Proceedings of the 2nd International Conference on Fluid Flow, Heat and Mass Transfer
Ottawa, Ontario, Canada, April 30 – May 1 2015
Paper No. 180

A Pre-Feasibility Study of a Small-Scale Concentrating Solar Power Plant for an Industrial Application in Sacramento, California

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Abstract- A technical and financial pre-feasibility analysis of a standalone concentrated solar power (CSP) plant, which has not been explored in depth in the northern region of the state of California, was performed. A small scale CSP plant (10 MW) in the Sacramento County was designed and analyzed with the assistance of the software System Advisor Model (SAM). The design and analysis were performed through the proper selection of CSP technology, the input of influential factors and the cash flow procedures. The results of the plant cost, followed by the most suitable CSP technology and the annual electricity output (GWh) over a certain period of time were evaluated. The simulated outcome was used to determine whether or not a CSP plant will be economically feasible and convenient in the Sacramento Region.

***Keywords*:** Concentrated solar power (CSP), Pre-feasibility analysis of CSP plants, System Advisor Model (SAM) plant simulation, Cost analysis, Northern Region of California, Sacramento County

1. Introduction

Since the industrial revolution, the demand for energy has been increasing exponentially. Dependence on oil, coal and natural gas sources, however, has been decreasing since 1973 while the consumption in the renewable resources sector has been increasing. In the state of California, about 28.1% of the total electric generation state wide comes from renewable sources such as wind, biomass, hydro and solar (Web-1). For years, the state of California through the California Energy Commission (CEC) has been making sure that the California Public and Private Utilities comply with renewable energy standards in order to reduce the carbon footprint. The primary program used to implement these standards is the Renewables Portfolio Standard (RPS), which keeps track of renewable energy resources and tracks down the carbon footprint. This program was established in 2002 under Senate Bill 1078; California's Renewables Portfolio Standards (RPS). It was accelerated in 2006 under Senate Bill 107 by requiring that 20% of electricity retail sales be served by renewable energy resources by 2010. Subsequent recommendations in California energy policy reports advocated a goal of 33% by 2020 (Web-2).

In-depth research has been performed worldwide into the investigation and development of technologies that can compensate for renewable energy demand and carbon footprint reduction. One of these technologies is the concentrated solar power (CSP). This re-emerging technology can provide not only low carbon emissions, if any, but also a vast amount of energy for the daily electricity demand. This resource can be harvested in regions with a very strong and direct normal irradiance (DNI), which means that these regions have clear skies and strong sun radiation for the majority of the day.

The paper aimed to provide a scope of how the concentrated solar power can make a big impact on the energy consumption with a simple small-scale (10 MW) CSP plant and how this type of technology can be a possible application that is implemented in the Sacramento County based on suitable technologies and economic parameters. This is the first time a technology of this type is considered as a potential renewable source of energy for Northern California. The document highlights and interprets the main economic cash flow results obtained from the simulation performed.

2. CSP Plant Components

The concentrated solar power (CSP) plants collect direct solar radiation by concentrating it to heat a working fluid. Through turbines and generators the heated fluid is used to produce electricity. There are four major CSP technologies: parabolic troughs and linear Fresnel reflectors (concentrated on a linear collector system), power towers and parabolic dish (concentrated on central focal point). All of them can be integrated with thermal storage. The three main parts of a CSP are, (1) the solar field that collects and concentrates the solar radiation and converts it to useable heat for the power block; (2) the thermal storage unit that stores solar energy from a solar field where the heat can be delivered to the power block in case of less solar radiation; and (3) the power block that uses the heat collected from the sun to produce electricity.

A comparison of the major features of the different CSP technologies is presented in Table.1. It is seen that the parabolic though technology has the most commercial experience, while the parabolic dish and linear Fresnel systems are still in their initial demonstration phase. The concentrated solar plant that uses the parabolic trough solar field not only has a low cost compared to the rest (Tiangco et al., 2005) but also a relatively low risk involved due to such a fact that the technology has been out in the market for a vast period of time. When it comes to a CSP plant of this magnitude where tons of money is going to be invested, it is reasonable to proceed with a technology that has been out there for a descent amount of time and has proven its worthiness. This brings up the next point which involves the importance of the low risk of the thermal technology. In the low risk technology it makes it more accessible and convincing for the public and investors to invest in a plant of this type. In terms of Levelized Cost of Energy (LCOE), even though it is relative high compared to the other thermal technologies, the LCOE is expected to drop to 0.06-0.08 in the future as the technology keeps improving (Darwish et al., 2013).

Three CSP technologies Parabolic Trough, Tower and Dish engine will be taken into consideration for the study with focus on Parabolic Though. It is intended to help in evaluating the total cost of a CSP plant and its potential impact that the project might have on Sacramento County.

Table 1. Comparison among CSP technologies (Darwish et al., 2013)

	Parabolic Trough	Tower	Dish Engine	Linear Fresnel
Commercial experience	➢ 20 years	<4 years	-	-
Technology risk	Low	Medium	High	Medium
Optimal scale/modularity	50 MW to >100 MW	50 MW to >100 MW	100 MW to >100 MW	50 MW to >100 MW
Construction requirement	Demanding	Demanding	Moderate	Simple to moderate
Operating temperature	300˚C - 550˚C	260˚C - 570˚C	750˚C	270˚C
Efficiency	14% - 16%	15% - 22%	24% - 31%	9% - 11%
Storage	Yes	Yes	No	No
Levelized cost of energy ($/kWh)	Current: 0.30 - 0.75 Future: 0.06 - 0.08	Current: 0.20 - 0.90 Future: 0.06 - 0.08	Future: 0.05 - 0.08	Future: 0.06 - 0.08
Water usage	High	High	Low	Medium
Land requirement	High	high	Variable/flexible	Variable
Leading developers	Acciona Solar, Abengoa Solar/Abener, Solar Mellenium, Solel/Siemens	Abengoa Solar/Abener, Bright Source Energy, Torresol, eSolar	Tessera Solar/Stirling Energy Systems (SES)	Ausra/Area (small scale projects), Novatec Solar

3. Modelling Tool

The tool used in the study is the System Advisor Model (SAM) version 2014.4.1. It is a free software package provided by NREL (Web-3). Fig.1. shows the SAM's flowchart specifying the process for CSP Parabolic Trough System and the output results. The software's main function is to make performance predictions and cost of energy estimates for a grid-connected power project. It is based on the installation and operation costs and the system design parameters that the user can specify as inputs into the model. SAM analysis allows selecting the important parameters such as the economic options as well as the type of CSP technology that is more suitable for the selected site. The main expectation from the pre-feasibility analysis is to determine whether or not the CSP plant will be suitable within the Sacramento County and whether it will be worth the risk to move on to a next phase. This will save time and money for further investment evaluation. For the present analysis an empirical parabolic trough technology was chosen to reduce the costs and risks; simulated results will be discussed next.

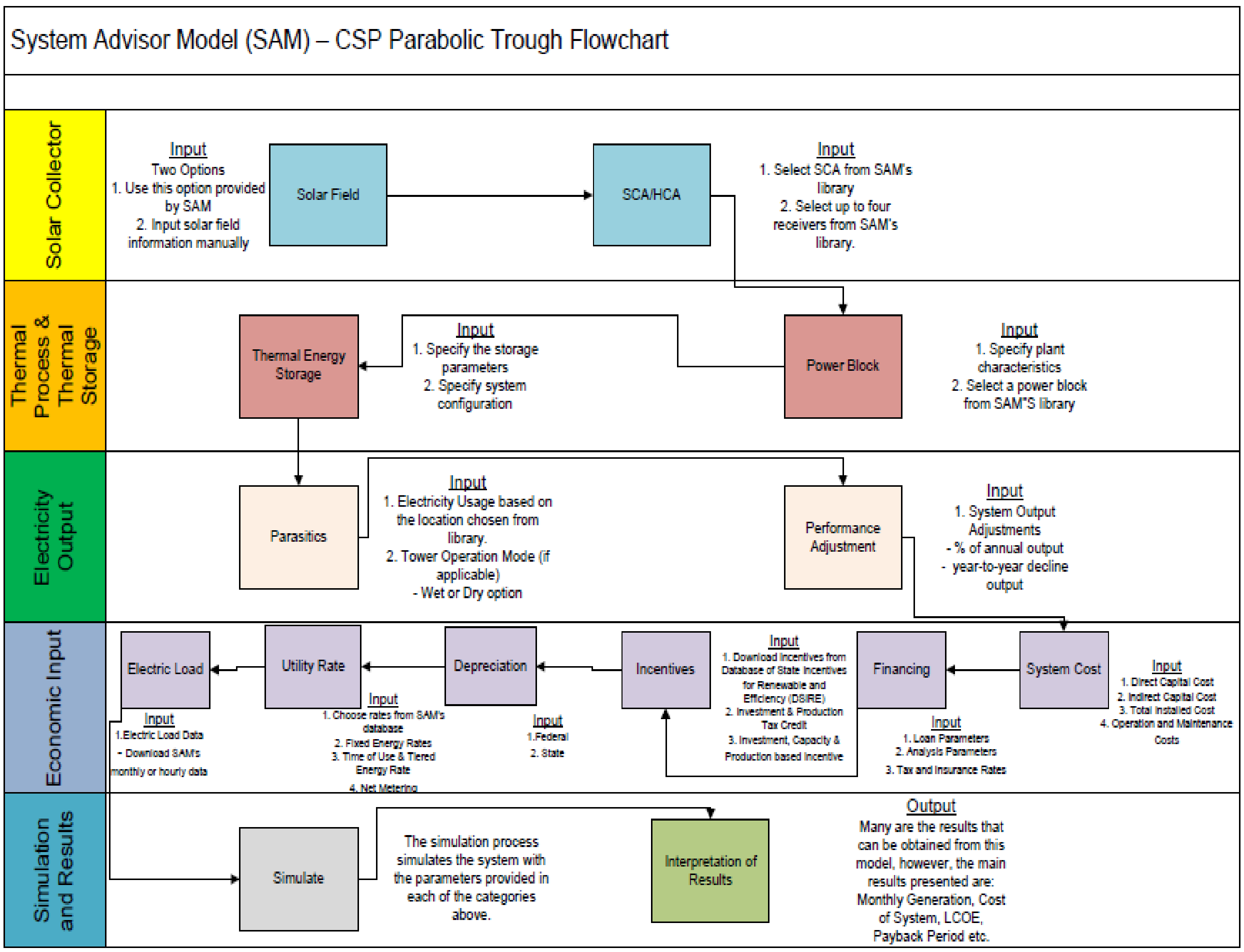


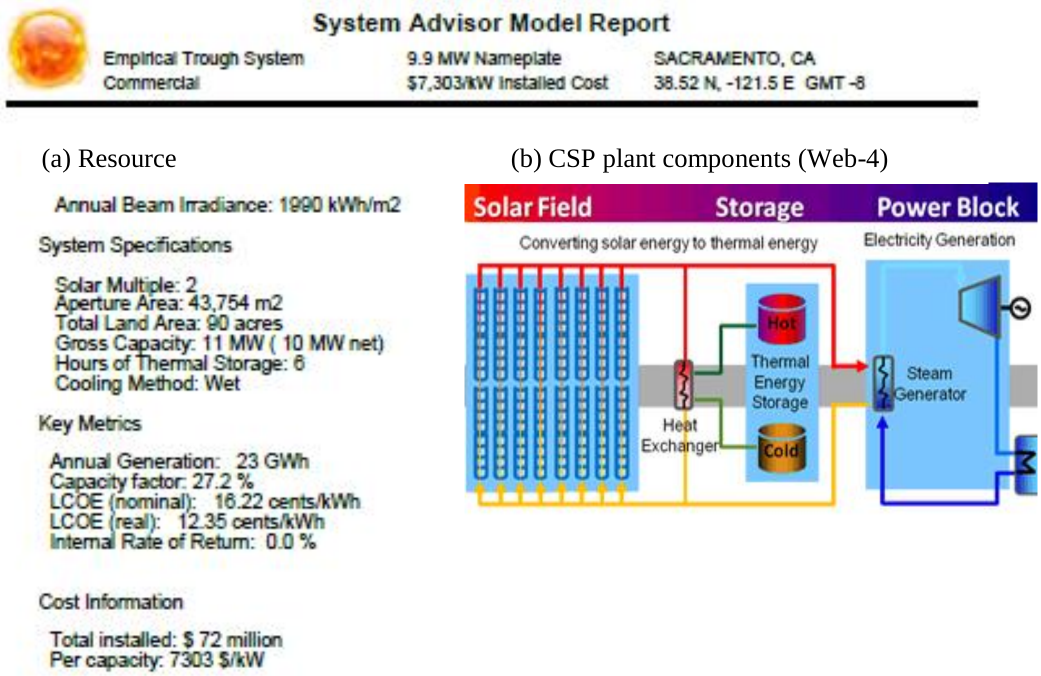
Fig. 1. SAM's flowchart specifying the process for CSP Parabolic Trough System

4. CSP Plant Modelling Results and Analysis

4. 1. System Advisor Model Report and Cost Analysis

The System Advisor Model (SAM) provided a list of pages that require fewer inputs and are more self-automated. However, the solar field, storage system, and power block along with the cost and financing were the main pages which required meticulous observation for the present analysis. Fig.2 shows part of the SAM report, indicating that the CSP plant has an annual beam irradiance of

1990kWh/m^2 and 2 solar fields with an aperture area of 43,754 m^2. The thermal energy storage is composed of a two tank configuration system with a capacity to store energy for 6 straight hours. The power block is designed to have an output of 11 MWe. With an estimated gross to net conversion factor of 0.9 (as shown in Table.3 later), it will derive into a net output of 10 MWe.



(a) Resource
(b) CSP plant components (Web-4)

Fig. 2. SAM simulation report

The cost of this project, as shown in Table.2 below, is broken down into two sections, (1) Direct Capital Costs and (2) Indirect Capital Cost. The direct capital cost is calculated to be $62,083,526, which includes site improvements, solar field, storage, fossil backup, power plant, balance of plant and contingency. The indirect capital cost is concluded to be $10,142,344, which includes cost per acre, percent of direct cost, fixed cost and sales tax. Overall, the total cost for the plant is estimated to be $72 million ($71,743,598) with an estimated cost per capacity of 7,303($/kW).

Another important output of the SAM model is the capital costs section as shown in Table.2 with the following parameters being provided by SAM. The solar field costs $270/$m^2$ while the cost for a 176 MWht thermal storage system is $80/kWht. The power block has a cost of $830 $/kWe and the balance of the plant is $110/kWt. It is noted that the solar field costs more than the storage system itself. The indirect capital costs section, on the other hand, provides a scope of the total land that should be bought at a location that meets with the desired requirements. For the current project, 91 acres are needed at a cost of $10,000 per acre. This is not very expensive considering that at different locations the price per acre is relatively higher in the state of California. In terms of sales tax, 5% sales tax is applied to 80% of the total direct cost.

The installed cost of this project is calculated at $72,304,288 as shown in Table.2. A big part of the installation fee goes to the cost of the solar field which is calculated at $23,872,428 (2.41 cents/W). This indicates that the solar field price is relatively high compared to the cost of the storage system and other costs involved as shown in Table 2. The total cost of the thermal storage cost for this project is about $14,083,755. The cost for solar field and thermal storage for a CSP project used to be relatively high as shown in Fig.3 and they are expected to be falling in the future.

Table 2. Direct and indirect capital costs data

Direct Capital Costs

Site Improvements	88416.4	m2	30.00 $/m2	$ 2,652,492.00
Solar Field	88416.4	m2	270.00 $/m2	$ 23,872,428.00
HTF System	88416.4	m2	80.00 $/m2	$ 7,073,312.00
Storage	176.047	MWht	80 $/kWht	$ 14,083,755.67
Fossil Backup	11	MWe, Gross	0 $/kWe	$ 0.00
Power Plant	11	MWe, Gross	830 $/kWe	$ 9,130,000.00
Balance of Plant	11	MWe, Gross	110 $/kWe	$ 1,210,000.00
		Contingency	7 %	$ 4,061,539.14
			Total Direct Cost	$ 62,083,526.80

Indirect Capital Costs

Total Land Area 91 acres Nameplate 10 MWe

	Cost per acre	% of Direct Cost	Cost per Wac	Fixed Cost	Total
EPC and Owner Cost	$ 0.00	11 %	$ 0.00	$ 0.00	$ 6,829,187.95
Total Land Cost	$ 10,000.00	0 %	$ 0.00	$ 0.00	$ 908,172.21
Sales Tax of	5 %	applies to	80 %	of Direct Cost	$ 2,483,341.07
				Total Indirect Cost	$ 10,220,701.23

Total Installed Costs

Total Installed Cost	$ 72,304,228.03
Total Estimated Installed Cost per Net Capacity ($/kW)	$ 7,303.46

Fig. 3. Falling Cost of CSP (Web-6)

The operation and maintenance costs are presented in Table.3. One important subsection to take into consideration is the fixed cost by capacity in the first year. For the current CSP plant simulation, the fixed cost by capacity is calculated to be about $65/kW-yr. This cost is considered to be reasonable for the project based on the information obtained and populated into this model from previous CSP projects in the state of California (Zhang et al., 2013).

Table 3. Operation and maintenance costs data

Operation and Maintenance Costs

	First Year Cost		Escalation Rate (above inflation)
Fixed Annual Cost	0.00	$/yr	0 %
Fixed Cost by Capacity	65.00	$/kW-yr	0 %
Variable Cost by Generation	4.00	$/MWh	0 %
Fossil Fuel Cost	0.00	$/MMBTU	0 %

Escalation rates apply only to single values, not to values in annual schedules.

4. 2. Results of Solar Field, Heat Transfer Fluid, Power Blocks

The solar field data from the SAM output in Fig.2 also show that the Solar Multiple (SM) is 2 for 6 hours Thermal Energy Storage (TES). The SM value is an important indicator, representing a ratio of the solar energy collected at the design point to the amount of solar energy required to generate a rated turbine gross power. An SM of 1.0 means that the solar field delivers exactly the amount of energy required to run the plant at its design output. A larger SM indicates a larger solar field, implying that the cost of the solar field will exponentially increase as the solar multiple increases. Therefore, for this type of CSP plant, it has to be taken into consideration whether a larger solar field will be beneficial and whether it will be worth the cost. On the design point section of the SAM simulation, the input only represents the reference set of conditions selected for designing this parabolic trough system. The SAM uses the following design conditions: $\cos\theta = 0$ (the incidence angle is zero degrees or the sun is normal to the collector aperture). Also, this system has an ambient temperature of 25^{o}C and a wind speed of 5 m/s.

The heat transfer fluid (HTF) used for this project is heat-transfer oil (Therminol VP1) and the operating conditions are as follows. The minimum and maximum operating temperatures given by SAM for this model are 12^{o} C and 400^{o} C respectively. The design loop inlet and outlet temperatures are 293^{o} C and 391^{o} C accordingly. The minimum and maximum single loop flow rates are 1 kg/s and 12 kg/s respectively. It is worth mentioning that these numbers can be modified to any specified values. The above parameter values populated by SAM are used because the heat-transfer oil is less expensive than molten salt. The disadvantage of using HTF is that using HTF will cut down on storage hours in comparison to using molten salt. The output of these parameters is expected to impact the total cost of the plant.

Table.4 shows the simulation results for the power block of the plant, indicating a net efficiency of 0.3749. The efficiency is defined as the energy produced-out over the heat rate output of the steam generator and it represents the average net efficiency of the currently operating CSP plant. The heat is generated at a rate of 29.3412 MWt in the steam generator. The ratio of the steam generator heat output to the solar heat is in between 65 % and 70%, implying that the required solar heat input is 45 MWt (that is the ratio of 29.3412 to 0.65) when the thermal energy storage is considered.

4. 3. Metric Summary of SAM Simulation

The SAM metric summary is presented in Table.5. It shows that the annual energy output is about 24 GWh (23,619,366kWh), with a nominal and real LCOE (Levelized Cost of Energy) of 16.08 cents/kWh and 12.29 cents/kWh respectively. These LCOE values for a small project are relatively high compared to the cost of energy for a bigger project with a greater capacity. Moreover, one of the important assumptions for this section simulation was that this project was going to have a 90% debt fraction. Based on that input, the simulation results showed that it will take approximately 28 years to pay it back.

This payback is not the desired outcome. The U.S. Department of Energy stipulates that this type of project is only operational for a 25 - 30 year range (Web 5). This implies that this project will be in debt for almost all the life of this plant.

Table 4. Power Block Data

Plant Characteristics

Design Gross Output	11	MWe
Estimated Gross to Net Conversion Factor	0.9	
Estimated Net Output at Design	10	MWe

Parasitic losses typically reduce net output to approximately 90 % of design gross power

Power Cycle

Current power block: SAM/CSP Trough Power Cycles/SEGS 30 MWe Turbine — Choose from library...

Design Cycle Thermal Input	29.3412	MWt	Frac of thermal power for startup	0.2	
Rated Cycle Conversion Efficiency	0.3749		Boiler LHV Efficiency	0.9	
Max turbine over design operation*	1.15		Max. Thermal Input	33.6447	MWt
Min turbine operation*	0.25		Min. Thermal Input	8.70956	MWt

	F0	F1	F2	F3	F4
Cycle Part-load Therm to Elec	-0.0572	1.0041	0.1255	-0.0724	0
Cycle Part-load Elec to Therm	0.0565	0.9822	-0.0983	0.0596	0
Cooling Tower Correction	1	0	0	0	0

Temp. Correction Mode: Wet-bulb Basis

* Fraction of Design Point

Table 5. Summary of SAM Simulation

Metric	Value
Annual Energy	23,619,366 kWh
LCOE Nominal	16.08 ¢/kWh
LCOE Real	12.29 ¢/kWh
Electricity cost without system	$ -0.00
Electricity cost with system	$ -3,260,942.50
Net savings with system	$ 3,260,942.50
Net present value ($)	$ -11,301,763.00
Payback (years)	27.6256 years
Capacity factor	27.2 %
Gross to Net Conv. Factor	0.88
Total Land Area	90.82 acres

5. Conclusion

After performing a detailed analysis using the System Advisor Model (SAM), the results are summarized. Following are the major concluding remarks obtained:

1. The SAM model suggests that the total cost of the CSP plant at the location of Sacramento County is relatively high at the moment. Although additional factors as well as inputs can be attempted in the SAM model to partially reduce the total cost of the CSP plant, the potential to harvest solar resource is more viable and easier in the southern region of the state in comparison to the Sacramento region.
2. The solar field continues to be the most expensive part of the equipment. A larger SM indicates a larger solar field and exponentially increased total plan cost. A smaller solar multiple (SM) rather than 2 is recommended.
3. With a 90% debt fraction, the payback period for the project is approximately 28 years.

The above observations suggest that this analysis is the first step on the extensive process of initiating a CSP plant that will help on the possibility of finding a viable option for CSP technology in the region of Sacramento County. It is recommendable to continue to work on the development of specific scenarios at different locations throughout the county where the cost will change based on the location specified or even drop over time. To acquire additional information on funding sources for the CSP technology will likely reduce the cost as well as other economic parameters.

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