Design of a parabolic trough concentrated solar power plant in Al-Khobar, Saudi Arabia

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Abstract. The paper discusses the design options for a concentrated solar power plant in Al-Khobar, Saudi Arabia. The specific conditions, in terms of weather and sun irradiance, are considered, including sand and dust, humidity, temperature and proximity to the sea. Different real-world experiences are then considered, to understand the best design to adapt to the specific conditions. Concentrated solar power solar tower with thermal energy storage such as Crescent Dunes, or concentrated solar power solar tower without thermal energy storage but boost by natural gas combustion such as Ivanpah are disregarded for the higher costs, the performances well below the design, and the extra difficulties for the specific location such as temperatures, humidity and sand/dust that suggest the use of an enclosed trough. Concentrated solar power parabolic trough without thermal energy storage such as Genesis or Mojave, of drastically reduced cost and much better performances, do not provide however the added value of thermal energy storage and dispatchability that can make interesting Concentrated solar power vs. alternatives such as wind and solar photovoltaic. Thus, the concentrated solar power parabolic trough with thermal energy storage of Solana, of intermediate costs and best performances, albeit slightly lower than the design values, is selected. This design will have to be modified to enclosed trough and adopt a Seawater, Once-trough condenser. Being the development peculiar, a small scale pilot plant is suggested before a full-scale development.

1 Introduction

Concentrated solar power (CSP) parabolic trough (PT) are much simpler and reliable than CSP Solar Tower (ST). They still deliver much better capacity factors (ratio of average generating power to nominal power) in the real world (plants built and operated) despite the theoretically inferior performances in the virtual reality of model computations. [1],[2],[3],[4],[5]. With reference to wind and solar (photovoltaic), CSP has, if coupled to thermal energy storage (TES), the advantage of dispatchability vs. intermittency and variability [6], [7], [8]. While wind and solar photovoltaic are unable to supply any given output at a given time without external energy storage (even installed capacity of 18.1 GW are not enough to deliver even 0.2 GW to the grid after sunset if the wind is low), the coupling of CSP with molten salt TES is extremely attractive.

While CSP ST coupled to TES has so far performed badly in the real world, CSP PT with TES is already delivering good performances, [1],[2],[3],[4],[5], and hereafter. Solar photovoltaic (PV) works with annual average capacity factors about 0.29, but much larger than the capacity factor high-frequency standard deviations, for coefficients of variability in excess of unity [8], in the virtual reality of model computations CSP PT with TES may achieve much more uniform capacity factors, also addressing the issues of lack of production during nighttimes, and drastically reduced production with clouds. Opposite to PV, CSP, especially ST, suffers a lot of cloud coverage. As concluded in [1], [2], [3], [4], [5], CSP PT has the potentials, once a satisfactory design will be industrialized, deliver same or better than PV costs of electricity. And once intermittency and unpredictability are factored, also the addition of TES, similarly in need of a satisfactory design to be industrialized, will be cost-effective. Temperature and humidity affect the minimum temperature of the steam cycle. The condenser of CSP that usually adopts low maximum temperature steam Rankine Cycle is usually Fresh Water, Cooling Towers.

Sand and dust coverage of parabolic trough sections is a major issue for the Arab peninsula, where dust storms are not uncommon. The enclosed trough architecture proposed by Glasspoint [11] [12] encapsulates the solar thermal system within a glasshouse. The glasshouse creates a protected environment to withstand the elements that can reduce the reliability and efficiency of the solar thermal system. The air may be twelve times dirtier than in the U.S. Southwest, or Spain, making operation and maintenance difficult.

2 Weather and solar data

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Al-Khobar (latitude 26.145278, longitude 50.091944) is located in the Eastern Province, of Saudi Arabia, west of Bahrein, and north of Abu Dhabi. The parameters to consider for the design of a concentrated solar power plant are direct and diffuse solar radiation, temperatures, daylight times, humidity, clouds coverage. Weather conditions are given in [9] and reference annual average irradiance values are given in [10]. Specific for the area, also the sand coverage of the collecting surfaces in the solar field is relevant. Better sun irradiance measurements are unavailable.

In Al-Khobar, the summers are long, sweltering, humid, and arid but the winters are cool, dry, and windy. Over the course of the year, the temperature typically varies from 52°F to 109°F and is rarely below 45°F or above 115°F. It is mostly clear year-round, with however a cloud coverage having a seasonal pattern. The average percentage of the sky covered by clouds experiences significant seasonal variation over the course of the year. The clearer part of the year begins around September 6 and lasts for 2.2 months, ending around November 13. The clearest day of the year, the sky is clear, mostly clear, or partly cloudy 93% of the time, and overcast or mostly cloudy 7% of the time. The cloudier part of the year begins around November 13 and lasts for 9.8 months, ending around September 6. The cloudiest day of the year, the sky is overcast or mostly cloudy 44% of the time and clear, mostly clear, or partly cloudy 56% of the time.

The length of the day in Al-Khobar varies over the course of the year. The shortest day is 10 hours, 29 minutes of daylight; the longest day is 13 hours, 48 minutes of daylight. The earliest sunrise is at 4:46 AM, and the latest sunrise is at 6:29 AM. The earliest sunset is at 4:46 PM, and the latest sunset is at 6:36 PM on July 2.

The humidity data is based on the dew point. Lower dew points feel drier and higher dew points feel more humid. Unlike temperature, which typically varies significantly between night and day, dew point changes more slowly, so while the temperature may drop at night, a muggy day is typically followed by a muggy night. Al-Khobar experiences extreme seasonal variation in the humidity. The muggier period of the year lasts for 6.8 months, from May 1 to November 24. The muggiest day of the year has muggy conditions 61% of the time. In the least muggy day of the year, muggy conditions are essentially unheard of. The percentage of time spent at various dew points is often shown also as humidity comfort levels.

CSP usually adopts a low maximum temperature steam Rankine Cycle that is coupled to condensers using Fresh Water, Cooling Towers. Temperature and humidity affect the minimum temperature of the steam cycle. As Al-Khobar is located near a large body of water, there is the opportunity to have a Seawater, Once-trough condenser. Thus, the temperature of the water is an additional parameter to consider. The average water temperature experiences significant seasonal variation over the course of the year. The time of year with warmer water lasts for 3.5 months, from June 26 to October 10, with an average temperature above 87°F. On the day of the year with the warmest water, the average temperature is 92°F. The time of year with cooler water lasts for 3.4 months, from December 22 to April 4, with an average temperature below 70°F. The day of the year with the coolest water has an average temperature of 65°F.

Regarding solar irradiance, the annual average direct normal irradiation (DNI) is 1744 kWh/m^2, while the global horizontal irradiation GHI is 2091 kWh/m^2 and the diffuse horizontal irradiation DIF is 904 kWh/m^2. The global tilted irradiation at an optimum angle (GTI Opta) is 2264 kWh/m^2. The annual average air temperature is 26.9 °C. The terrain elevation is few meters (2 m). Fig. 1 summarizes the weather conditions. Images are reproduced modified from [9].

In the glass room design, [11] [12] The aluminium PT mirrors on single-axis trackers are enclosed in agricultural glass greenhouses that are cleaned automatically using well-proven agricultural technologies. In the Glasspoint design, [11] [12], proposed for oil extraction rather than power generation, steam is generated directly using oil field-quality water flowing along the length of the pipes, without heat exchangers or intermediate working fluids. Sheltering the mirrors from wind also allows higher temperatures, additionally from preventing dust build-up also a result of exposure to humidity.

Fig. 1 - Weather conditions. Images are reproduced modified from [9]. Top to bottom left to right, maximum and minimum temperatures across the year, clouds coverage across the year, dew point across the year, the average temperature of water across the year.

3 Sample CSP PT models

Thermoflow [13] has the models of different CSP PT plants without TES, for example Solar Electric Generating Station (SEGS) VI plant [14]. This is a historical power plant, part of a complex built in between the mid-1980s and early 1990s, with some units still operating despite the age well above the expected lifespan. SEGS VI is one of the nine Solar Electric Generating Station plants in California's Mojave Desert. The combined electric generating capacity of these plants, which use parabolic trough technology, was more than 350 MW. SEGS VI was located in Kramer Junction, California, US, in the Mojave Desert. The Solar Resource was 2725 kWh/m^2/yr. The Solar-Field Aperture Area was 188,000 m². The Heat-Transfer Fluid Type was oil (Therminol). The solar field Outlet Temp was 390 °C. The turbine had a capacity gross of 35 MW and a net of 30 MW. Power Cycle Pressure was 100 bar. Turbine Efficiency was 37.50% @ full load. The plant had a Fossil Backup Type Natural gas, to help ramp up production and help with transient clouds coverage

Solar rays reflect off parabolic trough mirrors focused on a pipe carrying thermal oil. The thermal oil loop transfers heat to the water loop making and reheating steam. The power plant is a single reheat Rankine cycle with six heaters. Modest steam conditions are used because of the limited operating temperature range of the thermal oil. The computed field consists of 100 rows of mirrors on a field of 660,000 m^2. At a peak rating of 35 MWe, the solar field land usage for this plant is 1.9 hectares per MW or 4.8 acres per MW.

Kramer junction is a much better solar site than Al Khobar. Direct normal irradiation DNI is 2980 kWh/m^2 (1744 kWh/m^2). Global horizontal irradiation GHI is 2195 kWh/m_2 (2091 kWh/m_2). Diffuse horizontal irradiation DIF is 431 kWh/m^2 (904 kWh/m^2). Global tilted irradiation at optimum angle GTI Opta is 2575 kWh/m^2 (2264 kWh/m^2). The air temperature is 18.1 °C (26.4 °C). The elevation is much larger 752 m (2 m). Humidity is also playing negatively for having this same plant design located in Al-Khobar, where the only advantage is the proximity to the sea with the option to use a Seawater, Once-trough condenser.

As an additional challenge and opportunity, as previously mentioned, the glass enclosure may keep temperatures of the fluids higher, but despite addressing the dust and sand coverage of the PT reflectors, it may limit the solar irradiance. Thermoflow [13] also has the model of the CSP PT Andasol 1 plant with TES [14]. This time, the plant also features a (limited) thermal energy storage by molten salt. The plant is located in Granada, Spain. This model uses a parabolic trough solar field together with a two-tank molten salt storage system. The storage system permits plant operation during cloudy periods and for some time after sunset. Plant load is governed by hot oil flow from the solar field with the storage system. Plant power output is computed based on available oil flowrate and oil temperature. Plant shutdown occurs when the solar field together with the storage system cannot deliver any hot oil. The storage system runs in all its modes as the day progresses. It begins in discharging mode, then is shutdown when depleted in the early morning. Sometime after sunrise, the storage begins to charge using the excess capacity of the solar field. Eventually, the hot tank is filled, and the storage system shuts down. As the sun drops in the sky, the storage begins to discharge and runs to capacity into the evening and overnight hours when all heat comes from storage.

Andasol-1 was the first parabolic trough power plant in Europe. The plant began operating in 2008. The nominal production capacity of 50 megawatts. A two-tank indirect thermal storage system holds 28,500 tons of molten salt. This reservoir can run the turbine for up to 7.5 hours at full load. The Solar Resource here is a much smaller 2136 kWh/m^2/yr. The Solar-Field Aperture Area was 510,120 m². the # of Solar Collector Assemblies (SCAs) is 624. The # of Loops is 156. The # of SCAs per Loop is 4. The SCA Aperture Area is 817 m². The SCA Length is 144 m. The # of Modules per SCA is 12. The # of Heat Collector Elements (HCEs) is 11,232. The HCE Length is 4 m. The Heat-Transfer Fluid Type was Dowtherm A. The Solar-Field Inlet Temp is 293ºC. The Solar-Field Outlet Temp is 393ºC. The Solar-Field Temp Difference is 100ºC. The power Block has Turbine Capacity Gross 50 MW and Net 49.9 MW. The Steam Rankine Power Cycle has a Pressure 100 bar. The Cooling Method is Wet cooling by Cooling towers. The Turbine Efficiency is 38.10% @ full load. The Thermal Storage Type is 2-tank indirect, with Storage Capacity 7.5 hour(s). Storage is 28,500 tons of molten salt. 60% sodium nitrate, 40% potassium nitrate. 1,010 MWh. Tanks are 14 m high and 36 m in diameter. In Grenada, Spain the irradiance conditions are comparable to those in Al-Khobar, but temperature and humidity are worse, same as dust and sand. Direct normal irradiation DNI is 2258 kWh/m^2, Global horizontal irradiation GHI is 1880 kWh/m^2, Diffuse horizontal irradiation DIF is 561 kWh/m^2, Global tilted irradiation at an optimum angle is GTI Opta 2190 kWh/m^2. The Air temperature is 14.4 °C. The Terrain elevation is 1187 m.

These plants models can be considered as a guideline for setting up the Al Khobar model.

4 Latest CSP PT performance data

While SEGS and Andasol are “historical” plants, the latest real-world performances of CSP ST and PT plants with and without TES can be gathered by considering the largest cps plants operational in the US. Electricity production data of CSP projects, in the United States have been obtained through the collection of public domain information mostly from the United States Energy Information Administration [15]. The data are available on an annual, quarterly or monthly basis as a net generation in MWh, and eventually natural gas use in MMBtu. From the net installed capacity (power) P in MW, annual and monthly capacity factors ε are computed by diving the annual and monthly electricity production by the product of capacity and number of hours in a year or a month. $\boldsymbol{\varepsilon = E/(P \cdot n)}$ where n is the number of hours in a year or in the specific month. The time series of the monthly capacity factors are used to supplement the synthetic information provided by the annual capacity factors to indicate the advantages and possible improvements of technology.

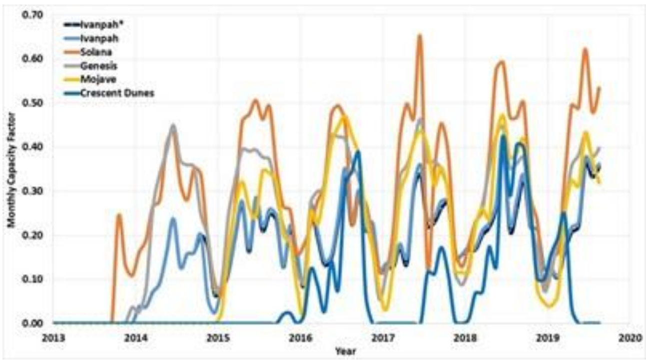
The latest list of CSP projects worldwide of [16], only 7 have net capacity more than 100 MW, and only 4 of the 7 have a net capacity exceeding 150 MW. The 4 are all in the US. They are the 377 MW Ivanpah Solar Electric Generating System (ISEGS), and the 250 MW each Solana Generating Station, Genesis Solar Energy Project and Mojave Solar Project. The 7th largest CSP plant in the world, the 110 MW Crescent Dunes Solar Energy Project, is also in the United States.

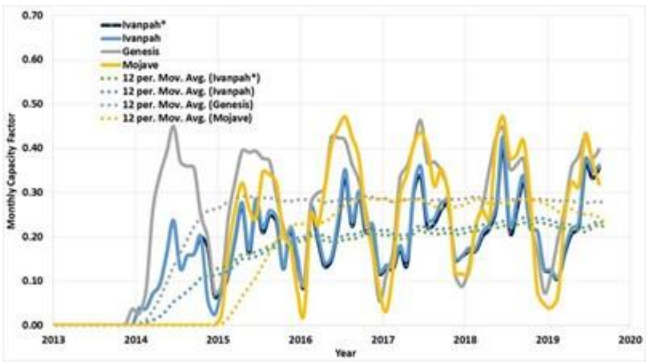
ISEGS started production in January 2014, Solana October 2013. Genesis March 2014, Mojave Solar Project December 2014 and Crescent Dunes November 2015. Hence, all of them are very recent. The historical Solar Energy Generating Systems (SEGS) plants, with 4 of 9 units still operational, is not considered. The technology of ISEGS is ST, without TES, with NG boost. The technology of Solana is PT, with TES 6 hours and no NG boost. Genesis and Mojave Solar Project are PT without TES and no NG boost. Crescent Dunes is ST, with TES 10 hours and no NG boost. Fig. 2 presents the capacity factors computed monthly for all these plants since the start of production till August 2019, plus the 12 months moving averages. The latest production data of ISEGS indicates capacity factors in the low 20%, despite burning substantial amounts of NG, translating in significant additional generating costs and pollution. The actual capacity factors drastically reduce more than one third, to less than 15%, once the consumption of NG is properly accounted for at the fuel energy conversion efficiency of a reference CCGT plant. The planned capacity factor was 32.68%, with a much-limited boost by the burning of NG. Crescent Dunes had a planned capacity factor of 51.89%. However, it is working at about 10% capacity factor. The plant has been out of service many times.

In the much simpler and reliable PT technology, CSP is certainly performing much better. Solana has a production much better than Crescent Dunes and ISEGS, even if still less than the planned values. While the planned capacity factor was 43.11%, the latest capacity factor is 36.40%. Genesis and Mojave Solar Project, also featuring the more established PT technology but without any TES, are possibly performing even better than the design values, but less than Solana. The actual capacity factors are 28.11% for genesis, exceeding the planned capacity factors of 26.48%. Mojave was similarly performing above the design but recently has dropped production to 24.6% vs. the planned 27.40%.

Solana Generating Station is 70 miles southwest of Phoenix, Arizona. The thermal energy storage system provides up to 6 hours of generating capacity after sunset. Land Area is 780 hectares. Solar-Field Aperture Area is 2,200,000 m². The # of Solar Collector Assemblies (SCAs) is 3232. The # of Loops is 808. The # of SCAs per Loop is 4. The # of Modules per SCA is 10. The receiver fluid is Therminol VP-1. The Solar-Field Inlet Temp is 293ºC. The Solar-Field Outlet Temp is 393ºC. The Turbine Capacity Gross is 280 MW, Net 250 MW. The Steam Rankine Power Cycle Pressure is 100 bar. Thermal Storage type is 2-tank indirect, with Storage Capacity 6 hours using Molten salt.

Net and gross powers in MW of turbines in [16] are the following: Ivanpah, 377 (392), Solana, 250 (280), Genesis, 250 (250), Mojave, 250 (280), Crescent Dunes, 110 (110). The latest 12-months moving averages of the capacity factors are Ivanpah* 22.87%, Ivanpah 23.67%, Solana 36.40%, Genesis 28.11%, Mojave 24.45% and Crescent Dunes 12.46%.





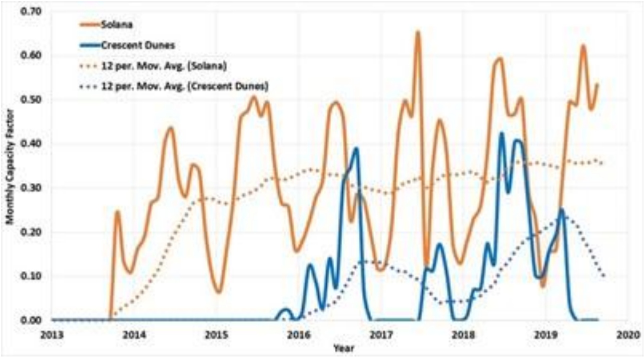


Fig. 2 –Comparison of monthly capacity factors of CSP ST and PT plants with or without TES. Data are shown from January 2013 to August 2019. Top, all the plants. Middle, CSP PT with TES of Solana and CSP ST with TES of Crescent Dunes. Bottom, CSP PT without TES of Genesis and Mojave and CSP ST without TES but NG combustion of ISEGS. The asterisk indicates the SUN only result of ISEGS. The 12 months moving averages are also added. Image reproduced modified from [17].

5. Discussion and conclusions

In the real world, CSP PT plants have the largest capacity factors than CSP ST plants. Capacity factors of CSP PT plants, without TES, solar only, such as Genesis or Mojave Solar Project, are about 30%, close to their design values. With 6 hours of TES, the capacity factors of the Solana plant, CSP PT, solar only, are up to 33%, however much lower than the design value of 43%. The CSP ST plants of Ivanpah (ISEGS), without TES but with boost by NG combustion, and Crescent Dunes, with 10 hours TES, solar only, have delivered so far much less than their planned capacity factors, and much less than the capacity factors delivered by the contemporary CSP PT plants. Without TES, actualized construction costs for CSP PT are 5,213-6,672 $/kW and 6,084 $/kW for CSP ST. With TES, the actualized costs of PT and ST increase to 8,258 $/kW and 9,227 $/kW respectively.

From these experiences, it seems, therefore, logic to avoid the construction of the potentially more performing CSP ST, that do not work as they should in the US, and for no reason should work better in the harsher conditions of Al-Khobar. Better performances and reduced costs in the US, plus the opportunity to take advantage of the glass enclosure surroundings the panels definitively suggest to select a CPS PT design. The designs of Mojave/Genesis without any TES, or Solana with TES, coupled to the glass enclosure, and a Seawater, Once-trough condenser have almost equal pros and cons. As the future is inevitably in the direction of TES, the selected technology is the Solana plant with a further expanded TES to 10 hours. This is the only plant giving advantages vs. PV systems, as it delivers significantly better annual average capacity factor, and much better standard deviation of the capacity factor, thanks to the TES. Being the specific application unconventional (high temperatures, sand, and dust, glass enclosure, humidity, proximity to the sea), a pilot plant is suggested first, before moving to a full-scale realization.

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