 (OTD1)-RPLC	
	2	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	4	3	197-22 (OTD1)-RPLC	
	2	1	197-20 (BTV1)-RPLC	
	4	4	197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
1C S				

1B N	End Qty	Srt Qty	Strut Type	Other Damage
	5	4	197-22 (OTD1)-RPLC	rivet fix on bot truss to torque plate diag
	3	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	1	1	197-22 (OTD1)-RPLC	missing module corner rib to rib diag strut, N end (not on Frame Assbly dwgs)
	2	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	3	3	197-22 (OTD1)-RPLC	
	1	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	3	3	197-22 (OTD1)-RPLC	(1) 197-20 completely sheared (replaced)
	1	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
O				
	1	1	197-22 (OTD1)-RPLC	rivet fix on0201-10 (N end)
			197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
			197-22 (OTD1)-RPLC	
	1	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	2	2	197-22 (OTD1)-RPLC	
	2	2	197-20 (BTV1)-RPLC	
	1	1	197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	3	3	197-22 (OTD1)-RPLC	
	4	2	197-20 (BTV1)-RPLC	
	1	1	197-21 (BTD2)-CBL	
	1	1	197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
1B S				

1A N	End Qty	Srt Qty	Strut Type	Other Damage
	2	2	197-22 (OTD1)-RPLC	(1) Axial Chord Strut rivets sheared (replaced)
	3	2	197-20 (BTV1)-RPLC	
	1	1	197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	4	3	197-22 (OTD1)-RPLC	
	4	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	1	1	197-22 (OTD1)-RPLC	
	2	2	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	1	1	197-22 (OTD1)-RPLC	
	2	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
O				
	5	3	197-22 (OTD1)-RPLC	S 197-22 about to shear
	1	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
			197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	5	3	197-22 (OTD1)-RPLC	N 197-22 about to shear
	1	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
	1	1	197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	4	2	197-22 (OTD1)-RPLC	
	1	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
	1	1	197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
	3	3	197-22 (OTD1)-RPLC	
	1	1	197-20 (BTV1)-RPLC	
			197-21 (BTD2)-CBL	
	1	1	197-11 (ITD2)-CBL	
			0201-10 (OTD2)-CBL	
1A S				

Appendix B: SCA Short Term Performance Acceptance Test

WorleyParsons

resources & energy

EcoNomics™

MEMORANDUM

DATE	29-Jan-16
TO	Ken MacKenzie (City of Medicine Hat)
FROM	Ryan Bowers (Mechanical/Process/Solar Engineer, WorleyParsons)
COPY	
PROJECT	CoMH CSTD Project
SUBJECT	Short-Term SCA Performance Test Results Summary
ATTACH	"1" - Sept. 10th Graphical Results, "2" - Oct. 8th Loop Pressure Gauges, "3" - Oct. 8th Graphical Results

The memo serves to summarize the SCA performance test efforts conducted in September and October of 2015.

BACKGROUND

An internationally recognized test code (ASME or otherwise) does not currently exist for concentrating solar power (CSP) plants, although ASME is currently developing an applicable performance test code; ASME PTC 52. In the absence of a formal performance test code, the CSP industry often refers to NREL's work on the subject, which will inform the ASME PTC 52 development. There are two applicable guidelines that cover parabolic trough performance testing; "*Utility Scale Parabolic Trough Solar Systems: Performance Acceptance Test Guidelines*" (NREL/SR-5500-48895) and "*Acceptance Performance Test Guideline for Utility Scale Parabolic Trough and Other CSP Solar Thermal Systems*" (NREL/CP-5500-52467).

The NREL guidelines lay out two types of tests; a short-term power test (thermal output and efficiency) and a long-term energy test, conducted over several days, weeks, or months. The SkyFuel guarantees are applicable to the short-term thermal output test. During the final stages of the CSTD Project design, WorleyParsons, Kearney & Associates and SkyFuel created a rough draft thermal output test plan, following the guidance of the NREL guidelines.

TESTING PARAMETERS

For short-term power tests, there are basically two fundamental equations of importance;

$$P_t = \dot{m}\,\bar{C}p\,(Th - Tc) \qquad \text{(Eqn. 1)}$$

Where;

$P_t = Thermal\ power\ delivered\ to\ HTF\ (kW_t, \frac{kJ}{s}, \frac{mmBtu}{hr}, etc)$

$\dot{m} = HTF\ mass\ flow = (\dot{q} \times \rho), [\dot{q} = volumetric\ flow\ rate, \rho = HTF\ density]$

$\bar{C}p = integral\ average\ of\ HTF\ specific\ heat$

$Th = HTF\ bulk\ outlet\ (hot)\ temperature\ of\ the\ solar\ field$

$Tc = HTF\ bulk\ inlet\ (cold)\ temperature\ of\ the\ solar\ field$

$$\eta = \frac{P_t}{ANI \times A} \qquad \text{(Eqn. 2)}$$

Where;

$\eta = overall\ collector\ efficiency\ (combined\ optical\ and\ thermal)$

$ANI = aperture\ normal\ irradiance = DNI\ \times \cos(\theta)$

$DNI = direct\ normal\ irradiance$

$\theta = beam\ radiation\ incident\ angle, relative\ to\ aperture\ plane\ of collector$

$A = aperture\ area\ of\ solar\ field\ in\ focus = 5{,}248\ m^2\ when\ all\ 8\ collectors\ are\ focused$

The specific heat and density properties of the HTF are published by the manufacturer. However, the HTF is a complicated synthetic oil blend and its properties are not universal like water or air, so in order to understand and reduce uncertainty around the properties, fluid samples were sent to the Department of Aerospace and Mechanical Engineering at the University of Arizona in Tucson, AZ. Table 1 shows the density results. In general there is good agreement over the normal operating temperature range (250°–340℃) between the published data and the tested HTF, although there are significant deviations at the lower end of the temperature scale. The calculated uncertainty is <1%.

Table 1

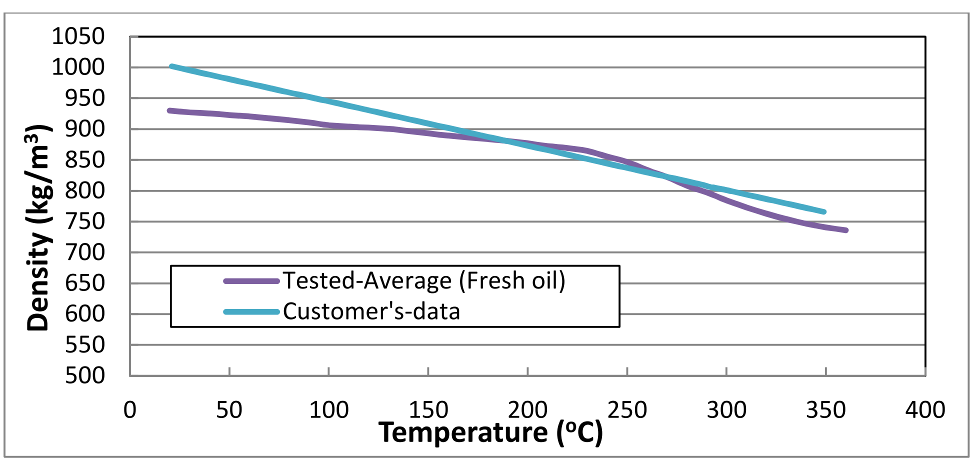


Table 2 shows the results of the specific heat testing. The calculated uncertainty is <6% above 110℃. However, when comparing the tested (measured) specific heat to the published data, there are significant differences that have detrimental impacts on the CSTD Project.

Table 3 shows the comparison between the measured and published specific heat data. It can be seen in the normal operation temperature range (250° – 340℃), the actual measured specific heat is about ~12% – 14% less than published data from the manufacturer. Based on conservation of energy (see Eqn. 1), if the specific heat is ~13% less than anticipated, the mass flow must be increased ~13%. This has the following negative consequences on the system performance;

- The HTF pumps must put out ~13% more flow than originally designed, and, due to the use of VFDs, the parasitic load consumption will be ~ 44% higher than originally planned. The HTF pumps make up the largest parasitic load for the CSTD Project so this has significant consequences.
- The HTF system, including the pumps, was designed based on the published data. Because the system now needs to handle ~13% more flow, for a given amount of absorbed thermal energy, the system will not be able to handle the originally designed peak solar thermal input and thus the troughs will need to be defocused more often than originally foreseen.

Table 2

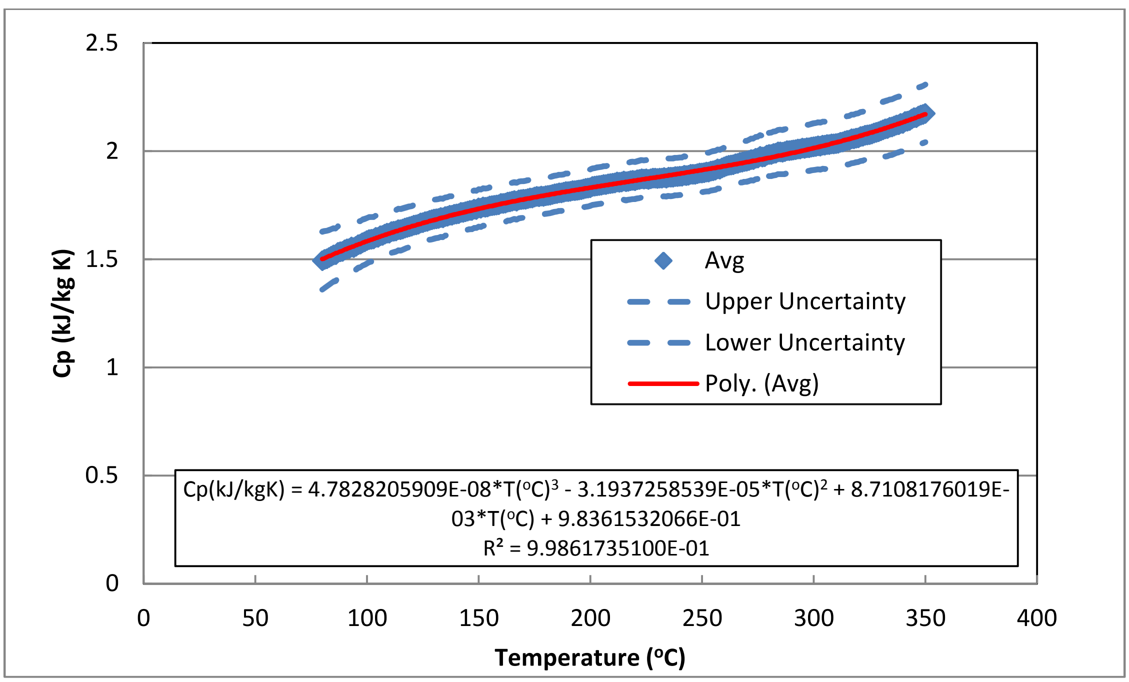
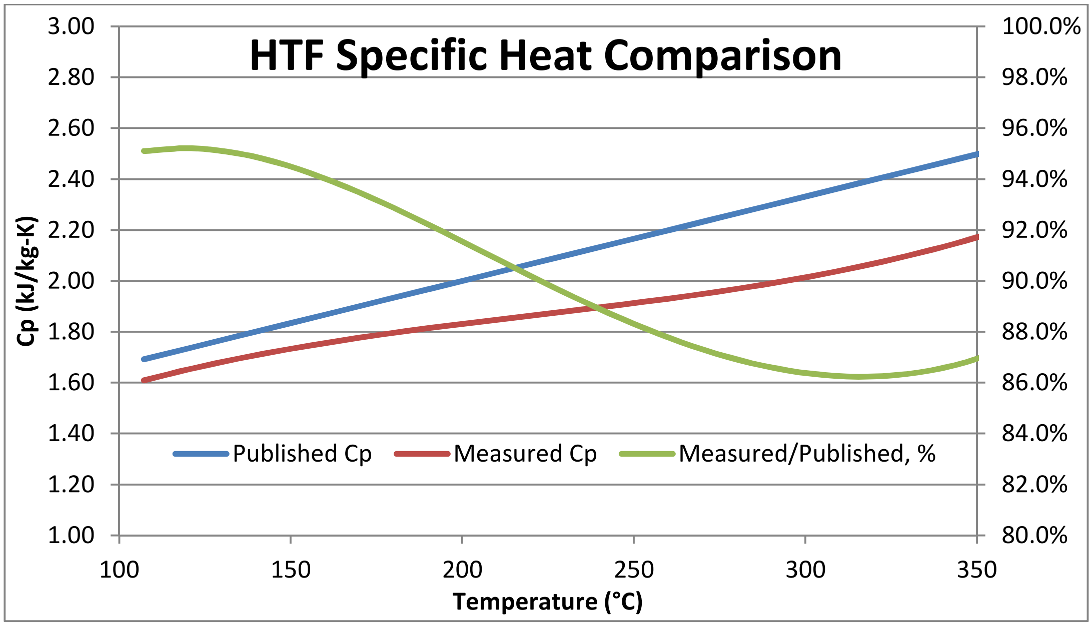


Table 3



SOLAR FIELD PERFORMANCE TESTING & OBSERVATIONS

Once the solar field construction and commissioning issues were mostly resolved, it allowed the solar field to be able to reach a quasi-steady state condition, which is a prerequisite of a proper performance test. Unfortunately this did not occur until September where the ANI is significantly lower than the guaranteed design value so the tests were conducted far from the guarantee reference values.

On September 10th, 2015 the DNI was consistent for long enough duration to attempt a performance test. The original overarching goals of the performance test were;

1. Have all 8 SCAs focusing for at least 15 minutes prior to taking measurements,
2. Have at least 15 minutes of steady state conditions after #1 achieved; no clouds, steady HTF mass flow,
3. Maintain constant T_h and T_c at each loop,
4. T_c temperature is governed by the solar steam generator (SSG) and requires maintaining a constant steam pressure in the SSG,
5. All SCAs should be cleaned just prior to the test (which occurred a few days prior to September 10th).

It took until 1:30 p.m. to reach the goals, but then clouds started rolling in over the field and disrupted the test. This cycle continued until around 5:00 p.m., when the intermittent clouds dispersed and quasi-steady state conditions were reached. In order to maintain T_h at a constant temperature, it was determined that loop 2 outlet balancing valve needed to be continuously adjusted throughout the day; something that should not be required and which impacts steady-state conditions. Attachment 1 shows the results of the test from 5:10 p.m. until 5:45 p.m. This data is just provided for information as steady state conditions were not properly achieved and the test is considered invalid. Nonetheless, a few important observations can be drawn from Attachment 1;

- While the desired steady-state conditions did not exist due to the re-balancing of the flow, the troughs were substantially underperforming (comparing *Measured HTF Power* to *Predicted HTF Power* or similarly *Measured Loop Eff* to *Predicted Loop Eff* (which is η from Eqn. 2).
- T_h of each loop (Tout in Attachment 1) and the HTF flow (kpph= thousand lb_m/h) were held fairly constant and rode through the DNI transient that occurred at 5:14 p.m. (17.23 in Attachment 1) without a hitch.
- It should be pointed out that there are no shading impacts at this time of the day/year.

After going through the Sept 10th performance test trials, it was determined that goal #3 from above needed to be revised to better obtain quasi-steady state conditions, given the varying performance from Loop 1 vs. Loop 2 that required constant flow adjustment throughout the day. The revised goal #3 became;

3. Balance flows equally to each loop (50:50) by using loop inlet and outlet pressure gauges and adjusting the manual loop flow balancing valve to achieve the same differential pressure. Once flow is balanced, no further valve manipulation is allowed throughout test.

On October 8th, 2015 the plant again achieved favorable conditions to attempt the performance test. Attachment 2 depicts the inlet and outlet pressure gauge readings of the two loops from October 8th prior to achieving the steady state conditions, which is evidence of good flow balancing. While this is not the most accurate means of establishing equal flows, it was decided not to bring in temporary flow meters and/or recalibrate the gauges. Attachment 3 shows the entire day of operation from start of steam generation to steam generation curtailment. Several key observations can be made from Attachment 3;

A. Quasi-steady state conditions existed from about 11:35 a.m. → 12:50 p.m. and specifically the HTF flow was held constant so as best to observe performance behavior. The ANI was 530 W/m^2 at the beginning of this period and 475 W/m^2 at the end (~10% drop). While not shown, T_c remained basically constant from 11:00 a.m. until 2:00 p.m.
B. Loop 1, while its outlet temperature was steadier than Loop 2, underperformed Loop 2 from the start of the day until about 12:50 p.m. It had a slow relative improvement over the quasi-steady state time frame described in (A); as the ANI reduced, its outlet temperature increased slightly.
C. Loop 2 outlet temperature, while substantially over performing Loop 1 in the earlier hours, reached parity with Loop 1 at 1:00 p.m. and continued to decline, especially after solar noon (sun directly overhead, or solar angle= 90°).
D. The solar field is severely underperforming and is outside the realm of uncertainty analysis bands. While a full test uncertainty analysis is required for any official test, upon inspection of the results it is not necessary in order to draw conclusions. At its best point throughout the day, the solar field was still underperforming by >20% (around 12:30 p.m.). It is important to note that no

reflectivity measurements were taken because the O&M staff does not possess a reflectometer. While this is an extremely important variable, it simply could not be quantified. For the *Predicted HTF Power*, the assumed average reflectivity of the field is shown in Attachment 3 (82%). New and clean reflectivity is 93% and thus an 88% cleanliness factor was assumed.

E. The severe underperformance led to an inability to operate the Project ~30 minutes past solar noon (solar angle ~97°). During normal operation, the HTF flow would be controlled so as to maintain the hot HTF temperature at least above ~590°F (310°C), which could extend the useful steam generation operation period, although not by much.

CONCLUSIONS

It is evident that the solar field is substantially underperforming and unfortunately this could not be analyzed until the end of the year. As is described in other reports, the yearly performance severely underperformed compared to that predicted during Phase 1 and Phase 2 of the Project. Obviously a key reason why is that the troughs are underperforming; so much so that they become inoperable in the afternoon.

It should be stressed that the underperformance is not necessarily due to permanent optical and physical characteristics of the troughs themselves. These troughs have been placed in operation in two other locations in the world and have reportedly been observed to perform properly. The good news is that they can likely be adjusted to perform much closer to their guaranteed performance. The most probable cause why the solar field is severely underperforming is mostly due to tracking issues;

1. Upon inspection of the SCA positions (from inclinometer output), the troughs were all attempting to focus for the entire day on October 8th. However, a few observations can be made;
    a. Loop 1 position is on average about 0.5° ahead of Loop 2.
    b. Loop 1's four SCAs, relative to the loop average, deviate 50% more than Loop 2.
    c. SCA 1B (Loop 1, A=coldest, D=hottest) appears to be consistently about 0.6° behind the average.
    d. SCA 1C appears to be consistently about 1.0° ahead of the average.
    e. SCA 2B appears to be consistently about 1.0° behind of the average.

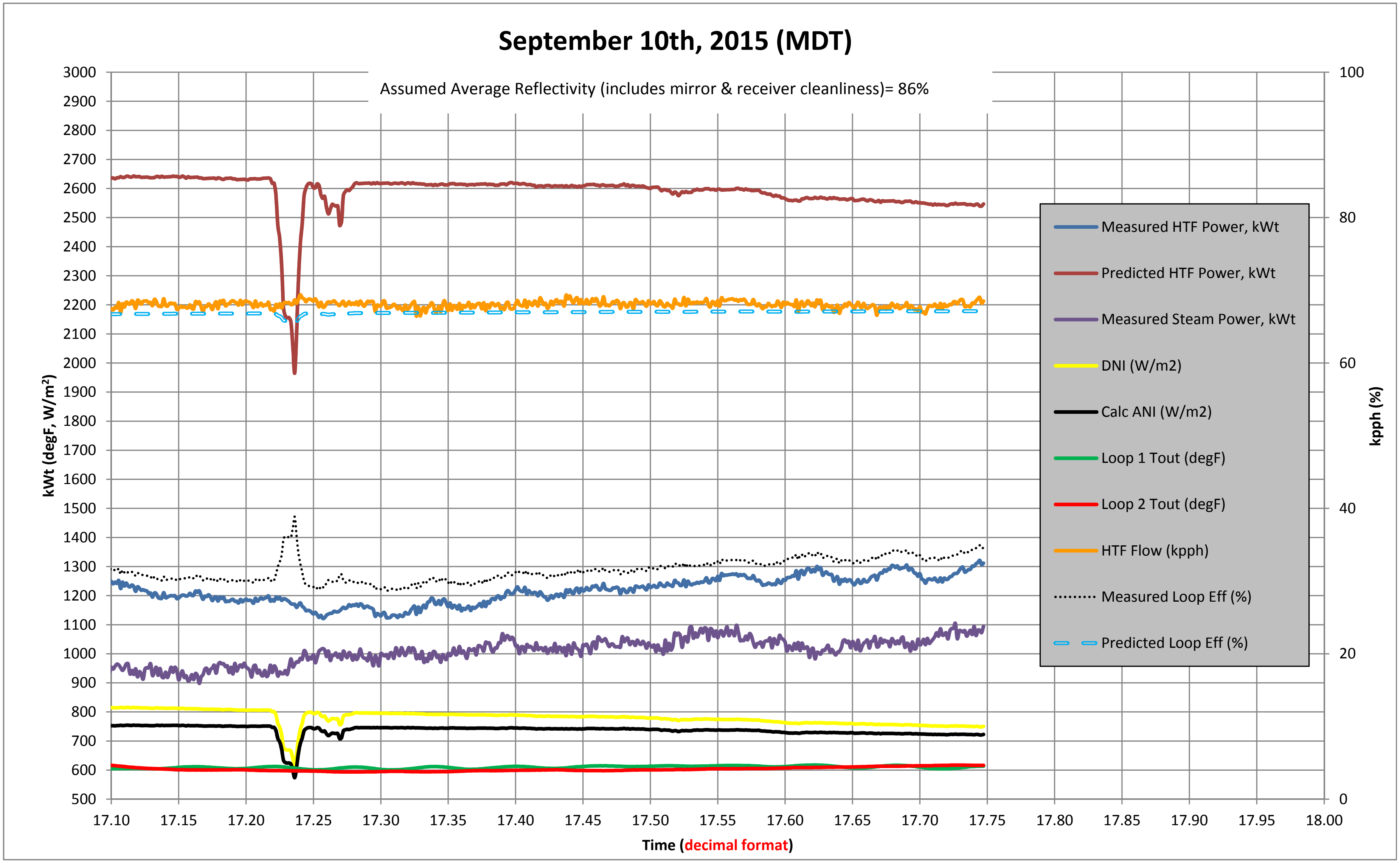
   These variations are much larger than desired by any trough supplier and contribute substantially to the underperformance.

2. The increased weight of the troughs (due to the fixes made to solve the strut design issue, which is discussed elsewhere in the Final Report) has probably not been taken into account in the trough tracking algorithm (which accounts for effects like slight sag due to weight).
3. The inclinometers had many problems during 2015 and the O&M staff had to troubleshoot and re-install a few. They may not have been installed and calibrated to the precision necessary to obtain the best tracking performance and positioning feedback.
4. The hydraulic controls of the troughs had some issues and a few refurbishments/upgrades needed to be performed in the field by the O&M staff throughout 2015. The manufacturer should

be brought to site, along with SkyFuel, to check on the installation and assure everything is in proper working order.

While the above tracking issues should resolve most of the underperformance, there may be core alignment issues that should be checked. While SkyFuel was brought to the site during construction to perform a final alignment before operation began, several events have occurred since this time that could have impacted alignment. SkyFuel will be given the chance to check alignment again when they attempt to fix the tracking issues in spring of 2016.

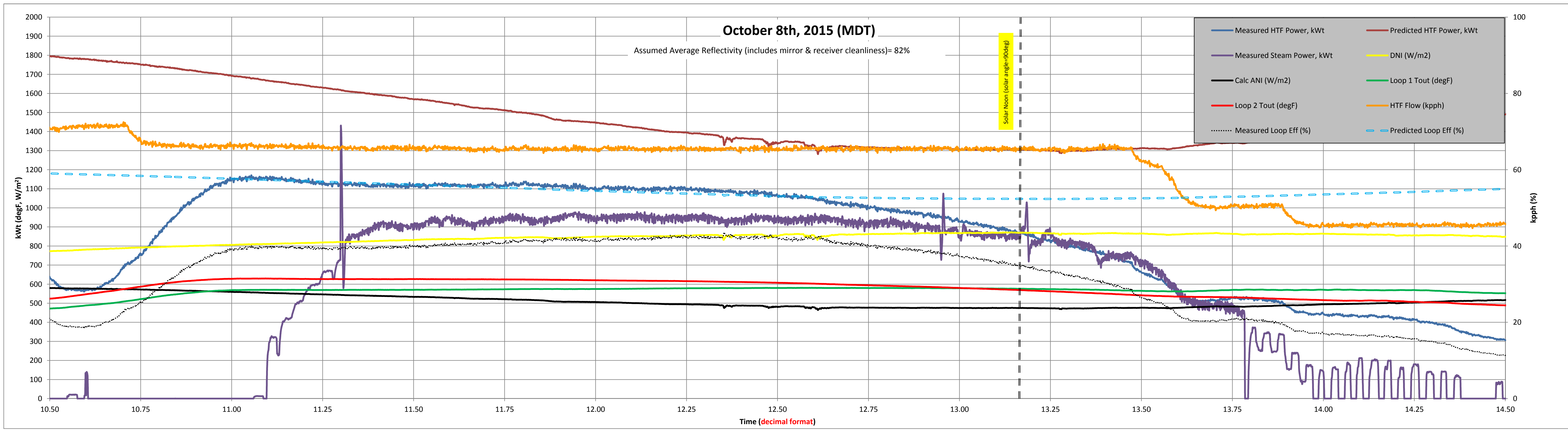
Attachment 1



Attachment 2

Δ 17Psi

Attachment 3



Appendix C: Solar Analysis Measured DNI versus Typical Meteorological Year

2015 Solar Data Analysis

Data

Three datasets were used:

1. 2015 Hourly Solar and Meteorological Data: provided by Campbell Scientific
2. The 1998-2008 Solar and Meteorological Hourly Data
3. TMY Data: generated by BECL in 2011

Process – Dataset Review and Organization

2015 Data

The 2015 dataset was processed as follows:

1. Reviewed the data file for missing data.
2. Discovered one line of missing data, which was promptly provided by Campbell Scientific.
3. Formatted the date columns to parse month, day and hour data; in the process Hour 24 was replaced with zero to match the next dataset.
4. Sorted the hourly data from Hour zero to 23.
5. Deleted 01-15 January hourly data, which was deemed invalid.
6. Used Average DNI, Minimum DNI, Maximum DNI, Air Temperature, Wind Speed and Wind Direction columns.

1998-2008 Data

The 1998-2008 dataset was refined as follows:

1. Filtered the data using Topocentric Zenith Angle to eliminate the non-daylight hours.
2. Examined the dataset for anomalies and deleted lines of data with temperature in the 92-degree Celsius range and at the 999.99 level.
3. Deleted 29-February range of data from the 11-year dataset.
4. Deleted 01-15 January hourly data to match the 2015 dataset.
5. Used Pivot Table over the 11-year data range to obtain – for every hour of every day of every month – Average DNI, Minimum DNI, Maximum DNI, Dry Bulb Temperature, Wind Speed and Wind Direction.
6. Used Pivot Table over the 11-year data range to obtain monthly total DNI by year.
7. Used the results produced in Step 6, to obtain monthly minimum and maximum numbers from the 11-year total DNI numbers.
8. Used the refined 2015 dataset as lookup data array to align the filtered and summarized 1998-2008 dataset with the corresponding 2015 Day-Month-Hour data points.

TMY Data

The TMY dataset was refined as follows:

1. Deleted 01-15 January hourly data to match the 2015 dataset.
2. Filtered the data to eliminate the non-daylight hours.
3. Used pivot table to obtain monthly totals of the hourly DNI.

4. Used the refined 2015 dataset as lookup data array to align the filtered TMY dataset with the corresponding 2015 Day-Month-Hour data points.

Charts

Several charts were generated to compare the 2015 data to 1998-2008 and TMY data as follows:

1. Annual Average DNI by Day-Hour Time Interval (2015 vs. 1998-2008) – 1 Chart
2. Monthly Average DNI by Day-Hour Time Interval (2015 vs. 1998-2008) – 12 Charts
3. Monthly Maximum DNI by Day-Hour Time Interval (2015 vs. 1998-2008) – 12 Charts
4. Monthly Minimum DNI by Day-Hour Time Interval (2015 vs. 1998-2008) – 12 Charts
5. Monthly Average Dry Bulb Temperature by Day-Hour Time Interval (2015 vs. 1998-2008) – 12 Charts
6. Monthly Average Wind Speed by Day-Hour Time Interval (2015 vs. 1998-2008) – 12 Charts
7. Monthly Average Wind Direction by Day-Hour Time Interval (2015 vs. 1998-2008) – 12 Charts
8. Annual 2015 Average Hourly DNI vs. 1998-2008 Minimum and Maximum Hourly DNI by Day-Hour Time Interval – 1 Chart
9. Monthly 2015 Average Hourly DNI vs. 1998-2008 Minimum and Maximum Hourly DNI by Day-Hour Time Interval – 12 Charts
10. Annual Average DNI by Day-Hour Time Interval (2015 vs. TMY) – 1 Chart
11. Monthly Average DNI by Day-Hour Time Interval (2015 vs. TMY) – 12 Charts
12. Monthly Average Dry Bulb Temperature by Day-Hour Time Interval (2015 vs. TMY) – 12 Charts
13. Monthly Average Wind Speed by Day-Hour Time Interval (2015 vs. TMY) – 12 Charts
14. Total 2015 Average Hourly DNI by Month Time Interval vs. Total Hourly TMY and 1998-2008 Minimum and Maximum of total monthly DNI – 1 Chart

The charts are contained in two attached Excel files.

Observations – 2015 Dataset

The combined refined 2015 and 1998-2008 dataset (4,169 lines of data) contains a total of 590 lines of data the 2015 DNI is equal to zero. This is about 14% of the data in the refined dataset. Further investigation of the meteorological data is required to explain the reasons for these occurrences.

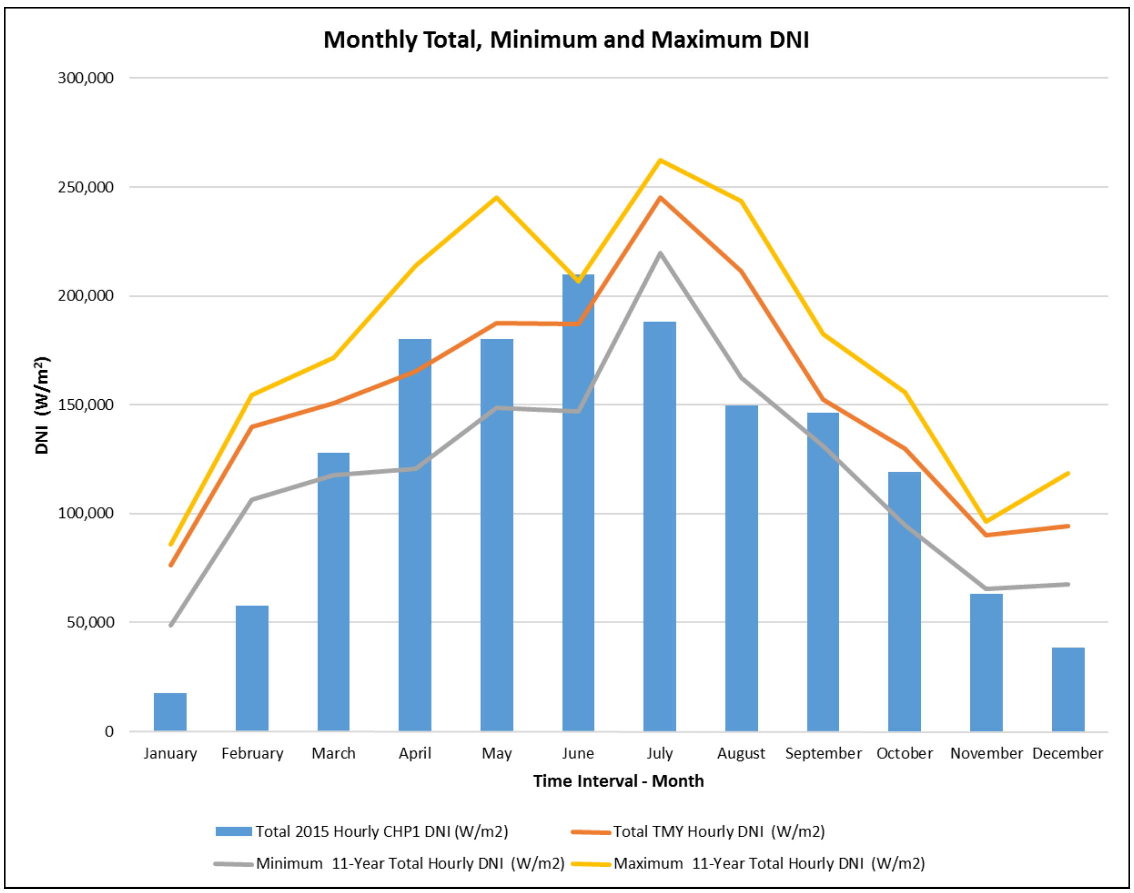
The 2015 data is visually reasonably placed within the TMY and 1998-2008 minimums and maximums ranges.

As there is only one year of actual data available, statistical analysis will not yield any meaningful result. As additional years of data is compiled, statistical tests can be conducted to measure variations – on the monthly or hourly basis

Table 1: Comparison of Monthly DNI Totals

Month	Total 2015 Hourly CHP1 DNI (W/m^2)	Total TMY Hourly DNI (W/m^2)	Minimum 11-Year Total Hourly DNI (W/m^2)	Maximum 11-Year Total Hourly DNI (W/m^2)	Percent Difference 2015 vs. TMY
January	17,792	76,282	48,804	86,006	-77%
February	57,870	139,987	106,545	154,336	-59%
March	127,941	150,897	117,608	171,820	-15%
April	180,113	165,370	120,441	213,836	9%
May	180,001	187,370	148,728	245,111	-4%
June	209,715	187,088	146,969	206,769	12%
July	188,179	245,312	219,501	262,512	-23%
August	149,763	211,226	162,466	243,388	-29%
September	146,246	152,325	130,910	182,549	-4%
October	119,381	129,804	94,662	155,872	-8%
November	63,214	90,040	65,397	96,565	-30%
December	38,564	94,351	67,360	118,634	-59%
Total	**1,478,778**	**1,830,052**			**-19%**

Figure 1: Comparison of Monthly DNI Totals



Appendix D: Overall System Performance Summary

WorleyParsons

resources & energy

EcoNomics™

MEMORANDUM

DATE	31-Jan-16
TO	Ken MacKenzie (City of Medicine Hat)
FROM	Ryan Bowers (Mechanical/Process/Solar Engineer, WorleyParsons)
COPY	
PROJECT	CoMH CSTD Project
SUBJECT	2015 Performance Summary, Estimated CO_2e Reduction & Operational Outcomes Discussion
ATTACH	"1" – 2015 Performance Summary & Estimated CO_2e Offset, "2" – 2015 & 2014 MET Station Summary, "3" – Wind & Wind Gust Monthly Analysis
REF	WorleyParsons Memo: "*Short-Term SCA Performance Test Results Summary*"

This memo serves to summarize the Project performance over 2015, describes the CO_2e reduction estimate & methodology, and presents a general discussion of the Project operational outcomes.

PROJECT PERFORMANCE GOALS

The Project had two main guiding principles; (1) Project shall be capable of generating a minimum of 750 kWe (at design point), and (2) targeted CO_2e greenhouse gas emissions reduction of 600 tonnes/year.

PERTINENT EQUATIONS

$$P_{t\_htf} = \dot{m}_{htf}\, \bar{C}p\, (Th - Tc) \qquad \text{(Eqn. 1)}$$

Where;

$P_{t\_htf} = Thermal\ power\ delivered\ to/by\ the\ HTF\ (kW_t, \frac{kJ}{s}, \frac{mmBtu}{hr}, etc)$

$\dot{m}_{htf} = HTF\ mass\ flow = (\dot{q} \times \rho), [\dot{q} = volumetric\ flow\ rate, \rho = HTF\ density]$

$\bar{C}p = integral\ average\ of\ HTF\ specific\ heat$

$Th = HTF\ bulk\ outlet\ (hot)\ temperature\ of\ the\ solar\ field$

$Tc = HTF\ bulk\ inlet\ (cold) temperature\ of\ the\ solar\ field$

$$P_{t\_stm} = \dot{m}_{stm}\, (h_{stm} - h_{H2O}) \qquad \text{(Eqn. 2)}$$

Where;

$P_{t\_stm} = Thermal\ power\ delivered\ to/by\ solar\ steam\ cycle\ (kW_t, \frac{kJ}{s}, \frac{mmBtu}{hr}, etc)$

$h_{stm} = enthalpy\ of\ the\ steam\ at\ the\ outlet\ of\ the\ solar\ steam\ generator\ (SSG)$

$h_{H2O} = enthalpy\ of\ the\ feedwater\ delivered\ to\ the\ SSG\ from\ the\ HRSG$

$$P_{e\_gr} = \eta_{t \rightarrow e} \times P_{t\_stm} \quad \text{(Eqn. 3)}$$

Where;

$P_{e\_gr} = Gross\ electric\ solar\ power\ delivered\ by\ the\ Project$

$\eta_{t \rightarrow e} = Solar\ use\ efficiency\ (conversion\ factor\ from\ thermal\ to\ electric\ power);$

$defined\ as\ incremental\ kWe\ produced\ to\ the\ grid\ (while\ holding\ fossil\ heat\ input\ constant\ to\ the\ plant)$

$divided\ by\ solar\ thermal\ input\ to\ the\ Rankine\ cycle.$

The net electric solar power from the Project is calculated by subtracting the measured parasitic loads of the Project from P_{e_gr} . All variables in Eqn. 1 and the mass flow in Eqn. 2 are measured by the Project. The enthalpies in Eqn. 2 are calculated using IAPWS-'97 from the associated measured pressure and temperature. All variables, including parasitic load consumption, are continuously measured by various PLCs and the data is archived on the main power plant sequel server. $\eta_{t \rightarrow e}$ is calculated from numerous heat and mass balance calculations of the entire Medicine Hat ISCC. This was an extensive and non-trivial effort and involved analyzing gas turbine data from 2015 RATA emissions testing over 40-100% load range so as to calibrate the CoMH ISCC performance model with actual gas turbine performance, which varies substantially compared to OEM predicted performance.

As discussed in the Reference Memo, the HTF specific heat and density were tested in a lab and these properties were used in the performance analysis (Eqn. 1) vs. the data published by the manufacturer.

2015 RESULTS & OBSERVATIONS

Attachment 1 provides a summary of the 2015 Project performance. Attachment 2 provides a summary of 2015 and 2014 meteorological data information, as well as the TMY DNI for reference.

Attachment 1 is broken into five main categories; MET Data (column A, B), Solar Field Data (column C-F), SSG Energy Data (column G-J), Solar Electric Data (column K-O) and CO_2e (column P). A detailed analysis of the meteorological (MET) data, including DNI, is provided in another section of the Final Report and won't be discussed here.

- **Solar Field Data:** Column C provides the “valuable DNI”, subjectively defined as DNI meeting two criteria: (1) DNI > 250 W/m^2 and (2) Unit 15 gas turbine load > 20 MW. If Unit 15 load is too low, the Project is locked out in the PLC from delivering solar steam to its HRSG. Column D and E provide the portion of the “valuable DNI” that was attempted to be captured by the solar field. If the SCAs were determined to be tracking the sun, they were counted as attempting to use or capture the solar energy. If only a portion of the solar field was tracking, the used DNI was scaled accordingly. Column F provides the operational hours per month where the entire field was tracking; if only a portion of the field was tracking, the associated hours were scaled accordingly.

  It can be seen in Column E that the used/valuable DNI fraction was very poor; 40% on average. The best month was July with a 67% fraction, which still is much less than desired and should approach $95\text{-}98^{+}\%$ in the summer months. The full field tracking hours were 866 hr/yr, although the number of desired full field tracking hours for 2015 should have ideally been 1,443 hr/yr (number of hours where the DNI > 250 W/m^2 and U15 gas turbine load was greater than the minimum required for acceptance of solar steam); i.e. Project achieved 60% of the yearly desired tracking hours.

- **SSG Energy Data:** All data in this category is reported in Gigajoules (GJ). Column G provides the gross HTF energy delivered to the SSG, using Eqn. 1. Column H provides the “net” HTF energy delivered to the SSG by the solar field. The term “net” is used to account for a portion of the energy in Column G that was attributed to heating the HTF with steam energy extracted from the combined cycle. It should be noted that losses to atmosphere from the HTF piping system are accounted for in these values as the temperature measurements used for the calculations are adjacent to the SSG (which is located near U15), whereas the solar field is ~0.5km away from the combined cycle plant. Column I represents the amount of the Column H energy that is wasted via venting solar steam to atmosphere. Column J represents the net useful solar steam energy delivered to Unit 15 HRSG, using Eqn. 2.

  24% of the HTF energy delivered to the SSG was wasted by venting to atmosphere. 38% of the gross energy delivered to the SSG was from the HTF Heater (i.e. steam extraction energy from the combined cycle). Both fractions are substantially higher than planned during the design phase. It can be seen that O&M procedures were revised at the end of the year and the HTF Heater energy use was curtailed significantly; October, November plus December HTF Heater energy use was 73 GJ vs. January, February plus March HTF Heater energy use was 704 GJ.

- **Solar Electric Data:** All data in this category is presented as electric data; power in kW_e and electricity in MW_eh. Only the parasitic load is actually measured directly. All other values are calculated. Column K presents the peak net solar power per month (using Eqn. 3). Column L shows the gross solar electricity (calculated per Eqn. 3), Column M is the measured Project auxiliary power consumption and Column N is the net solar electricity (Column L minus M). Column O represents the equivalent electricity reduction associated with extracting steam from the combined cycle, for use in the HTF Heater, and the portion of the reported net solar electricity in Column N that is attributed to HTF Heater heat addition that in turn was used to generate solar steam. It should be stressed that the HTF Heater heat addition can't directly be used to generate "solar" steam of sufficient quality to integrate with Unit 15 HRSG; the solar field must add substantially more temperature to the HTF before proper steam quality can be reached. Nevertheless, the extracted steam energy is used to heat up the HTF faster than the sun would do otherwise and so conservatively the HTF Heater energy that was not otherwise lost to atmosphere is accounted for in Column O.

The main Project goal of obtaining at least 750 kWe (net) was obtained, with a peak of 1,148 kWe (53% increase over Project goal) in September. The gross electricity generated (314 MW_eh) was only 22% of the Phase 1 estimated 1,460 MW_eh. The parasitic load of 124 MW_eh was 65% higher than the annual estimates used in Phase 1 (75 MW_eh). Part of the reason relates to the specific heat of the actual fluid, as described in the Reference Memo, which increases the annual HTF pump auxiliary power consumption (which is the largest parasitic load of the Project) about 44% above what would have been required had the manufacturer met its published properties. The HTF Heater energy use, expressed as equivalent MW_eh, is considerable at 120 MW_eh, especially given that no use was assumed in Phase 1 estimates.

- **CO_2e:** Column P represents the estimated CO_2e net offset from the Project. The calculation takes the net electricity from Column N, subtracts Column O, and multiplies by a factor of 0.485 tonnes CO_2e/MWh. This factor may be adjusted slightly once the CoMH 2015 greenhouse gas validation is completed.

  The net CO_2e offset, or savings, related to the Project is substantially below the Project target of 600 tonnes, and below the Phase 1 estimate of 590 tonnes (which assumed 0.427 CO_2e/MWh). There are a tremendous amount of variables that led to this reality and most of these will be addressed in 2016 and should result in substantial improvements over 2015. The next section presents an overview of the operational outcome shortfall.

2015 OPERATIONAL OUTCOMES DISCUSSION

The Project far exceeded the minimum net electric output requirement of 750 kWe and achieved a peak net output of 1,148 kWe. The Project only met 5% of the targeted 600 tonne CO_2e reduction; 34.5 tonnes. Table 1 below summarizes the nine contributions to the 95% CO_2e reduction shortfall. The Phase 1 estimated reduction of 590 tonnes has been factored by 1.14 (0.485/ 0.427) to account for the current assumption vs. Phase 1 assumed CO_2e/MWh factor.

Table 1

#	Variable Impacting Performance	Phase 1 Estimate	Actual	Performance Reduction	Remarks
	CO_2e Tonnes Offset	**670**	**34.5**	**95%**	Phase 1 CO_2e adjusted for 2015 CO_2e/MWh factor
1	Trough Underperformance, Unoptimized Operation & Cleanliness	5%	30%	27%	5% Phase 1 assumption is trough reflectivity reduction due to cleanliness
2	DNI, W/m^2 (Jan-Oct)	1784	1400	22%	TMY vs. actual DNI (W/m^2)
3	Increased Project Parasitic Load	5%	18%	14%	Due to HTF specific heat, final design and O&M procedures
4	Trough Mechanical Outage-Monthly DNI Wghtd	2%	12%	10%	Mechanical outage of troughs during DNI
5	Trough Wind Alarm Outage-Monthly DNI Wghtd	4%	13%	9.4%	TMY high wind vs. trough strut design influenced actual wind outage
6	Solar Steam Vented to Atmosphere	0%	5%	4.7%	Captured solar energy not used to create MWh
7	Non-Trough Project Forced Outage-Monthly DNI Wghtd	0%	3%	3.4%	DNI-weighted outage time
8	Combined Cycle Unavailable-Hrly DNI Wghtd	0%	3%	3.3%	CC Unavailable and Project Available
9	No Operations in Nov, Dec	2%	0%	1.5%	Modeled Energy Fraction from Nov, Dec
	Total			**95%**	Total of #1-9

The following presents a discussion on the nine variables that contributed to the CO_2e shortfall presented in Table 1 and the potential remedy actions.

1) The most significant contributor to the shortfall was the trough underperformance. This variable has 3 key sub-components;

   a. As described in the Reference Memo, the troughs have tracking and possible alignment issues that need to be addressed in order to achieve performance similar to that modeled/estimated during Phase 1 and guaranteed by SkyFuel. It is planned for SkyFuel to be brought back to site in spring 2016 to address the several items that contributed to the trough underperformance.

   b. The communications between the SkyFuel individual SCA controllers and the SkyFuel supervisory control system, and ultimately the plant PLCs/HMI screens in the control room, had persistent interruptions that led to many field outages and operational disruptions that impacted availability - that are not otherwise reported under another variable's contribution. In addition, the Project control loops (non-SCA tracking related controls) were tuned throughout 2015 (not before) but due to (1.a) the HTF main control loop could never be tuned and therefore the operations team needed to operate in somewhat of a quasi-manual state. While this can theoretically be done but it requires much more human interaction, operator expertise and resources (man-hours) than would otherwise be required. If there is not a dedicated solar operator, then the Project will necessarily have a lower reliability because the Project control system will end up automatically stowing the field on high temperature or the HTF temperature will not be properly maintained at a high enough temperature to produce the required steam quality for injection into Unit 15. In 2015, the HTF pumps were ran on average at a much higher capacity than they should have been due to these and other reasons. The most substantial impact here was that the HTF temperature was too cool on average and this did not allow the solar energy to be converted to useful solar steam. A substantial amount of the absorbed solar energy was thus wasted. There is a learning curve with operating solar thermal plants vs. conventional power plants and while it is difficult to quantify the impacts, they were qualitatively observed. There is also the reality that the operators have, understandably, a mandate to prioritize the operations of the combined cycle over the Project and therefore the Project operations will suffer.

c. Reflector and HCE cleanliness is a non-trivial O&M optimization exercise. On larger solar plants, reflectivity maintenance costs vs. associated benefits of improved performance is tracked daily or weekly and the entire field ends up being washed between 25 to 100 times per year. For the demonstration project, there were so many other mechanical and controls issues that washing was not a prioritized O&M activity. In addition, the O&M staff does not have reflectometer(s) to monitor the reflectivity/cleanliness. Refer to other sections of the Final Report on mirror washing but it can be said that the field was only washed a few times in 2015. Once the other major items are addressed, the O&M staff will likely wash the field more often in 2016 and realize associated performance improvements.

2) The 2015 DNI was significantly lower than the TMY DNI, which was generated from satellite data from 1998 to 2008 by BECL & Associates. Refer to other sections of the Final Report on DNI discussions. It can be said that the actual DNI appears to be incredibly low statistically, although there were not ground-based measurements (before the Project) from which to analyze. There are no pyrheliometer cleaning records kept, although Campbell Scientific did reportedly clean the instrument a few times in 2015. Going forward it is suggested that the O&M staff regularly clean the instrument and keep associated logs.

3) The increased Project auxiliary power consumption has several sub-contributors. First, the most significant parasitic load is the HTF pumps, which have VFDs to reduce part-load power consumption. As mentioned above and in the Reference Memo, the actual HTF's specific heat was less than the manufacturer's published data, which contributes to a ~44% increase in HTF pump parasitic load during normal operation. In addition, the HTF pumps were ran at a high load than they should have been (as described in (1.b)) and this resulted in more parasitic load than necessary. The Phase 1 estimates focused on this pump and the SCA tracking power

requirements. However, the other parasitic loads required for the Project end up becoming significant, given the ~1 MWe Project peak output. Items like lighting, HVAC, and control power, usually insignificant on commercial scale solar projects, end up making a significant difference with such a small Project capacity. There are four Project buildings that are heated/cooled/ventilated (and lighted) and it is suggested that their temperature settings and ventilation be analyzed/adjusted. It can be seen in Attachment 1 that even though the Project was off-line for November and December, the parasitic load was still significant. One benefit of the selected HTF is that it has a freezing point << water and therefore at least two of the building can be allowed to cool to ambient temperature, at the expense of human comfort.

4) The SkyFuel troughs had a lot of mechanical outages during 2015, as described in detail in other sections of the Final Report. These issues were major and unexpected. However, it is believed that this outage rate should substantially improve in 2016 and beyond, given many of the outages were related to one-time permanent solutions/upgrades.

5) As described in other sections of the Final Report, the strut design issue was fully addressed at the end of July. Prior to this, the trough stow command sustained & gust wind speed alarm settings were set artificially low for human safety reasons and to minimize potential further damage to the troughs. Attachment 3 summarizes the impacts that these lower settings had on outage hours of the field. These impacts were unique to 2015 and will not occur in 2016 and beyond.

6) As described in (1.b) the hot HTF temperature was too cool on average and this did not allow the solar energy to be converted to useful solar steam. A substantial amount of solar energy was wasted due to this fact and much of it was vented to atmosphere. While steam venting to atmosphere will continue in 2016 for safety (to prevent overpressure) and start-up reasons, the quantity will be substantially less with optimal HTF temperature control and optimum start-up procedures. It can be seen that O&M procedures and dispatch decisions (e.g. DNI forecasting and O&M cost considerations) already improved the situation from January & February to November & December, where the total amount of vented steam energy went from 44 GJ to 9 GJ. There are also a few control settings that can be adjusted to help reduce the duration of venting.

7) These outages were related mostly to one-time mechanical issues with the HTF and solar steam/feedwater systems. These issues were one time commissioning-like problems that should not occur at the same frequency in 2016 and beyond.

8) One critical consideration during the development of any ISCC project is to be able to quantify the likely capacity factor of the "host" combined cycle plant in future years. If the combined cycle is unavailable, the DNI is unable to be used. A 3.3% reduction due to combined cycle unavailability is pretty low impact. In addition, Unit 15 is the most efficient of the four gas turbine/HRSG trains

and therefore benefits from being dispatched first, which will benefit the Project in the future given that the solar steam is injected into Unit 15.

9) As was discussed in the Phase 1 report, it was not believed to be economical on average to attempt to operate the Project in November, December and January (i.e. based on TMY data), due to the low solar elevation angle (not because the low ambient temperature). The Project is designed to and fully capable to operate in the winter, should the ANI be high enough for long enough, which may occur a few days a month in the winter season in the future. Due to the issues described in the Reference Memo, it would have been futile to attempt to operate in November and December. Due to CoMH decision to layup the Project in November and December, there was actually less of a negative impact on CO_2e emission reduction than had the Project been operated, let alone O&M cost savings. This can be seen by looking at Column P in Attachment 1, where January & February had a combined (-)30 tonnes vs. November & December had a combined (-)13 tonnes reduction.

Altogether, many of the contributors to the CO_2e shortfall have been corrected, or can be corrected in the future if there is the will and O&M budget. Due to the wide range of variables that contributed to the shortfall, as well as the magnitude of the shortfall, it is tough to speculate on what will likely be achieved in 2016.

Attachment 1

1/31/2016

CoMH CST Demonstration Project

2015 Performance Summary & Estimated CO_2e Offset

WorleyParsons
resources & energy

Info Type:	MET Data		Solar Field Data				SSG Energy Data				Solar Electric Data					CO_2e
Column Ref:	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Variable:	DNI (pyrheliometer)	DNIxCOS(θ_Z)[1] (pyranometer)	Valuable DNI[2]	Used DNI[3]	Used/ Valuable DNI	Full Field Tracking Hours[4]	Gross HTF Energy Delivered to SSG	Net HTF Energy Delivered to SSG from Solar Field[5]	Solar Steam Energy Vented to Atmosphere	Solar Steam Energy to U15	**Peak Net Solar Power[6]**	Gross Solar Electricity	Solar Parasitic Load	Net Solar Electricity	Approx. Lost MW$_e$h from Fossil Steam Extraction + Fraction of that Fossil Energy Converted to Solar MW$_e$h	**Net Tonnes CO_2e Offset[7]**
Units:	*kWh/m^2*	*kWh/m^2*	*kWh/m^2*	*kWh/m^2*	*%*	*hrs*	*GJ*	*GJ*	*GJ*	*GJ*	***kW$_e$***	*MW$_e$h*	*MW$_e$h*	*MW$_e$h*	*MW$_e$h*	***tonnes***
JAN	33	16	16	4	26%	14	2	(168)	15	-	-	-	17	(17)	13	**(14)**
FEB	58	23	27	3	11%	14	1	(276)	29	-	-	-	12	(12)	21	**(16)**
MAR	131	60	77	7	9%	23	36	(223)	13	0	-	-	10	(10)	19	**(14)**
APR[6]	173	102	133	35	27%	59	299	141	153	299	745	34	9	25	14	**6**
MAY[6]	186	118	164	47	29%	84	397	239	175	407	749	47	9	38	15	**11**
JUN	210	138	190	102	54%	168	834	748	94	652	**964**	74	10	64	9	**27**
JUL	188	124	178	120	67%	210	976	908	142	781	**935**	84	10	74	8	**32**
AUG	151	96	137	85	62%	149	614	585	115	436	**920**	47	8	39	4	**17**
SEP	149	76	142	60	42%	86	291	210	72	209	**1,148**	23	3	20	10	**5**
OCT	122	51	96	39	40%	56	92	28	21	47	**478**	6	9	(4)	7	**(5)**
NOV[8]	63	22	55	0	0%	2	0	(9)	9	7	-	-	11	(11)	1	**(6)**
DEC[8]	39	12	34	-	0%	-	0	0	-	-	-	-	15	(15)	0	**(7)**
SUM or AVG	***1,502***	***837***	***1,250***	***502***	***40%***	***866***	***3,543***	***2,184***	***838***	***2,838***	***848***	***314***	***124***	***191***	***120***	***34.5***

Notes:

(1) DNIxCOS(θ_Z) calculated from GHI-DHI and is usable direct beam radiation on a horizontal surface, where θ_Z is the solar zenith angle relative to horizontal surface. Parabolic trough ANI > DNIxCOS(θ_Z).

(2) DNI > 250W/m^2, U15 CTG > 20MW.

(3) "Valuable DNI" (see note 2), scaled by fraction of solar field that was focused.

(4) Approximate number of operational hours entire field was tracking. If only part of field was tracking, operational hour proportioned accordingly.

(5) Measured on HTF side. Energy extracted from U15 to heat HTF has been subtracted from gross values.

(6) April & May raw steam flow data has been adjusted to account for transmitter calibration and flow computer setup errors that existed before May 27th. Peak net solar power can't be validated for these months.

Peak solar power values indicated for Apr & May are based on HTF energy to SSG, measured ratio of steam energy to HTF energy from other months, thermal-to-electric conversion efficiency (based on actual U15 and STG loads), and measured solar auxiliary load.

(7) Assumes 0.485 tonnes CO_2e/MWh (to be confirmed after 2015 GHG validation). Gross tonnes (based on Column N) is reduced by accounting for energy extracted from U15 steam cycle, see note (5), and its associated impact on MW$_e$h (Column O), to arrive at net tonnes offset.

(8) Solar field put in layup at end of October for winter season.

Attachment 2

1/26/2016

COMH CST Demonstration Project

2015, 2014 MET Station Summary

WorleyParsons
resources & energy

Year:	TMY (BECL, 11/'11)	2015	2014	2014, '15 Max	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2015	2014	2014
Variable:	DNI (pyrheliometer)				DNIxCOS(θ_Z)[1] (pyranometers)		Avg Dry Bulb		Avg Dry Bulb (DNI>250W/m^2)		Avg Wind Speed		Avg Wind Speed (DNI>250W/m^2)		High Wind Condition (DNI>250W/m^2 & > 5 m/s (avg)		High Wind Condition (DNI>250W/m^2 & > 7 m/s (gust)
Units:	*kWh/m^2*				*kWh/m^2*		°C		°C		m/s		m/s		hr		#-hr[8]
JAN[7]	108	33	31	33	16	23	-5.4	-4.8	5.7	-0.8	1.8	2.7	2.6	3.3	3	7	16
FEB	140	58	78	78	23	31	-5.6	-11.7	-3.4	-9.6	2.4	2.4	2.9	2.4	15	6	23
MAR	151	131	79	131	60	61	4.2	-3.9	6.9	0.5	3.2	2.2	3.9	2.5	51	13	22
APR	165	173	40	173	102	121	8.4	6.7	12.8	10.9	3.8	2.5	4.1	3.2	70	10	28
MAY[3]	187	186	187	187	118	118	12.7	12.5	16.4	-	2.6	2.2	3.0	-	31	-	-
JUN[4]	187	210	127	210	138	109	19.6	15.2	23.9	20.4	2.3	2.1	2.5	2.8	18	10	46
JUL	245	188	222	222	124	69	21.1	21.7	25.8	25.3	2.7	1.9	3.0	2.0	30	18	67
AUG	211	151	160	160	96	60	20.6	20.0	25.0	24.3	2.6	1.7	2.8	1.8	34	1	13
SEP[2]	152	149	157	157	76	36	13.8	13.9	19.6	19.3	2.3	1.6	3.0	1.9	18	2	24
OCT[5]	130	122	116	122	51	29	9.2	10.3	16.3	14.2	2.9	2.3		2.6		14	67
NOV[5]	90	63	33	63	22	20	0.0	-4.7	4.2	-3.0	3.3	2.4		1.7		-	4
DEC[5,6]	94	39	94	94	12	25	-4.3	-4.2	9.7	-	3.2	2.0		-		-	-
Sum or Avg:	***1,861***	***1,502***	***1,324***	***1,628***	***837***	***701***	***7.9***	***5.9***	***13.6***	***10.2***	***2.7***	***2.2***	***3.1***	***2.4***	***270***	***81***	***310***
Mo Avg or DNI-Wghtd Avg:	***155***	***125***	***110***	***136***	***70***	***58***	***12.0***	***10.6***	***16.9***	***12.4***	***2.8***	***2.0***	***3.1***	***1.8***			

Notes:

(General-1) 2015 data from plant PLC data logger, gathered at 15min intervals (u.k.o), 2014 data from Campbell Scientific, gathered at 1hr intervals.

(General-2) Anemometer height adjusted (3m-->10m) on Feb. 18, 2015; therefore year-over-year comparisons must be adjusted accordingly.

(General-3) TMY P95 DNI (95% confidence in exceedance) for 1 year is 1,637 kWh/m^2 (+/-5% uncertainty). Therefore 2014, 2015 datasets appear statistically unprecedented, and other data influences may be present (e.g. instrument cleanliness).

(1) DNIxCOS(θ_Z) calculated from GHI-DHI and is usable direct beam radiation on a horizontal surface, where θ_Z is the solar zenith angle relative to horizontal surface. Parabolic trough ANI > DNIxCOS(θ_Z).

(2) Noted 2015 values based on Campbell Scientific Monthly Report summaries. January DNI not recorded until Jan 15th, data scaled by 31/17.

(3) Solar radiation data not recorded in May-2014. Substituted TMY DNI, and 2015 DNIxCOS(θ_Z)

(4) Solar radiation data from 6/1 to 6/9/2014 not recorded. Scaled measured data by factor of 30/21.

(5) OCT, NOV, DEC Avg Dry Bulb (DNI>250W/m2) data estimated from average relationship of '14 & '15 temperature results for MAR, FEB, JAN, respectively.

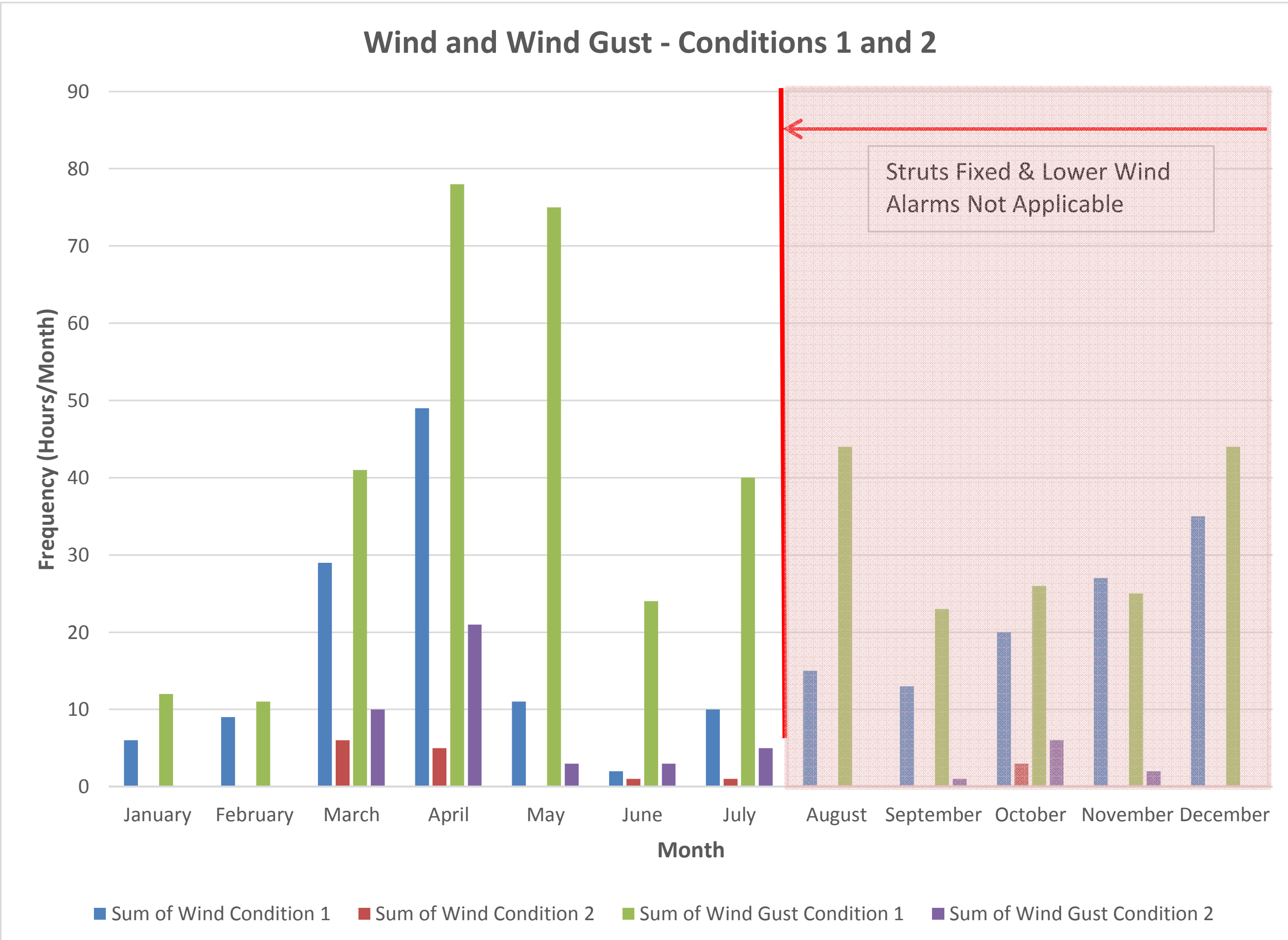
(6) Solar radiation data for December-2014 invalid due to sun tracker. Substituted TMY DNI.

(7) DNI data before not recorded before Jan 8th. Scaled measured data by factor of 31/24.

(8) Wind gust analysis based on wind gust occurance over hourly time increments, it does not translate to entire 60min of wind gust duration.

Attachment 3

From 16-January to 31-December 2015



Wind Condition 1: Sustained winds (hours/month) that fall between NW to SE (covering N and E) above 5 m/s when DNI >0
Wind Condition 2: Sustained winds (hours/month) from NW to SE (covering W and S) above 10 m/s when DNI >0
Wind Gust Condition 1: Gust winds (hours/month) that fall between NW to SE (covering N and E) above 7 m/s when DNI >0
Wind Gust Condition 2: Gust winds (hours/month) from NW to SE (covering W and S) above 15 m/s when DNI >0

Appendix E: Solar Logsheet Summary

Solar Log Sheet - Monthly Summary

February 2015

	SCA	SCA	SCA	SCA	SCA	SCA	SCA	SCA
Status	1A	1B	1C	1D	2A	2B	2C	2D
Total Hrs On	0	7	7	7	7	0	7	7
Total Hrs Off	670	663	663	0	663	670	663	663
Total Hrs W	0	11	11	11	11	0	11	11
Total Hrs C	0	9	9	9	9	9	9	9
Total Hrs M	641	457	457	457	457	632	457	457
Total Hrs O	29	117	117	93	117	29	117	93
Total Hrs S	0	0	0	0	0	0	0	0

March 2015

	SCA	SCA	SCA	SCA	SCA	SCA	SCA	SCA
Status	1A	1B	1C	1D	2A	2B	2C	2D
Total Hrs On	15	27	27	27	27	21	27	27
Total Hrs Off	729	717	717	0	717	723	716	717
Total Hrs W	164	207	207	207	207	171	188	208
Total Hrs C	22	22	22	22	22	22	22	22
Total Hrs M	150	31	31	31	31	73	80	31
Total Hrs O	8	8	8	8	8	8	8	8
Total Hrs S	55	55	55	55	55	55	55	57

April 2015

	SCA	SCA	SCA	SCA	SCA	SCA	SCA	SCA
Status	1A	1B	1C	1D	2A	2B	2C	2D
Total Hrs On	56	71	71	71	68	71	71	57
Total Hrs Off	670	655	655	0	658	655	655	669
Total Hrs W	78	78	78	78	71	78	78	39
Total Hrs C	44	68	68	68	68	44	68	43
Total Hrs M	148	85	85	85	108	119	85	151
Total Hrs O	7	17	17	17	17	7	17	17
Total Hrs S	0	0	0	0	0	0	0	0

May 2015

	SCA	SCA	SCA	SCA	SCA	SCA	SCA	SCA
Status	1A	1B	1C	1D	2A	2B	2C	2D
Total Hrs On	115	115	115	88	100	104	104	0
Total Hrs Off	629	629	629	0	644	640	640	744
Total Hrs W	127	127	127	113	122	127	127	0
Total Hrs C	97	97	97	86	86	97	97	0
Total Hrs M	29	29	29	159	92	42	42	655
Total Hrs O	38	38	38	38	34	34	28	0
Total Hrs S	0	0	0	0	0	0	0	0

June 2015

	SCA	SCA	SCA	SCA	SCA	SCA	SCA	SCA
Status	1A	1B	1C	1D	2A	2B	2C	2D
Total Hrs On	212	212	212	212	128	128	128	122
Total Hrs Off	508	508	508	0	568	568	568	574
Total Hrs W	39	39	39	39	12	12	12	0
Total Hrs C	124	123	124	124	42	42	42	27
Total Hrs M	39	39	39	39	364	364	364	415
Total Hrs O	0	0	0	0	0	0	0	0
Total Hrs S	0	0	0	0	0	0	0	0

July 2015

	SCA	SCA	SCA	SCA	SCA	SCA	SCA	SCA
Status	1A	1B	1C	1D	2A	2B	2C	2D
Total Hrs On	216	220	220	218	218	218	218	218
Total Hrs Off	528	524	524	0	526	526	526	526
Total Hrs W	22	22	22	22	22	22	22	15
Total Hrs C	81	81	81	81	81	81	81	76
Total Hrs M	57	53	53	55	55	55	55	55
Total Hrs O	0	0	0	0	0	0	0	0
Total Hrs S	55	55	55	55	55	55	55	55

August 2015

	SCA	SCA	SCA	SCA	SCA	SCA	SCA	SCA
Status	1A	1B	1C	1D	2A	2B	2C	2D
Total Hrs On	154	146	146	129	154	154	154	154
Total Hrs Off	589	597	597	0	589	589	589	589
Total Hrs W	11	11	11	11	11	11	11	11
Total Hrs C	134	134	134	134	147	147	147	98
Total Hrs M	13	31	37	46	0	0	0	0
Total Hrs O	0	0	0	0	0	0	0	0
Total Hrs S	0	0	0	0	0	0	0	0

September 2015

	SCA	SCA	SCA	SCA	SCA	SCA	SCA	SCA
Status	1A	1B	1C	1D	2A	2B	2C	2D
Total Hrs On	93	93	93	93	87	87	87	87
Total Hrs Off	627	627	627	0	633	633	633	633
Total Hrs W	15	15	15	15	15	15	15	15
Total Hrs C	119	119	119	119	119	119	119	119
Total Hrs M	0	0	0	0	0	0	0	0
Total Hrs O	0	0	0	0	6	6	6	6
Total Hrs S	0	0	0	0	0	0	0	0

October 2015

	SCA	SCA	SCA	SCA	SCA	SCA	SCA	SCA
Status	1A	1B	1C	1D	2A	2B	2C	2D
Total Hrs On	102	102	102	102	102	102	102	102
Total Hrs Off	641	641	641	0	641	641	641	641
Total Hrs W	10	10	10	10	10	10	10	0
Total Hrs C	149	149	149	149	149	149	149	149
Total Hrs M	9	9	9	9	9	9	9	5
Total Hrs O	0	0	0	0	0	0	0	0
Total Hrs S	0	0	0	0	0	0	0	0

November 2015

	SCA	SCA	SCA	SCA	SCA	SCA	SCA	SCA
Status	1A	1B	1C	1D	2A	2B	2C	2D
Total Hrs On	6	6	6	6	6	6	6	6
Total Hrs Off	714	714	714	0	714	714	714	714
Total Hrs W	0	0	0	0	0	0	0	0
Total Hrs C	550	550	550	550	550	550	550	541
Total Hrs M	0	0	0	0	0	0	0	0
Total Hrs O	0	0	0	0	0	0	0	0
Total Hrs S	0	0	0	0	0	0	0	0

December 2015

	SCA	SCA	SCA	SCA	SCA	SCA	SCA	SCA
Status	1A	1B	1C	1D	2A	2B	2C	2D
Total Hrs On	0	0	0	0	0	0	0	0
Total Hrs Off	744	744	744	0	744	744	744	744
Total Hrs W	0	0	0	0	0	0	0	0
Total Hrs C	744	744	744	744	744	744	744	744
Total Hrs M	0	0	0	0	0	0	0	0
Total Hrs O	0	0	0	0	0	0	0	0
Total Hrs S	0	0	0	0	0	0	0	0

CONCENTRATED SOLAR PROJECT STATUS		
CODE		
1	IN SERVICE HOURS	The total time the SCA is in service. Also referred to as operating time.
2	OFF-PEAK SHUTDOWN HOURS	The total time a SCA is in off-peak hours but is available for operation.
3	UNIT 15 SHUTDOWN HOURS	The total time a SCA is available for service, but Unit 15 is offline.
4	WEATHER OUTAGE HOURS	The total time a SCA is unable to supply energy to the system due to the removal of the SCA from service due to weather conditions. Must pick an outage code.
5	MAINTENANCE OUTAGE HOURS	The total time a SCA is unable to supply energy to they system due to the removal of the SCA from service due to system conditions. Must pick an outage code.
OUTAGE CODES		
W	WIND OUTAGE HOURS	The total time a SCA is unable to supply energy to the system due to sustained wind/wind gusts.
C	CLOUD/RAIN/SNOW/HAIL OUTAGE HOURS	The total time a SCA is unable to supply energy to the system due to rain, snow or cloudy conditions.
M	MECHANICAL OUTAGE HOURS	The total time a SCA is unable to supply energy to the system due to mechanical failures.
O	HTF SYSTEM OUTAGE HOURS	The total time a SCA is unable to supply energy to the system due to problems with HTF system components.
S	STEAM SYSTEM OUTAGE HOURS	The total time a SCA is unable to supply energy to the system due to problems with the feedwater or steam system components

Appendix F: Operations and Maintenance Costs

Category	January	February	March	April	May	June	July	August	September	October	November	December	total
OWNER's DIRECT O&M Labor	2,431.88	1,621.69	1,148.51	8,023.16	10,491.69	17,142.34	8,611.55	9,636.78	15,116.01	14,783.94	13,726.17	5,646.25	105,948.09
													-
PROFESSIONAL/CONSULTING		6,125.13				-	2,366.52			-	4,246.96	5,212.37	17,950.98
													-
CONTRACTED SERVICES	5,202.00	6,218.37	47,866.75	35,058.01	46,279.33	30,685.70	19,946.67	53,734.64	2,684.50	8,886.42	14,388.55	6,929.40	272,678.34
													-
MATERIALS & SUPPLIES	506.39	10,542.00	4,182.12	289.58	5,709.47	7,376.02	5,183.64	838.98	3,876.73	6,255.65	1,819.76	1,587.78	47,661.73
													-
COMH UTILITIES	860.94	585.37	484.95	280.91	280.91	236.96	292.73	407.69	301.40	261.07	378.43		3,510.42
													-
MONTHLY SUBTOTALS	9001.21	25092.56	53682.33	43651.66	62761.4	55441.02	36401.11	64618.09	21978.64	30187.08	34559.87	19375.8	447,749.56

Appendix G: Natural Resources Canada Paper “Potential of Concentrating Solar Power in Canada”

Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 49 (2014) 2303 – 2312
Energy Procedia

SolarPACES 2013

Potential of concentrating solar power in Canada

R. Djebbar[a,]*, D. Belanger[b], D. Boutin[b], E. Weterings[a], M. Poirier[c]

[a]Natural Resources Canada, CanmetENERGY, 580 Booth Street, Ottawa, ON, Canada
[b]Natural Resources Canada, Centre for Topographic Information, 2144 King Street West, Sherbrooke, QC, Canada
[c]Natural Resources Canada, Mapping Information Branch, 615 Booth Street, Ottawa, ON, Canada

Abstract

In this paper, results of an analysis to assess the potential of concentrating solar thermal power applications in Canada are presented. First, a direct normal solar resource (DNI) resource map for Canada is introduced. This map indicates the locations where the DNI is the highest in Canada and is derived from the most recent Perez's SUNY satellite-based solar resource model Version number 3. Second, the methodology and results of a GIS analysis to identify the locations of the most suitable lands for concentrating solar thermal power (CSP) applications in Canada are discussed. The total areas of the CSP-suitable lands are presented in a tabulated and a map formats for each of the Canadian provinces where there is a maximum DNI solar resource. Third and finally, results of a technical economical analysis for two CSP system designs are discussed. The two CSP systems considered include parabolic trough with synthetic oil heat transfer fluid with and without storage, molten salt power tower with and without storage.

Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
Final manuscript published as received without editorial corrections.

Keywords: Solar Resource, Concentrating Solar Power, Geographic Information Systems, Technical and Econmical Assesment

1. Introduction

On September 2012, the Canadian Federal Government issued the final version of regulations aimed at reducing carbon dioxide emissions from coal-fired electricity generating units. Current low natural gas prices together with these carbon emission regulations have eliminated the possibility of any new coal fired generating capacity being built in Canada for the foreseeable future. Alberta and Saskatchewan have adequate solar resources as will be

* Corresponding author. Tel.: +1-613-996-8828; fax: +1-613-996-9416.
E-mail address: rdjebbar@nrcan.gc.ca

1876-6102 Crown Copyright © 2013 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/3.0/).
Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
Final manuscript published as received without editorial corrections.
doi:10.1016/j.egypro.2014.03.244

discussed below in this paper. The government analysis of the impact of this new regulations will result in a retirement of coal-fired generation capacity of about 8,127 MW in these two provinces in addition to the business as usual scenario retirement of about 5,860 MW for a total reduced coal-fired generation capacity by the year of 2035 of about 14,000 MW. At the same time natural gas capacity-fired generation capacity is expected to increase by close to 11,000 MW. Industry and stakeholders will be looking for opportunities and solutions to ensure sustainable development of this anticipated future natural gas generation capacity including improving systems efficiencies and the use of renewable technologies such as integrated solar combined cycle power generation to limit greenhouse gas emissions.

Literature data on concentrating solar thermal power (CSP) is extremely rich. Almost all of this literature deals with CSP applications in the sun-belt countries, e.g., south-west USA, southern Europe (Spain) and North Africa. On the other hand, literature relevant to CSP applications in high-latitude geographical locations such as Canada is very poor (non existent). No studies have been done on locating or potential efficacy of applications of large-scale CSP electricity production in Canada. Natural Resources Canada (NRCan) and the City of Medicine Hat completed in 2007 a study to assess the feasibility of solar-augment the City's existing natural gas combined cycle (NGCC) power plant using CSP. The City of Medicine Hat has secured funding in order to proceed with the construction and monitoring of a megawatt class Parabolic Trough integrated solar combined cycle pilot project with commissioning planned for end of this calendar year 2013. This will be the first CSP-assisted power plant in Canada and the first CSP plant in the world located at such a high latitude.

NRCan is currently undertaking a study which will allow public domain, high-quality analysis data and information relevant to Canadian weather and market reality to be generated, for the first time. This study is aimed at assessing the solar-augment and GHG emission reductions potential of NGCC power plants located in these two provinces, Alberta and Saskatchewan. The first task of this study is to characterize the technical and economical potential of CSP applications under Canadian skies and to identify and map the location the most suitable for CSP applications in Canada. In this paper, results of a solar and land resource GIS analysis to locate and estimate the suitable lands for CSP application are discussed first. After, results of an initial technical economical analysis to estimate the levelised cost of CSP electricity generation in Canada are summarized and discussed.

2. Solar and land resources assessment

2.1. Solar resource analysis

The solar resource analysis was completed using a dataset of fourteen-year (1998-2011) yearly-averaged satellite-derived DNI (Direct Normal Irradiance) solar resource data for each 1/10th of a degree (~10km^2 grid) for the Canadian landmass south of 58 degrees latitude. This DNI dataset was produced using the latest version (Version number 3) of Perez's State University of New York (SUNY) GOES satellite-based solar model (Perez et al 2010 [1] and Dise et al 2013 [2]. This latest SUNY model makes use of both visible and infra-red channels satellite imagery and is meant to correct for the winter bias that is experienced when using previous versions 1 and 2 of the SUNY model, in particular during snow conditions and persistent cloud cover. This issue with the previous SUNY models is so-called "Eugene syndrome" and is discussed by Gueymard and Wilcox (2009) [3]. Assessment and comparison of Version 3 of the SUNY satellite-derived solar data with Canadian ground measured solar data is discussed in Djebbar et al 2012 [4].

A map of a fourteen year –averaged yearly sums of the DNI is presented in below Figure 1. The regions with the highest DNI are located south of the Prairie Provinces Alberta, Saskatchewan and Manitoba.

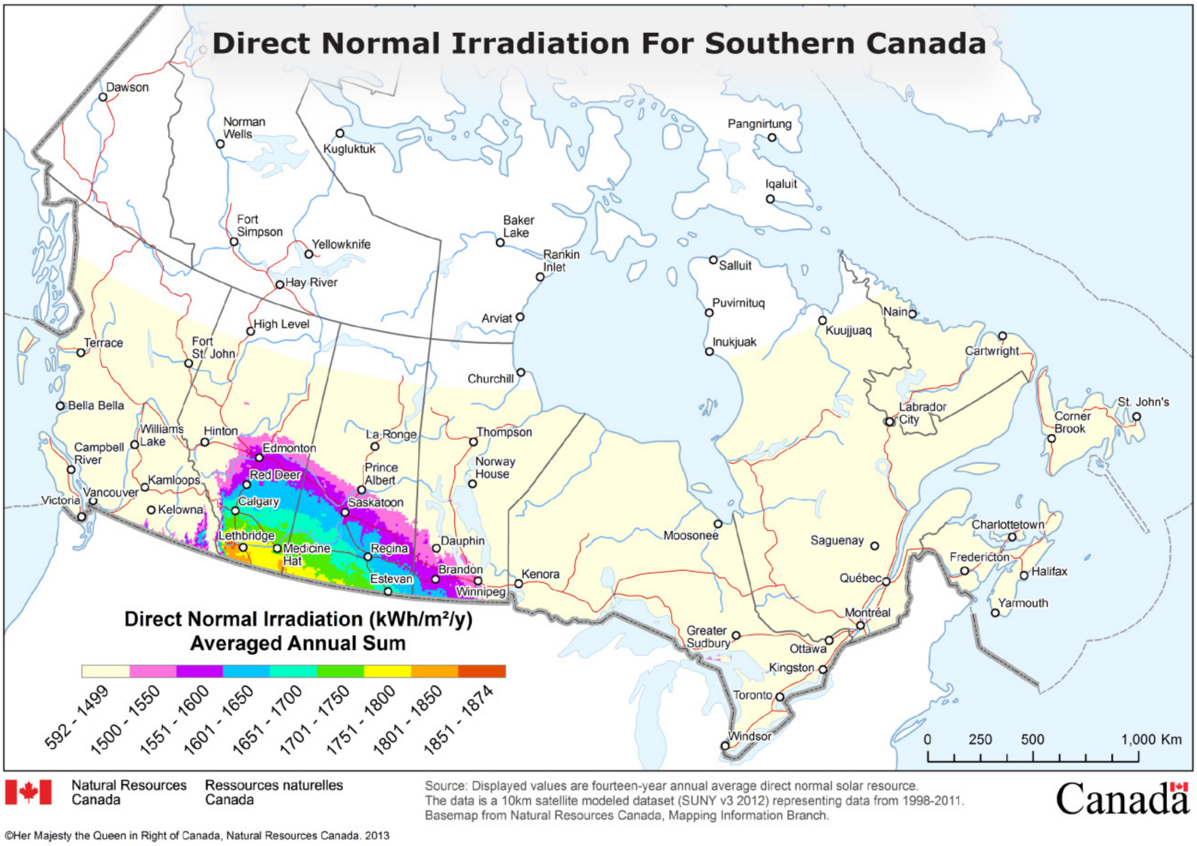


Fig. 1. Direct Normal Irradiation for Canada south of 58° Latitude

2.2. Land resource data and GIS analysis

A GIS (geographical information system) assessment methodology to determine areas of suitable land for CSP electricity generation was developed. First, GIS assessment was done using fourteen-year-averaged (1998-2011) yearly sums of direct normal solar irradiances (DNI) values covering the area south of the 58th parallel in Canada. Lands where DNI values are below a minimum threshold of 1500 kWh/m^2/Year are excluded. The minimum DNI threshold of 1500 kWh/m^2/Year is same as is used by Bravo et al (2007) [5] to estimate the CSP potential for Spain and is also equivalent to the mimmum threshold (1460 kWh/m^2/Year) used by Turchi et al (2011) [6] to estimate the solar-augment potential of US Fossil-fired power plants. The locations where the DNI is greater than this minimum threshold are indicated in color in Figure 1.

In the second step, exclusion masks were generated from geospatial data from NRCan's Mapping Information Branch and from NASA. The following geomorphologic exclusion masks were used on the data:

- An exclusion mask for moisture regions generated from the GeoBase National Hydro Network in order to remove the polygons of major lakes and rivers;
- An exclusion mask for wetlands generated from GeoBase soil cover data (eg., wetlands along Hudson Bay);
- An exclusion mask for urban agglomerations generated from CanVec data;
- An exclusion mask for steep inclines in Canada (higher than 4%) generated from NASA Shuttle Radar Topography Mission (SRTM) elevation data. A parametric analysis for three additional maximum slopes (1%, 2% and 3%) was also performed knowing that low terrain-slope translates in lower construction costs.

Slope data is generated from the SRTM3 data and calculations are done using the horn's formula for slope calculation. At the end of the processing, raster files (geotiff) are produced with the same grid size and extent as the SRTM and pixels values are set to the slope percentage. SRTM3 is an elevation dataset that has coverage across Canada below 60 degrees latitude. It has a resolution of 3 arc seconds, about 90 meters, at the equator and is distributed in a 5X5 degree mosaic. This SRTM version is based on CGIAR (http://srtm.csi.cgiar.org/) and was post-processed to reduce the number of no-data regions over waterbodies and heavy shadow. The absolute vertical accuracy of original data (SRTM1) is evaluated to 5.5 meters with LIDAR high precision satellite data originating from the ICESat program. This accuracy reflects the average accuracy over the whole SRTM datasets covering Canada with a confidence level of 90%. Furthermore, according to the literature and internal tests, the absolute horizontal accuracy of the original data (SRTM1) is about 15 meters. This accuracy is presented as the circular error at 90% confidence.

The final geomorphologic mask is a combination of all created masks, see Figure 2. As all masks (raster files) have their pixels aligned with the SRTM grid and they are simply multiplied to generate a complete mask. Four combined masks are produced (using the different slope masks: 1%, 2%, 3% and 4%). Each of the 4 combined raster masks are applied to the DNI raster data. A combined mask and DNI raster have their pixels aligned and can be simply « multiplied » to generate a potential CSP land suitability map in raster format. The end result is a raster file with each pixel value set to either the DNI value for suitable land or « no data value » if it is unsuitable land as illustrated on Figure 3.

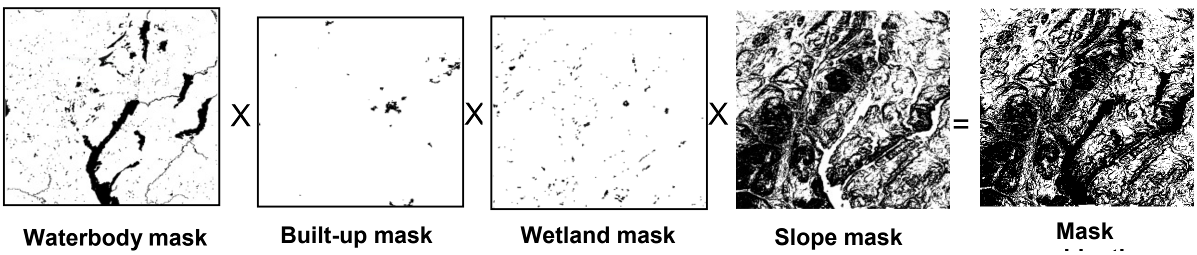


Fig. 2. Land Geomorphology mask combination

Fig. 3. (a) DNI raster data; (b) Land geomorphology mask raster data; (c) Resulting potential CSP map in raster format.

2.3. Results and discussions

A series of raster slope masks to exclude areas above a given maximum percent slope of 1, 2, 3 and 4% were generated from the produced slope raster files. This allowed to calculate the area of the CSP suitable land (in square km) by province and for Canada and classified by DNI value range. While the slope algorithm evaluator applied is based on a highly accurate and published methodology, the slope estimates are limited by the accuracy of the source data. In fact, the relative error (between pixels) may affect the slope calculation. In this case, there is a lack of information on the vertical relative accuracy. The effect of the relative vertical accuracy will be higher when considering small slope values, i.e., less than 1 %. To improve confidence levels in the results (mainly for slopes less than 1%) additional investigation into related published studies is needed on vertical relative accuracy evaluation. For slopes less than 1%, these accuracy limitations should be taken into consideration. Total suitable lands based on the criteria used in this study were estimated for each of the provinces where there is sufficient DNI (greater than 1500 kWh/m^2/year). Results for the example of 4% maximum slope terrains are summarized in Table 1.

GIS analysis allowed identifying a total land area of about 417,000 km^2 when considering land with a maximum slope of 4%. A total of about 130,000 km^2 were identified when considering a premium lands with a slope of less than 1%, see Figure 4.

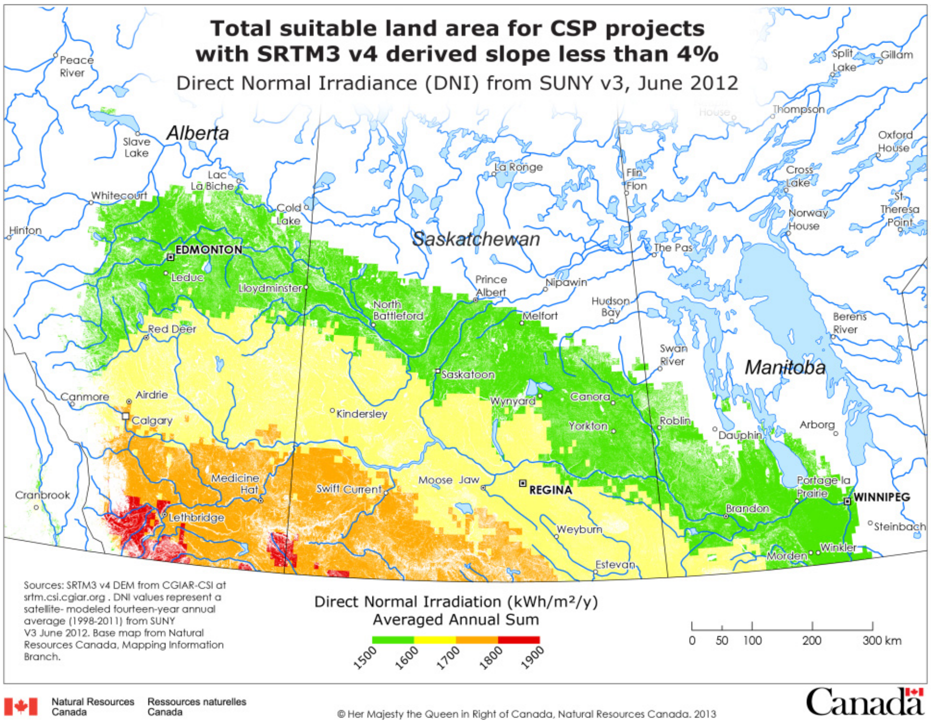
In order to estimate the technical potential of CSP under Canadian skies, a simple approach based on Trieb et al (2009) [7] methodology was applied in this study. Considering a well proven conventional parabolic trough CSP technology with a conservative solar-to-electric efficiency of 11% (annual net power generation/annual DNI on aperture) and a land use factor of 35% (aperture area of reflector/total land area required) the net power generation was estimated for several DNI classes greater than 1500 kWh/m^2/Year. Results are summarized in Table 2.

Table 1. Areas of suitable land in km^2 for CSP generation in Canadian Provinces classified by DNI for the example maximum slope less than 4%

DNI Class (kWh/m^2/Year)	British Columbia	Alberta	Saskatchewan	Manitoba	Ontario	Canada [km^2]
1500-1600	532	51,832	79,357	48,038	809	180,567
1600-1700	210	47,725	95,466	7,552	-	150,953
1700-1800	-	38,170	40,185	-	-	78,355
1800-1900	-	6,750	960	-	-	7,710
Total [km^2]	742	144,476	215,969	55,590	809	417,586

Table 2. Technical CSP Potential in GW. h/Year in the Canadian Provinces classified by DNI considering lands with slope less than 4%

DNI Class (kWh/m^2/Year)	British Columbia	Alberta	Saskatchewan	Manitoba	Ontario	Total Provinces [GW. h/Year]
1500-1600	31,742	3,093,048	4,735,610	2,866,668	48,295	10,775,363
1600-1700	13,350	3,031,725	6,064,488	479,724	-	9,589,287
1700-1800	-	2,571,704	2,707,494	-	-	5,279,198
1800-1900	-	480,739	68,401	-	-	549,140
Total [GW. h/Year]	45,093	9,177,215	13,575,993	3,346,392	48,295	26,192,988
Total Electricity Generated in 2007 [GW. h/Year]	71,833	67,432	20,574	34,403	158,234	352,477



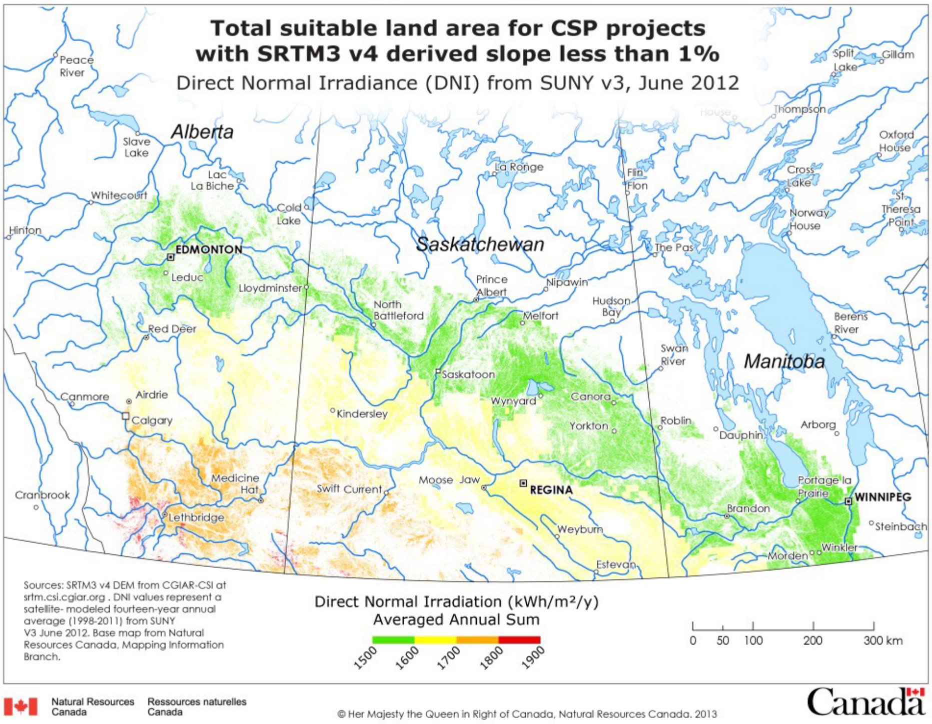


Fig. 4. Maps of CSP suitable land south of Alberta, Saskatchewan, and Monitoba Provinces (a) 4% slope, (b) 1% slope

The analysis yields a total CSP potential for Canada of about 26,190 TWh/Year considering lands with slope less than 4%. Considering lands with slope less than 1% results in a potential of about 8,265 TWh/Year. By comparing these numbers to the Canadians electricity generation for domestic use of 573 TWh/Year (2007) it becomes apparent the available technical CSP potential could theoretically cover this demand many times, i.e., over 45 times when considering lands with slope less than 4%. The greatest potential being located mainly in Saskatchewan, followed by Alberta, Manitoba. In Saskatchewan, the estimated technical potential of CSP of 13,575 TWh/Year is equivalent to about 660 times the total yearly electricity generated in 2007 in that province (20.5 TWh). In Alberta, the CSP potential of 9,177 TWh/Year is equivalent to 136 times the 67 TWh that what was generated in 2007. Both Alberta and Saskatchewan heavily depend on fossil fuels, mainly coal and natural gas, for electricity generation. Solar power including CSP may play a role in the future to displace some of this dependence and lower the GHG emissions from the power generation sector.

3. Economical analysis

The technical and economic performance of two CSP system designs were analyzed considering the weather data of Medicine Hat located south east of Alberta (see Figure 1). The US Department Of Energy (DOE) - National Renewable Energy Laboratory (NREL) System Advisor Model (SAM) analysis tool was used to estimate the levelised cost of electricity (LCOE) for these five utility-scale CSP technologies and systems. The SAM tool is freely downloadable from the NREL web site. A Typical DNI meteorological Year (TDY) for the City of Medicine Hat was established and used. SUNY V3 satellite-derived hourly solar resource data is used in this TDY yielding a yearly DNI of about 1750 kWh/m^2/year. The remaining required weather input data for building the TDY are derived from Environment Canada nearby ground observations.

The two CSP technologies considered are the default system designs available in SAM (Version no. Jan 15, 2013) and include (i) parabolic trough collectors with synthetic oil heat transfer fluid with and without two-tanks indirect molten salt storage; (ii) molten salt heat transfer fluid power tower system with and without two-tanks direct molten salt storage. For the purpose of a first analysis for comparing the two solar power systems, same financial assumptions were considered for both types solar power systems. They are summarized in Table 3.

Table 3. Financial common assumptions used in all SAM Analysis

Location	Medicine Hat	Loan Rate (%)	7
Analysis period (years)	25	Loan Term (years)	20
Inflation rate (%)	2.5	Debt Fraction (%)	65
Real Discount Rate (%)	8	Up-front fee (% of principal)	SAM Default
Federal Income Tax (%)	5	Federal / Provincial Depreciation	SAM Default
Provincial Tax (%)	0	Federal / Provincial Cash Incentives	0
Sales Tax (%)	0	Minimum Required Internal Rate of Return (%)	SAM Default (15%)
Federal Tax credit (%)	0	Minimum Debt Service Coverage Ratio (%)	65
Provincial Tax Credit (%)	0	Months prior to Construction	SAM Default
Property Tax (%)	SAM Default	Contingency on direct costs	SAM Default
Operation and Maintenance Costs	SAM Default	Indirect Capital Costs (% of direct cost)	SAM Default

The capital, operation and maintenance costs input data are updated by NREL following each release of a new version of SAM and so the latest version of SAM (Version no. Jan 15, 2013) was used for this study. The default costs in SAM are provided by NREL as a reasonable rough estimate of current costs for a system in the United States. Costs in Canada are not expected to deviate significantly from those in the USA. Also, minor effort was completed to optimize and or alter the design of all the two solar power systems. The nameplate capacity of all the systems were kept as provided in the SAM software. Therefore results of this initial technical and economical analysis should be considered preliminary and only useful for the purpose of a comparison between the two solar power technologies considered in the present study. However, conclusions found in this first analysis are not expected to change dramatically. LCOEs shown in figures 5 and 6 are reported as 2013 US dollars.

The main default design parameters of both power systems considered for this study are those provided in SAM. They were not altered with the following exceptions:

- For the case of parabolic trough with synthetic oil, a heat transfer fluid (HTF) capable of sustaining lower freezing point of about -37 °C was considered for this analysis. The collector loop inlet/outlet temperature was also lowered to be consistent with the selected HTF.
- For the case of molten salt power tower with storage, the minimum and maximum optimization tower heights were limited to 100 and 200m respectively.

Figures 5 and 6 summarize the results of the impact when proven two-tank molten-salt storage is considered for CSP generation. These two figures are generated by varying the solar multiple and storage hours and selecting the conditions that provide the minimum LCOE. The first point in the x axis corresponds to the case when storage is not considered.

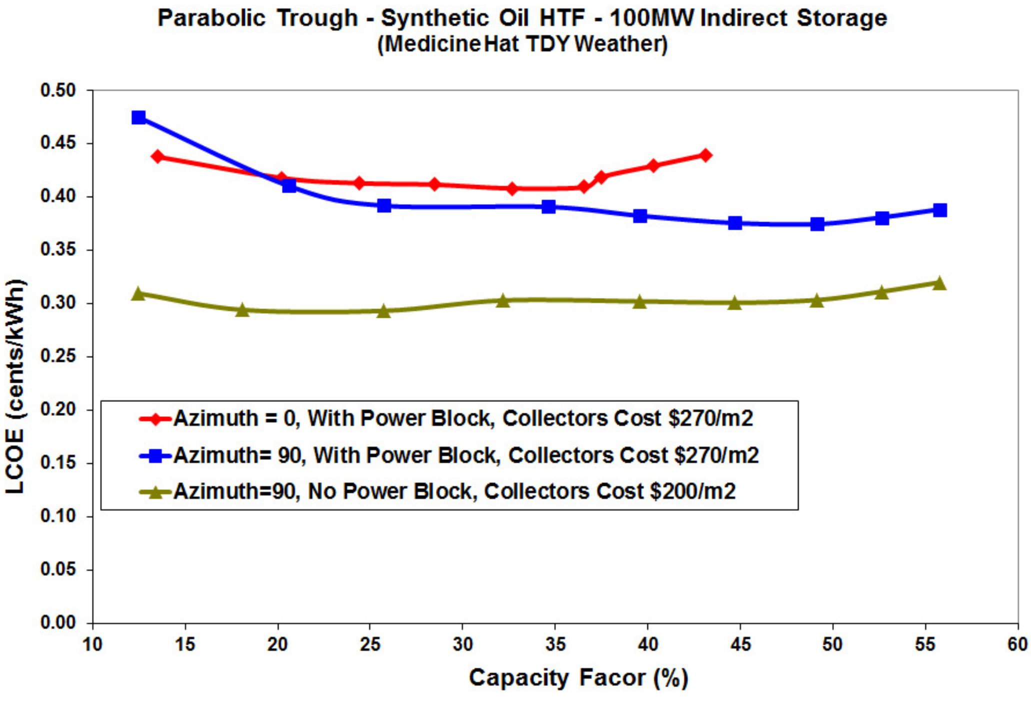


Fig. 5. Levelised cost of parabolic trough system when considering Medicine Hat typical weather

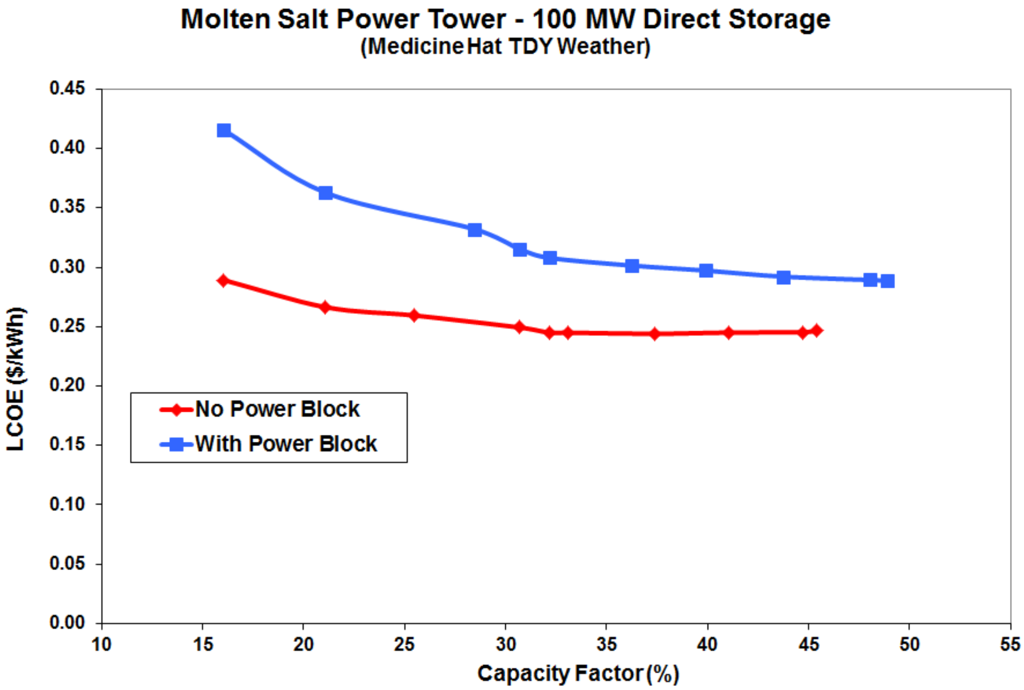


Fig. 6. Levelised cost of molten salt power tower when considering Medicine Hat typical weather

Results show that the cost of increasing the capacity factor slightly increases if at all for parabolic trough systems and actually improves for the case of molten salt power tower when size of the solar field, i.e., number of concentrating solar collector assemblies, and the size of the storage tanks increase. These results for the power tower with storage systems are consistent with Turchi et al 2010 [8].

For the case of parabolic trough, the layout of the solar collectors is critical. North-south (azimuth=0) oriented collectors axis seems to perform well when there is no storage. When storage is considered, east-west axis collectors (azimuth=90) tracking the sun on the south horizon result in higher capacity factor.

The capacity factors achieved by the two CSP systems with storage considered in this analysis are significantly higher than what is achieved for example by PV Cristal-silicon solar system under the same weather conditions.

The impact of the cost of parabolic trough collectors and the power block, both which are a significant part of the system cost is also shown in both Figures 5 and 6. The molten salt power tower with direct storage and no power block, approximating the example case of solar-augment of natural gas combined cycle power plant, results in significantly lower LCOEs especially at the low end of the delivered capacity factor.

4. Conclusions

Up-to-date solar resource dataset for Canada has been developed. This hourly solar dataset on a $10km^2$ grid was produced using version number 3 of Perez's State University of New York (SUNY) GOES satellite-based solar model. This latest SUNY model makes use of both visible and infra-red channels satellite imagery and is meant to correct for the winter bias that is experienced when using Version 1 of the SUNY model in particular during snow conditions and persistent cloud cover, so-called "Eugene syndrome", which is important for the particular case of the Canadian weather. The solar resource data was uploaded to a geographic information system (GIS) and processed together with geospatial data from both NRCan's Mapping Information Branch and NASA on built-up areas, water bodies, wetlands and land topography and slope. The result yields Canadian maps of DNI on land area that is potentially suited for the placement of CSP plants in Canada, which are presented in this paper. Results show that there is an adequate solar resource for CSP applications south of the Canadian Prairie Provinces, Alberta, Saskatchewan and Manitoba. Also, results of a high level assessment of the technical potential show that the CSP potential south Saskatchewan and Alberta is significant enough to justify the on-going comprehensive evaluation of the potential for CSP to Canada's electricity generation mix, particularly for locations in Western Canada where there is a high direct beam solar resource. The southern regions of Alberta and Saskatchewan, both provinces rely heavily on fossil fuels for electricity generation, enjoyed a maximum solar resource up to 1900 kWh/m^2/year on average during the past 14 years from 1998-2011. However most of this solar resource occurs outside the winter months.

The SUNY model solar resource dataset, in combination with the other required weather data, were used to build Typical Meteorological Year hourly simulation input files for the Canadian locations of interest. When considering two CSP proven technologies, parabolic trough and power tower with or without storage, preliminary results for the particular location of Medicine Hat-Alberta presented in this paper show that the levelised cost of conventional standalone CSP plants with boiler auxiliary back-up are still high enough, more than 30 cents/kWh, which makes it difficult to compete on the current Canadian electricity market. When the cost of the power block is ignored approximating the case of solar-augment of fossil-fuel fired power plants, such as Medicine Hat-Alberta integrated solar combined cycle (ISCC) project, results show that the solar LCOE is significantly lower than the LCOE obtained for standalone CSP plant with potential LCOEs less than 25 Cents/kWh as in the case of power tower with storage.

Acknowledgements

Results presented in this paper were developed within the frame of Natural Resources Canada's research activities funded by the Government of Canada both Clean Energy Fund and ecoENERGY Innovation Initiative. Contribution of Mr. Robert Morris for developing the Typical DNI Year input files in the required format for SAM technical and economic analysis is sincerely appreciated.

References

[1] Richard Perez, Jim Schlemmer, Sergey Kivalov, Karl Hemker, Jr. , Antoine Zelenka (2010): Improving the performance of satellite-to-irradiance models using the satellite's infrared sensors. American Solar Energy Society – Proc. ASES Annual Conference, Phoenix, AZ, May 2010

[2] Dise J., A. Kankiewicz, J. Schlemmer, K. Hemker, Jr., S. Kivalov, T. Hoff, & R. Perez, (2013): Operational Improvements in the Performance of the SUNY Satellite-to-Solar Irradiance Model Using Satellite Infrared Channels. IEEE Transactions, (39th PV Specialists, Tampa, Florida, June 2013.

[3] Gueymard C., and S. Wilcox, (2009): Spatial and temporal variability in the solar resource: Assessing the value of short-term measurements at potential solar power plant sites. Proc. ASES National Solar Conference, Buffalo, New York.

[4] Reda Djebbar; Robert Morris, Didier Thevenard, Richard Perez, James Schlemmer., Assessment of SUNY version 3 global horizontal and direct normal solar irradiance in Canada, Energy Procedia 30 (2012) 1274 – 1283

[5] Bravo, J.D., Casals,X.G.,Pascua,I.P.,2007. GIS approach to the definition of capacity and generation ceilings of renewable energy technologies. Energy Policy 35, 4879–4892.

[6] Craig Turchi, Nicholas Langle, Robin Bedilion, Cara Libby. Solar-Augment Potential of U.S. Fossil-Fired Power Plants. Technical Report NREL/TP-5500-50597, February 2011.

[7] Franz Trieb, Christoph Schillings, Marlene O'Sullivan, Thomas Pregger, Carsten Hoyer-Klick. Global Potential of Concentrating Solar Power., SolarPaces Conference, Berlin, September 2009.

[8] Craig Turchi, Mark Mehos, Clifford K. Ho, Gregory J. Kolb. Current and Future Costs for Parabolic Trough and Power Tower Systems in the US Market., SolarPACES 2010, Perpignan, France, September 21-24, 2010.