Comparative Study of Concentrated Solar Power Technologies for Storage and Location

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ABSTRACT: Renewable energy sources allow us to address climate change, as they cannot be depleted. The most common forms of Renewable Energy are solar, wind, Hydropower, and Geothermal. This paper will focus solely on Concentrated Solar Power (CSP), a form of solar power. This research was conducted to provide more insight into renewable energy sources, specifically Concentrated Solar Power. In addition, this study seeks to determine the potential of different CSP technologies in the USA. Through the System Advisory Model, simulations on three CSP technologies (Parabolic Trough, Power Tower, and Linear Fresnel Systems) were carried out for eight locations (San Bernardino, CA; Barstow, CA; Blythe, CA; Nye County, NV; Boulder City, Nevada; Harper Lake, CA; Indiantown, FL; and Kramer Junction, CA) at four different storage capacities (0, 4, 8, and 12 hours). Results indicated that the Power Tower system produced the highest energy levels regardless of location. The 8-hour and 12-hour storage produced better results.

KEYWORDS: Solar; Sustainable Design; Concentrated Solar Power; Direct Normal Irradiation; Parabolic Trough.

Introduction

Climate change is one of the most pressing problems of today’s day and age, worsening exponentially. The Intergovernmental Panel on Climate Change (IPCC) estimated that emissions from fossil fuels (Coal, Oil, Natural Gas) are the dominant cause of global warming.¹ In 2018, 89% of global CO2 emissions came from fossil fuels and industry. Coal is the dirtiest of them all, responsible for over 0.3°C of the 1°C increase in global average temperatures, making it the largest source of global temperature rise. In addition, oil, approximately a third of the world’s total carbon emissions, releases a large amount of carbon when burned. In particular, oil spills in recent years have had a devastating impact on our ocean’s ecosystem.

The IPCC strongly recommends that fossil fuel emissions must be halved within 11 years if global warming is to be limited to 1.5°C above pre-industrial levels. In 2015, the world’s governments signed up to the Paris Agreement committing to reduce carbon emissions. Yet, a recent report by the UN Environment Programme shows that globally, we are on track to produce more than double the amount of coal, oil, and gas by 2030 than we can burn if we are to limit global warming by 1.5°C.

Renewable energy is a potential solution. Renewable energy is an environmentally friendly alternative to nonrenewable energy, creating pollution and greenhouse gases entering the atmosphere. Renewable energy is energy derived from natural sources that can be replenished, but both the energy density and the time availability are limited. For example, solar irradiation is only available during the day and not at night. Another concern is cost, which is the main factor hindering sustainable energy usage.²

Renewable energy includes sustainable sources such as sunlight, wind, rain, tides, water, and geothermal heat.³ In our research, we focused specifically on Concentrated Solar Power. Concentrated solar power technologies use mirrors to reflect and concentrate sunlight onto a receiver. The concentrated sunlight heats a heat transfer fluid in the receiver. Next, the heat is transferred to a thermal cycle where the heat is transformed into electricity. Surplus heat can then be stored to generate electricity later, independent from solar irradiation.

Other research on comparisons of Concentrated Solar Power technologies compares aspects such as combined power and cooling production. This research results in the finding that Solar towers exhibit higher efficiency and require lower aperture area and investment costs compared to Parabolic Troughs.⁴ Our research is focused on the storage capacity and the plant’s location, differing from other comparison research.

Our goal is to provide more insight into Concentrated Solar Power and its different technologies. By comparing the outputs of Linear Fresnel, Parabolic Trough, and Power Tower systems, along with the Direct Normal Irradiation of the location, a data basis was created to optimize these systems’ future optimization.

Methods

To solve these problems, the System Advisor Model, a techno-economic software model developed by the National Renewable Energy Laboratory, was used to simulate these three different CSP technologies. These simulations aimed to decide which technologies are best suited for these specific locations and the United States in general.

The System Advisor Model was used to simulate different scenarios for comparisons between the technologies. The size of the solar system is kept constant, and eight different locations are used. These locations were found based on their Direct Normal Irradiation values, proximity to a hydroelectric station, and Geothermal potential. These criteria make the locations ideal for all types of renewable energy, thus making them very interesting locations. These locations were:
San Bernardino County, CA; Barstow, CA; Blythe, CA; Nye County, NV; Boulder City, Nevada; Harper Lake, CA; Indiantown, FL; and Kramer Junction, CA. In addition, three different Concentrated Solar Power technologies were used: Linear Fresnel, Power Tower, and Physical Parabolic Troughs. Lastly, four different storage hours were simulated: 0, 4, 8, and 12. The storage capacity hours simulate the time the energy stored can be used without sunlight. For example, if there were 0 storage hours, then during the night or periods of time with no sunlight, the technology would not be able to produce any electricity.

The Physical Parabolic Trough is a set of concave mirrors concentrating solar onto the receiver tube. The sunlight, entering the mirror parallel to the plane of symmetry, is focused on the focal line. Parabolic Troughs are the most mature type of Concentrated Solar Power energy.

Power Tower plants use heliostats, essentially sun-tracking mirrors, to focus sunlight on a receiver at the top of the tower. A heat transfer fluid is heated up in this tower to approximately 600 degrees Celsius and is used to generate steam. The steam produces electricity in a turbine generator. The System Design for the Power Tower system is shown in Figure 2. The parameters that were set for the simulation runs are circled. The nameplate capacity (estimated net output at design) of the Parabolic Trough system was held constant at 100 MWe; however, each simulation run had a different storage capacity varying from 0, 4, 8, and 12 hours.

Linear Fresnel systems are very similar to the Parabolic Troughs. They contain a collector field, which consists of many collectors in rows. These mirrors are laid flat on the ground and reflect the solar rays to the pipe above. Like the Power Tower and the Parabolic Trough, the pipe can either store the energy or generate steam to produce energy. For the Linear Fresnel model, the nameplate was kept at 100.00 MWe and the equivalent full-load thermal⁸ storage hours were 0, 4, 8, and 12, as shown in Figure 3.

![Figure 1: System Design Parabolic Trough](Source: System Advisor Model⁵)

The System Design for the Parabolic Trough is shown in Figure 1. The parameters that were set for the simulation runs

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**Figure 1:** System Design Parabolic Trough [Source: System Advisor Model⁵]

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**Figure 2:** Solar Field Design Point Data [Source: System Advisor Model⁴]

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**Figure 3:** System Design Power Tower [Source: System Advisor Model⁴]

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**Figure 4:** Types of Concentrated Solar Power Technologies [Source: Bing Images]

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**Figure 5:** Comparison of monthly total Direct Normal Irradiance values across all eight Concentrated Solar Power technology locations.
Monthly Direct Normal Irradiance (DNI) values for all eight of the locations chosen: Kramer Junction, CA; San Bernardino, CA; Barstow; CA, Indiantown; FL, Harper Dry Lake; CA, Blythe, CA; Nye County, NV; and Boulder City, NV are shown in Figure 5. Kramer Junction has the highest DNI value for each month, with the highest being 321 kWh/m² in June. This data will help us better understand the CSP technology output data and make it easier to compare and contrast the different technologies and their functions. In addition, the results of the analysis for these locations can be transferred to other sites with similar irradiation profiles.

The 0 Storage Hour energy generation serves as our control group to allow us to compare the locations before adding in storage hours. For example, we can see that a Power Tower plant in Harper Lake, CA, would produce the highest annual energy (3.19*10^8 kWh), and a Power Tower plant in San Bernardino, CA, would produce the lowest annual energy (1.90*10^8 kWh).

Figure 6: Comparison of 0 storage hour annual energy generation by a parabolic trough for each location.

![Figure 6](image6.png)

The 0 Storage Hour energy generation serves as our control group to allow us to compare the locations before adding in storage hours. For example, we can see that a parabolic trough in Blythe, CA, would produce the highest annual energy (3.08*10^8 kWh), and a parabolic trough in Indiantown, FL, would produce the lowest annual energy (1.88*10^8 kWh).

Figure 7: Comparison of 0 Storage hour annual generation by a Linear Fresnel Plant for each location.

![Figure 7](image7.png)

The 0 Storage Hour energy generation serves as our control group to allow us to compare the locations before adding in storage hours. For example, we can see that a linear fresnel plant in Kramer Junction, CA, would produce the highest annual energy (2.68*10^8 kWh), and a Linear Fresnel plant in Boulder City, NV, would produce the lowest annual energy (1.87*10^8 kWh).

Figure 8: Comparison of 0 Storage hour annual generation by a Power Tower Plant for each location.

![Figure 8](image8.png)

The 0 Storage Hour energy generation serves as our control group to allow us to compare the locations before adding in storage hours. For example, we can see that a Power Tower plant in Harper Lake, CA, would produce the highest annual energy (3.19*10^8 kWh), and a Power Tower plant in San Bernardino, CA, would produce the lowest annual energy (1.90*10^8 kWh).

Figure 9: Comparison of Parabolic Trough Energy Generation.

![Figure 9](image9.png)

Figure 9 shows the Annual Parabolic Trough energy generation for all 8 locations and 4, 8, and 12 storage hours. We can see that across every location besides Indiantown, FL, eight storage hours and 12 storage hours produce more energy than four storage hours. The locations with the highest energy generation are Kramer Junction (3.8*10^8 kWh at eight storage capacity hours) and Barstow (3.88*10^8 kWh at eight storage capacity hours.) Thus, we can conclude that the parabolic trough is best suited for locations with similar DNI values as Kramer Junction and Barstow and eight storage capacity hours. Because 8 and 12 storage hours produce similar energy levels, eight storage hours will be more cost-effective. The Parabolic Trough is most unsuitable for Indiantown, FL, with the highest amount of energy produced being 2.54*10^8 kWh.

Figure 10: Comparison of Linear Fresnel Annual Energy Generation.

![Figure 10](image10.png)

Figure 10 shows the Annual Linear Fresnel energy generation for all 8 locations and 4, 8, and 12 storage hours. We can see that across every site besides Indiantown, FL, eight storage hours and 12 storage hours produce more energy than four storage hours. The locations with the highest energy generation are Harper Lake (3.83*10^8 kWh at 8 and 12 storage capacity hours) and Kramer Junction (3.64*10^8 kWh at 8 and 12 storage capacity hours.) Thus, we can conclude that the Linear Fresnel is best suited for locations with similar DNI values as Kramer Junction and Harper Lake and eight storage capacity hours. Even though 12 storage hours produce more energy for some locations, eight storage hours will be more cost-effective. The Linear Fresnel is most unsuitable for Indiantown, FL, with the highest amount of energy produced being 2.41*10^8 kWh.
Figure 13 shows the Capacitor Factor (efficiency of a capacitor with a relationship to energy losses) for all the locations. Linear Fresnel for Harper Dry Lake, California, has the highest percentage of capacitor energy with a value of approximately 62%. At the same time, the Parabolic Trough consistently produced a capacitor factor while the Power Tower differed slightly in percentages.

Figure 14 shows the First Year kWh/kW for all the locations. Linear Fresnel for Harper Dry Lake, California, has the highest value in the first year, approximately 5700 kWh/kW, and the Power Tower system consistently produced the first-year value. At the same time, the Parabolic Trough fluctuated in value.

### Conclusion

Based on our data, we can conclude that the Power Tower system consistently produces the highest annual energy for 6 locations: Blythe, CA; Nye County, NV; Boulder City, NV; Indiantown, FL; Kramer Junction, CA; and Harper Lake, CA. However, the Power Tower system produces the lowest annual energy for San Bernardino, CA, and Barstow, CA. Thus, for these two locations, it would be advisable to use a Linear Fresnel or Parabolic Trough model instead. We also found that 8-12 storage hours produce consistently higher energy levels than four storage hours. This is because storage hours allow energy to be used during the night or times when the sun is not out, meaning that more energy is produced to allow for this to happen.

We can also apply our results to other locations with similar DNI values. Thus, our research does not only apply to these locations but to locations all across the world. This paper could help future researchers develop in-depth studies about concentrated solar power plants and learn about the variability between various Concentrated Solar Power technologies.

### References

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Author
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