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Simulation and Lessons Learned from the Ivanpah Solar Plant Project

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Abstract

The Ivanpah CSP plant is studied herein. Ivanpah's Tower 1 central collector was simulated using the NREL SAM software toolkit. Input parameters for the Ivanpah CSP was found via public domain websites regarding Ivanpah. Outputs from NREL SAM were compared to hand calculated values and available data from the actual output of Ivanpah. Solar Irradiation data was used from the National Solar Radiation. The solar insolation data was taken for the year 2015 in which there is data available for the energy production from Ivanpah. The actual total output from Ivanpah 1 during 2015 was 209,975,000 kWh. It is published that Ivanpah underproduced significantly in 2015 meaning that calculated values are drastically greater than the data given. The simulations herein show that NREL SAM gave an annual output of 292,469,024 kWh and hand calculations gave an output of 318,414,566 kWh. The paper concludes with a section on lessons learned.

Keywords: *CSP, modeling, simulation*

1. Introduction

The Ivanpah CSP Plant was built utilizing three separate Power tower central collectors named Ivanpah 1, 2 and 3. The focus of this report will be Ivanpah 1, the first tower built. This is a 126 MW tower utilizing 53,500 heliostats of 14 m^2 focused at a 140 m tall tower and energy is harvested through a rankine cycle utilizing a Siemens SST-900 steam turbine (www.brightsourceenergy.com). This paper presents a case study of the Ivanpah solar plant including a comprehensive literature review regarding the motivation and construction of the facility. The case study provides insight into how the theory, modeling and actual performance data of a large scale concentrated solar energy project such as Ivanpah can be used to examine the overall efficiency and benefits of renewable energy technologies. The Ivanpah solar plant located in Southern Nevada was simulated using the National Renewable Energy Laboratory System Advisor Model (NREL SAM) simulation software with the power tower concentrating solar power utilizing direct steam option. The NREL SAM simulations includes information on performance of the system and data on the cost for the lifetime of the system including Levelized Cost of Energy (LCOE) and Internal Rate of Return (IRR). The outputs from NREL SAM are verified using measured data collected from the Ivanpah power-plant. The results are also compared to fundamental solar energy engineering theory. The paper concludes with a discussion on lessons learned from the Ivanpah solar project. The paper concludes with a narrative

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illustrating how Ivanpah can be used as a learning tool and aid in rolling out renewable energy technologies to a wider population.This system was modelled in NREL SAM with parameters matching as close as possible to the actual design of Ivanpah 1. This includes heliostat size and layout, tower size, turbine design and location resource. Table 1 shows the various design parameters in which NREL SAM and the hand calculations were performed with to model the system. An aieral view of the Ivanpah CSP facility is shown in Figure 1.

Fig. 1: Ivanpah CSP Facility (www.ucsusa.org)

Ivanpah was built utilizing three separate Power tower central collectors named Ivanpah 1, 2 and 3. The total cost of the project was $2.2B. The Ivanpah Solar Electric Generating System (ISEGS) is located in the Mojave Desert, near the California / Nevada border, in San Bernardino County, CA, USA. The project was certified by the Energy Commission on September 22, 2010, and began commercial operation in December 2013. The ISEGS is a 386 megawatt (MW) project consisting of three individually certified solar concentrating thermal power plants, based on distributed power tower and heliostat mirror technology, in which heliostat (mirror) fields focus solar energy on power tower receivers near the center of each heliostat array. Power Plant 1 is a nominal 120 MW plant located on approximately 914 acres and consists of 53,500 heliostats. Power Plant 2 is a nominal 133 MW plant located on approximately 1,097 acres and consists of 60,000 heliostats. Power Plant 3 is a nominal 133 MW plant located on approximately 1,227 acres and contains 60,000 heliostats. Each site has a single receiver and heliostat array. The focus of this paper will be Ivanpah 1, the first tower built. This is a 126 MW tower utilizing 53,500 heliostats of 14 m^2 (914 acres) focused at a tower 140 m tall, energy is harvested through a Rankine cycle utilizing a Siemens SST-900 steam turbine. This system was modelled herein using NREL SAM (https://sam.nrel.gov/). This includes heliostat size and layout, tower size, turbine design and location resource. The model results are presented and compared to reported performance. Main take-aways are the energy performance of the system and financial analysis, namely Levelized Cost of Energy (LCOE) and Internal Rate of Return (IRR). In each solar plant, one Rankine-cycle reheat steam turbine receives live steam from the solar collector located in the power block at the top of a tower. Each plant also includes two natural gas-fired steam boilers: an auxiliary boiler and a nighttime preservation boiler. The auxiliary boiler is used for thermal input to the steam turbine during the morning start-up cycle to assist the plant in coming up to operating temperature. The auxiliary boiler is also operated during transient cloudy conditions, in order to maintain the steam turbine. Each solar plant uses dry cooling to conserve water, and limited to a combined 100 acre-feet per year of water for plant operations. The use of water in the desert has always been a contentious issue, and the drought has made water an even bigger issue in the West. Dry-cooling allows the project to reduce water usage by more than 90% over solar thermal technologies that use "wet-cooling" systems. We use water in two ways: to clean the mirrors, and to produce steam for electricity generation. To conserve water, we use a dry cooling process to condense the steam back to liquid, which is then recycled back to the boiler in a closed loop cycle. All power plants use water; dry cooling uses less water than nuclear (helioscsp.com a). No thermal storage is used in the Ivanpah power plant. Ivanpah doesn’t have storage, but most future projects, those that are being built in 2017 and beyond utilize thermal storage. The benchmark levelized cost of electricity (LCOE) for global CSP projects will fall below $50/MWh in 2018, two of the industry’s leading consultants predicted at CSP Seville 2017 (helioscsp.com b).

2. Modeling and Simulation

Herein the NREL SAM tool is used to model the Ivanpah 1 tower.The simulaton tool NREL SAM was used to perfrom modeling of the proposed PV farms. The software tool NREL SAM has a proven track record as a turn-key tool for aid in designing and simulating renewable energy systems (Blair et al. 2012, Blair et al. 2014, Freeman et al. 2013, Freeman et al. 2014)). NREL SAM is a program from the National Renewable Energy Laboratory used to evaluate performance and financial viability of renewable energy systems. NREL SAM has models for various renewable energies including: Photovoltaics, concentrating collectors, central towers, biofuel, geothermal and wind. Power tower central collectors utilizing direct steam will be the focus of this report. Table 1 lists the pertinent input parameters for the NREL SAM model of Ivanpah Tower 1.

Tab. 1: NREL SAM model inputs

Number of Heliostats	53,500
Single Heliostat Area (m^2)	14.04
Total Heliostat Area (m^2)	751140
Tower Height (m)	140
Boiler Height (m)	23.8
Turbine	Siemens SST-900
Output Rating (MW)	126
Capacity Factor	27.4%
Location Resource	35.57°N 115.47°W

Utilizing the paramters from Table 1, the NREL SAM calculations were performed. Below the inputs for both the NREL SAM simulation and independent hand calculations using EXCEL are discussed. The outputs from each of these will be discussed in the results section against actual data collected from published performance data of Ivanpah. The two main focuses of this researech are the energy performance of the system and financial analysis, namely LCOE (Levelized Cost of Energy) and IRR (Internal Rate of Return).

2.1 NREL SAM Modeling Methodology

NREL SAM takes into account many parameters when calculating the performance of the system, These include: heliostat, tower, central receiver and Rankine turbine designs. The inputs were made to closely resemble the values from Table 1. Figures 2 through 5 show the inputs used in NREL SAM Graphical User Interface (GUI) used to define, simulate and determine the performance of the system. This includes heliostat, Rankine cycle components and steam turbine generator.

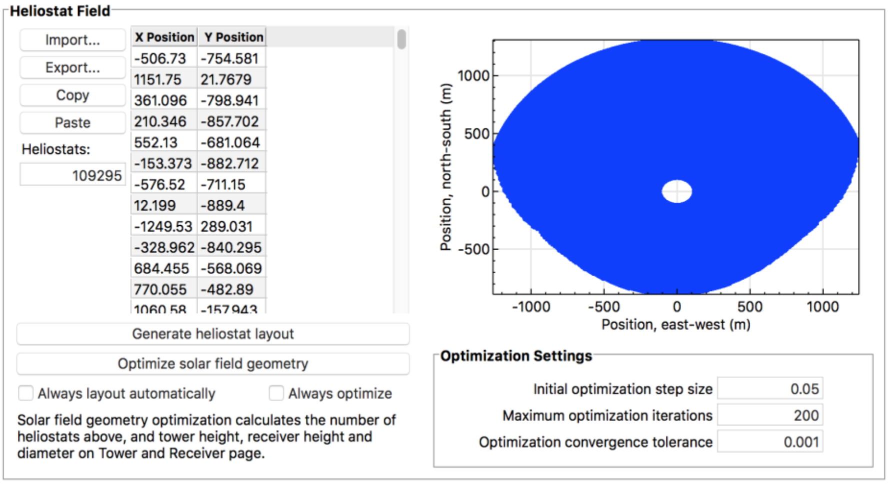


Fig. 2: Heliostat field NREL SAM GUI inputs

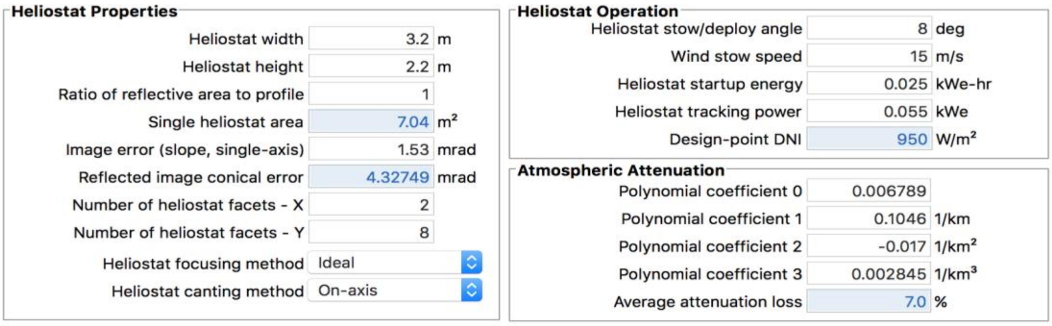


Fig. 3: Heliostat field NREL SAM GUI inputs

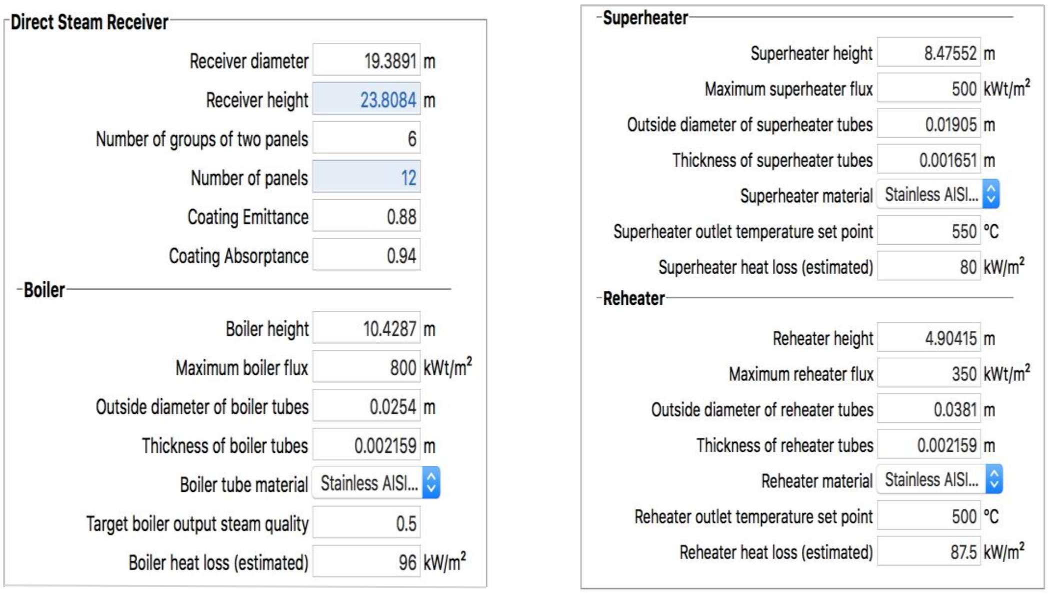


Fig. 4: Rankine Cycle NREL SAM GUI inputs

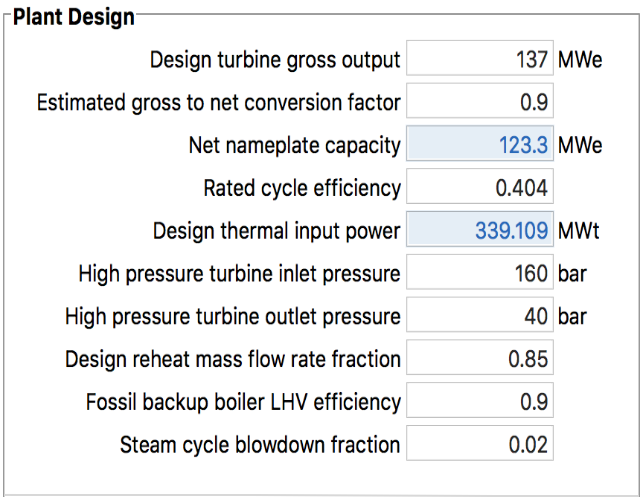


Fig. 5: Turbine design NREL SAM GUI inputs

The various parameters used to populate the GUIs of Figure 2 throug 5 are taken from practical experience, web based reserch on the specifications of Ivanpah CSP, and taking defaults from NREL SAM. The financial analysis GUI of NREL SAM is shown in Figure 6. This interface allows the user to define the direct capital costs associated with the particular renewable energy project being analyzed. Here, the direct capital costs of the heliostat field, tower, reciever, and power cycle are input into NREL SAM.

Fig. 6: Equipment capital cost NREL SAM GUI inputs

2.2 Excel Hand Calculations

In order to perform an indepent sanity check on the output produced by NREL SAM, an EXCEL spreadsheet was constructed based on hand-calculations. The performance of the system using EXCEL was modelled by taking the average annual solar irradiance for that location and multiplying it by the efficiency of the entire system including: collector losses, field losses and the steam turbine efficiency and finally by the total Heliostat area. Table 2 lists the efficiencies used in the EXCEL calculations.

Tab. 2: EXCEL hand-calculations component efficicencies

Component	Efficiency (%)
Convective / conduction parasitic losses	99.8
Radiative losses	93.7
Spillage losses	98.8
Reflective losses	90.0
Cosine / shadowing and blockage	82.9
Attenuation	94.6
Capacity factor	27.4

The various losses listed in Table 2 were based off of a design study done for solar thermal power plants done in 1979 by the Stearns Rogers Engineering company (www.powerfromthesun.net). The capacity factor was based off of the max efficiency of the Siemens SST-900 steam turbine (www.energy.siemens.com). The capacity factor is the efficiency of the steam turbine generator (ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at full nameplate capacity continuously over the same period of time).

3. Results

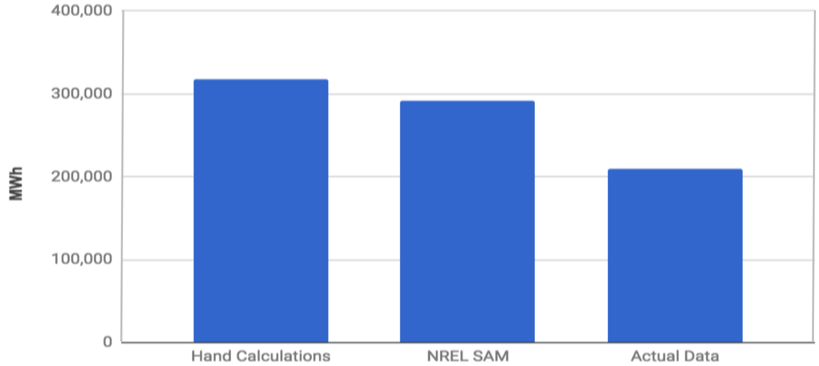
Results for the NREL SAM simulation and EXCEL hand-calculations are now compared to actual performace data for the Ivanpah CSP taken from (en.wikipedia.org). The performacne data used used for the year 2015 as shonw in Table 3.

Tab. 3: Ivanpah CSP Tower 1 performance data (https://en.wikipedia.org)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
2014	5,632	4,460	4,946	9,130	15,879	23,722	12,277	16,807	19,743	17,455	15,993	5,922	**151,966**
2015	4,448	16,471	20,010	25,281	12,380	25,126	19,575	23,404	21,333	11,813	16,230	13,904	**209,975**
2016	7,599	23,686	18,427	13,284	26,006	32,875	31,796	24,403	26,860	20,616	19,663	10,440	**255,655**
2017	11,310	11,699	12,283	11,656	28,709	34,797	21,742	23,437	24,803				**180,436**
												Total	**798,032 MWh**

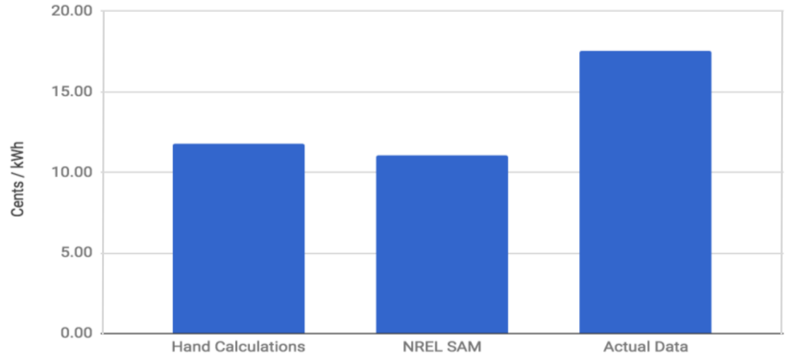
Table 4 shows the comparison of values of energy received (MWh) for EXCEL hand-calculations, NREL SAM simulation and data of Table 3 for Ivanpah Tower 1.

Tab. 4: Comparison of energy output



As shown in Table 4, the EXCEL hand-calculations were shown to have the largest output (being the most conservative), followed by the NREL SAM simulation, while the Ivanpah actual performance data was shown to be the worst. The actual output data of the Ivanpah CSP is lower than expected outcomes for the facility (en.wikipedia.org). The California Energy Commission (CEC) attributes this due to clouds, jet contrails and weather fluctuations (en.wikipedia.org). Table 5 shows the differences in LCOE of the different methods.

Tab. 5: Comparison of LCOE



The actual LCOE is the highest because the plant underproduced in the year 2015 causing the LCOE to jump when the cost of the plant is the same. Herein LCOE = (sum of costs over lifetime)/ (sum of electrical energy produced over lifetime). There are two different types of LCOE that can be calculated: nominal and real. Which of these is calculated depends on whether the nominal or real discount factor is used in the energy production term of the LCOE equation. The nominal LCOE is higher than the real LCOE because the nominal LCOE is a current value calculation that is not adjusted for inflation, whereas the real LCOE is a constant-value, inflation-adjusted calculation. The real LCOE is generally preferred for long-term analysis (http://solarprofessional.com).

Table 6 gives a summary of the main outputs from the NREL SAM simulation financial-economic analysis. The key metrics to take from this study are the annual energy output of 292,469,024 kWh correponsind to a LCOE (real) of 11.09 cents / kWh and an IRR of 12.59%.

Tab. 6: NREL SAM financial-economic analysis output summary

Metric	Value
Annual energy (year 1)	292,469,024 kWh
Capacity factor (year 1)	27.1%
Annual Water Usage	57,353 m^3
PPA price (year 1)	14.62 ¢/kWh
PPA price escalation	1.00 %/year
Levelized PPA price (nominal)	15.17 ¢/kWh
Levelized PPA price (real)	11.93 ¢/kWh
Levelized COE (nominal)	14.10 ¢/kWh
Levelized COE (real)	11.09 ¢/kWh
Net present value	$33,004,256
Internal rate of return (IRR)	11.00 %
Year IRR is achieved	20
IRR at end of project	12.59 %
Net capital cost	$490,318,112
Equity	$244,466,688
Size of debt	$245,851,440

The salient take-aways from Table 6, are that the Ivanpah CSP Plant 1 affords an annual energy output of 292,469,024 kWh corresponding to an LCOE of 11.09 ¢/ kWh (110.9 $/MWh) and IRR of 12.59%. This is in comparison US average LCOE of CSP in 2015 is 240 $/MWh. Next, the transient behavior of the Ivanpah CSP Tower 1 is presented. NREL SAM produces time history trends of the energy production of the powerplant. Figure 7 shows the ratio of reciever power to state ttoal (MWt) (blue trace) and cycle gross electrical power produced (orange trace) (Mwe) for a 5 day period in June. Recall, MWe (Megawatts electric) refers to the electricity output capability of the plant, and MWt (Megawatts thermal) refers to the input energy required, i.e. a coal-fired power plant rated at 1000 MWe and 3000 MWt will require supply of 3000 MW of heat from burning coal for every 1000 MW of electricity it produces (www.energyeducation.ca).The decrease in the electricity production illustrated in Figure 7 is due to the inefficiencies of the Rankine cycle and and the turbine.

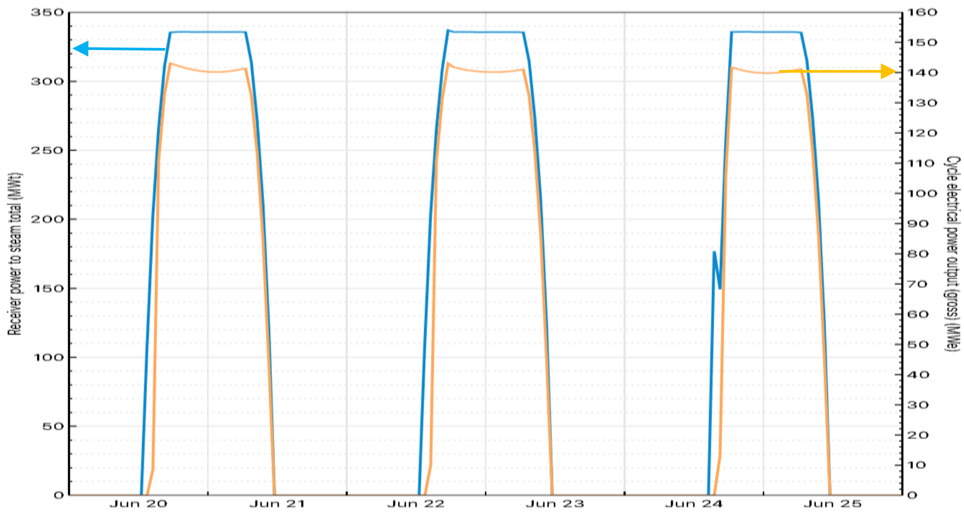


Fig. 7: NREL SAM receiver to steam power ratio and cycle electrial power output (blue trace = reciever power to stream total (MWt), orange trace = cycle gross electrical power output (MWe)

Figure 8 shows the total power generated from the system in the same period as above. Peaks and valleys correlate with bi-hourly irradiance data. Producing during the day and dropping below in dark hours.

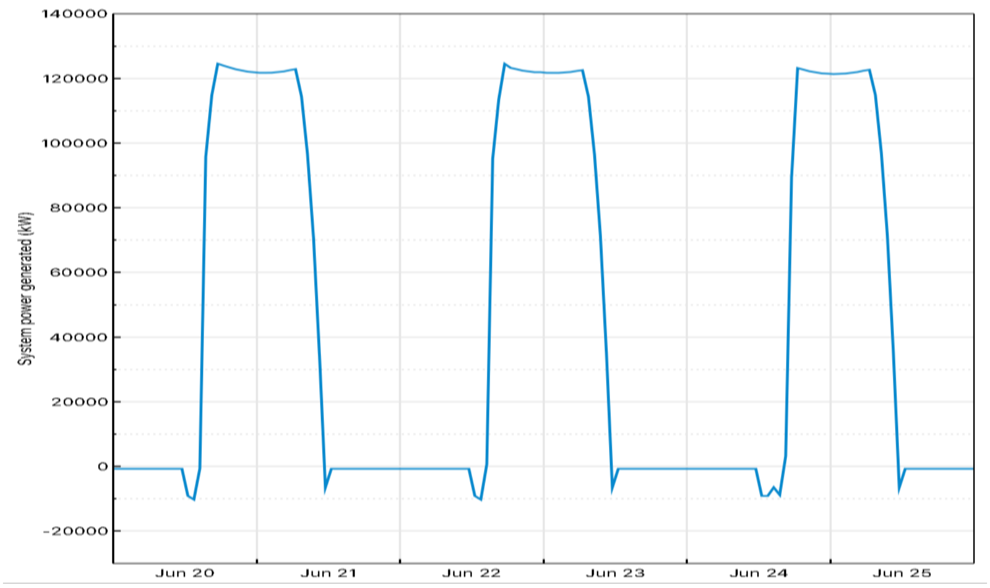


Fig. 8: NREL SAM system power generated

Speadsheet EXCEL calculations were performed using a yearly average Solar irradiance number in kWh/m^2/day. This was then used along with the total area of the heliostat field and the efficiency given by Table 2 to find the kWh per year. This is shown in Table 7 below.

Tab. 7: EXCEL hand-calcuation energy output

Component	Parametric value
Number of heliostats	53,500
Single heliostat area (m^2)	14.04
Efficiency	18%
Solar Irradiance per day (kWh/m^2/day)	6.5
Solar Irradiance flux (kWh/m^2)	2372.5
Total energy produced (kWh)	318,414,566

As shown in Table 7 this is the greatest calculation of energy output of all three methods (EXCEL, NREL SAM, actual perforamance data). The EXCEL calculations are over-conservative and place an upper bound on the analysis, since they were performed using a yearly average solar irradiance value. This data was then used along with the total area of the heliostat field and the efficiency to find the kWh per year. Calculation of LCOE and IRR using EXCEL were done by using cash flow values given by the NREL SAM simulation output. The IRR found from EXCEL was 12.43%. Table 8 shows a comparison of the calculated values of the energy production and the LCOE for each method (NREL SAM, EXCEL hand-calculations, actual data).

Tab. 8: EXCEL hand-calcuation energy output

Method of analysis	Energy produced (kWh)	LCOE (¢/kWh)
NREL SAM simulation	292,469,024	11.76
EXCEL hand-calculation	318,414,566	11.09
Actual performance data	209,965,000	17.53

It is worth noting that an LCOE of $50/MWh (5¢/kWh) is currently the baseline for for CSP with TES (helioscsp.com b). Thus, we see that the LCOE of Ivanpah 1, which does not utilize TES of 11.76 ¢/kWh is a factor of two great than renewable energy technology of CSP with TES. The rationale for the energy production of the actual peformance of the Ivanpah CSP Tower 1 is attributed to the use of natural gas fired auxiliary boilers as discussed below in the Lessons Learned section of this paper.

4. Lessons Learned

As noted above, the EXCEL hand calculations gave the greatest output of the system at 318,414,566 kWh. Next, was the simulations of NREL SAM predicted an output of 292,469,024 kWh. Finally, the actual output of Ivanpah was 209,975,000 kWh. This was much lower due to unexpected conditions experienced by the plant. The LCOE was calculated for each and they were 11.09 ¢/ kWh for NREL SAM, 11.76 ¢/ kWh for hand calculated data and 17.53 ¢/ kWh for actual performance data. If Ivanpah CSP Tower 1 was working at expected conditions then it would expect to closely resemble the results predicted by the NREL SAM model. Recently, several studies and reports have unveiled some of the reasons of sub-optimal performance of the Ivanpah CSP. In the study of (www.pe.com) it is noted that Ivanpah is using increasing amounts of natural gas. For 2015, the second year of Ivanpah's operation carbon emission were 68,676 metric tons, more than twice the pollution threshold for power plants in California to be required to participate in the California state cap and trade program to reduce carbon emissions. The fundamental operating premise of Ivanpah is to use hundreds of thousands of mirrors oriented in an array to focus heat from the sun onto boiler towers, thus boiling the water and generating steam to drive turbines to produce electricity. However, the Ivanpah plant also employs natural gas fired auxiliary boilers at nighttime in order to keep the system primed and to heat water in the tower boilers, This allows electricity production to start up more quickly when the sun rises each morning. Natural gas is also burned during periods of intermittent cloud cover. The use of natural gas auxiliary boilers was not fully publically disclosed at the onset of the construction of the Ivanpah power plant (www.pe.com). Carbon emissions from Ivanpah per (www.pe.com) are shown below in Figure 8.

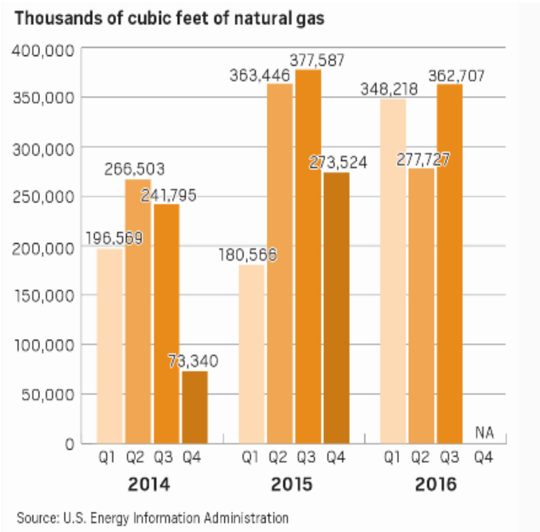


Fig. 8: Ivanpah carbon emissions (www.pe.com)

From the study (www.breitbart.com), it is reported that Ivanpah is using about 1.4 billion cubic feet of natural gas a year. Ivanpah has an exemption from state rules to qualify as an alternative energy source, because only 5% of its electrical generation is due to daylight burning of natural gas, according to the California Energy Commission. The report of (www.wsj.com) provides a commentary on the plant operational technical difficulties, which were not predicted upon installation of Ivanpah, such as the need for auxiliary gas boilers and unpredicted cloud, cover in the region of the 3500 acre (5.47 square miles) installation. According to the recent study of (www.renewableenergyworld) as of Feb. 2017 Ivanpah's electricity generation improved dramatically with utput from one of the boilers improving to 80% since the plant opened in 2014.

5. Conclusion

This paper has presented the simulation and analysis of the Ivanpah CSP Tower 1 facility. The software NREL SAM has been used to simulated the performance of the system. Results from NREL SAM have been compared to EXCEL based hand-calculations as well as actual performance data for the Ivanpah CSP Tower 1 energy production. A comparison of LCOE and energy production is given. The paper concludes with a brief summary of lessons learned from research performed on the Ivanpah project.

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