UNIVERSITY OF SOUTH FLORIDA

Group-5 Final Report

Design of 20 MW Concentrating Solar Power Plant in Santa Clara, Utah

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COURSE: Design of Solar Power Plants

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1. CAVEAT

The design presented in this report is based on preliminary assumptions and calculations using available data and industry-standard design tools. The accuracy of these assumptions and calculations depends on the quality of the input data and the validity of the underlying assumptions. Any changes to the input data or assumptions could result in significant changes to the design and performance of the proposed plant. Additionally, the cost estimates provided are based on current market conditions and may be subject to change due to unforeseen circumstances such as changes in material costs or regulatory requirements. Finally, the design presented in this report does not include a full set of engineering drawings and specifications, which would require further development and review by qualified engineers.

2. PURPOSE

The purpose of this report is to present a notional design for a 20 MW electrical concentrating solar power (CSP) plant in Cedar City, Utah. The report covers the process of selecting various components and layouts for the plant based on the available products and technologies in the market.

The design includes modeling of the solar collection and thermal plant system utilizing IPSE-GO and SAM software packages. Other design work including land selection, site ready preparation, electrical interconnect, security, and other supporting systems are also included. The report also evaluates the financial parameters of the project such as PPA price, IRR target, analysis period, tax rates, and insurance rates to assess the project's financial feasibility. However, this is a notional design and a complete set of engineering drawings and specifications, sealed and signed by a Registered Professional Engineer, would be required for the final implementation of the project.

3. DESIGN CONSTRAINTS

The following design constraints were established for the Cedar City Utah CSP project:

- 20 MW Electrical Power Output
- Concentrating Solar Power Technology
- Currently available technologies and systems, including a thermal storage capacity of 6 hours and approximately 1,762 heliostats for the plant at a cost of $2.5M USD.

4. REQUIREMENTS

The plant must be designed and built in accordance with all applicable local, state, and federal regulations and codes, including but not limited to building codes, electrical codes, fire codes, environmental regulations, and worker safety standards. All relevant permissions and approvals must be obtained prior to the plant's construction and operation. The plant must also be planned and built to meet or exceed industry best practices and standards for CSP technology, such as those established by the American Society of Mechanical Engineers, the Institute of Electrical and Electronic Engineers, and the National Fire Protection Association. All components and materials used in the plant must be of high quality and durability and must be chosen based on their ability to endure the project site's extreme climatic conditions. The plant must also be constructed with enough redundancy and backup systems to ensure reliable and continuous operation, as well as being easily maintenance and serviceable to save downtime and repair costs. References can be found below in table 1.

Source	Description
ASME	American Society of Mechanical Engineers - PTC (Performance Test Codes) for Thermal Plants, Mechanical, CSP, and Thermal Standards
IEEE	Institute of Electrical and Electronic Engineers - Electrical Standards and Interconnect
NFPA NEC	National Fire Protection Association, National Electric Code for safety
UL	Underwriters Laboratory for safety and certification of electrical equipment

Table 1: Engineering Codes and Standards

5. SOLAR RADIATION

In our project, it is important to consider solar radiation as CSP systems require direct sunlight to function. The location for our plant was chosen based on its direct normal irradiance which is in the range of 6.76 kWh/m2/day. To optimize efficiency while keeping costs in mind, we will be using 95% of the total direct normal irradiance which yields 950W/m2. We have also analyzed the beam irradiance by hours and months, as shown in Figure 1 and Figure 2 respectively.

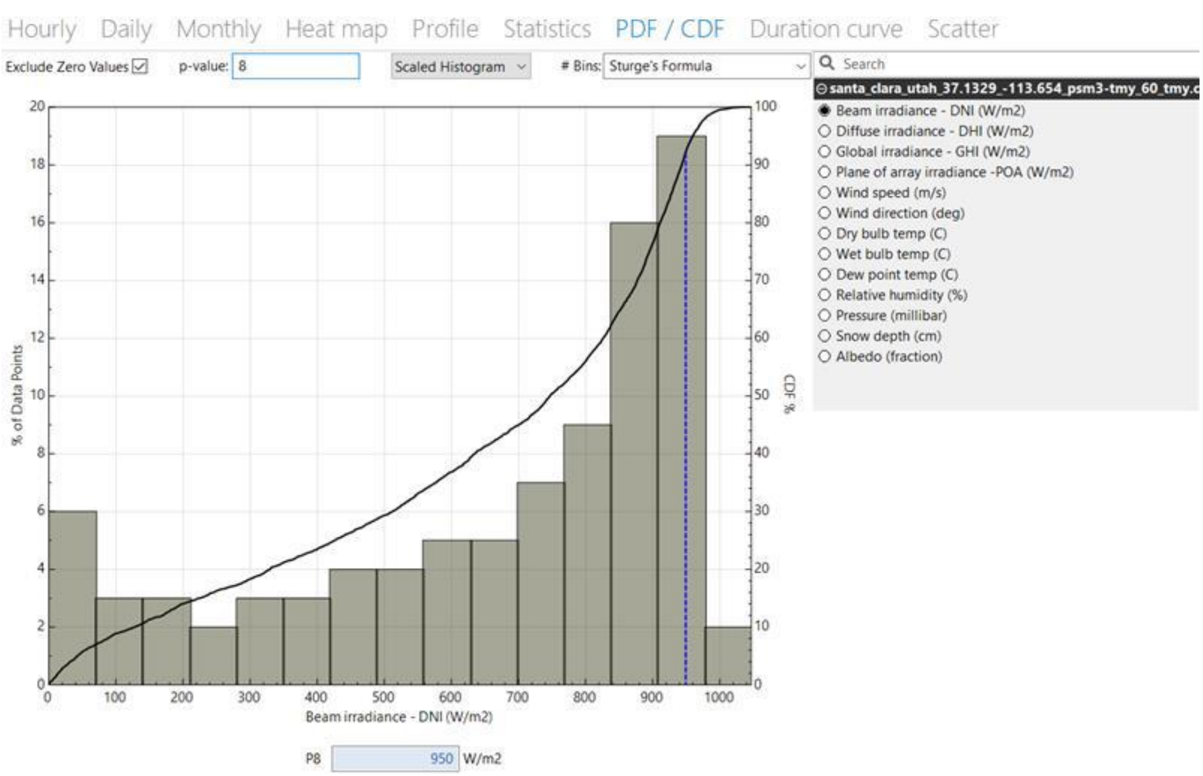


Figure 1: Solar Radiation in Santa Clara, Utah

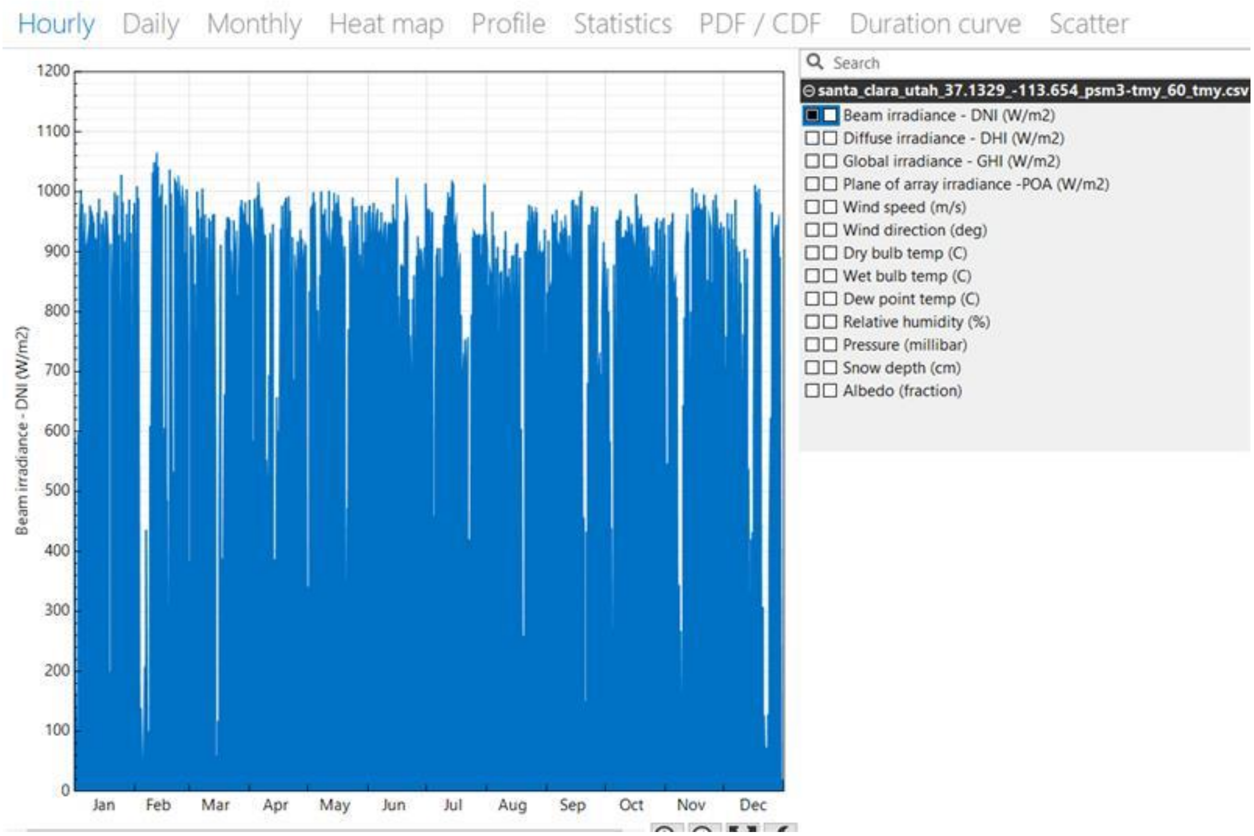


Figure 2: Beam Irradiance DNI (W per sq. meters), Monthly

6. SITE READY

This portion of the report is used to list out the prototypes for marking the readiness of CSP plant to be constructed. It depends on number of factors such as selection and availability of land, procurement, legal documentation, resource analysis, region analysis for weather and environmental conditions, preparation of site including security measures for safe and efficient construction of a CSP Plant. The following is the detailed report on site readiness for constructing a CSP plant in Utah.

6.1 Search Criteria

This step is to layout the requirements of a CSP plant in terms of land usage and resource availability. To build a Concentrating solar power facility, the primary criteria is to research about the availability and physical conditions of land, surrounding environment, water and solar resources availability, regulatory rules, and land area. We have analyzed several regions in Utah with the above-mentioned criteria and decided to go with Santa Clara in Utah as it meets all the demands. The project needs 419 acres of land for installation and setup of CSP in Utah operating at 6 hours of storage to produce 20 MW net electrical output.

6.2 Land Selection

The land for constructing the CSP plant in Santa Clara, Utah was found using the following search criteria.

- 420 and above acres of vacant land with hard soil.
- Electric Substation and water resource at minimum distance.
- Low cost of operation and maintenance with suitable regional zoning.

Since solar radiation was the same in all regions of Utah with minute variations, we selected three regions from Utah of above plot size and evaluated for all the criteria to best match the requirements as shown in figure 3. They were,

- Castle valley: It was suitable land with nearby water resource as castle creek river, but the nearest electric substation was 213 miles away.
- Cedar City: Land was available at cheaper rate of 1500 USD per acre, but there was no water resource in near facility.
- Santa Clara: This was the most efficient land at 2000 USD per acre with a running water source at 3 miles namely, Santa Clara River and electric substation unit at 23.2 miles which is hurricane electric substation.

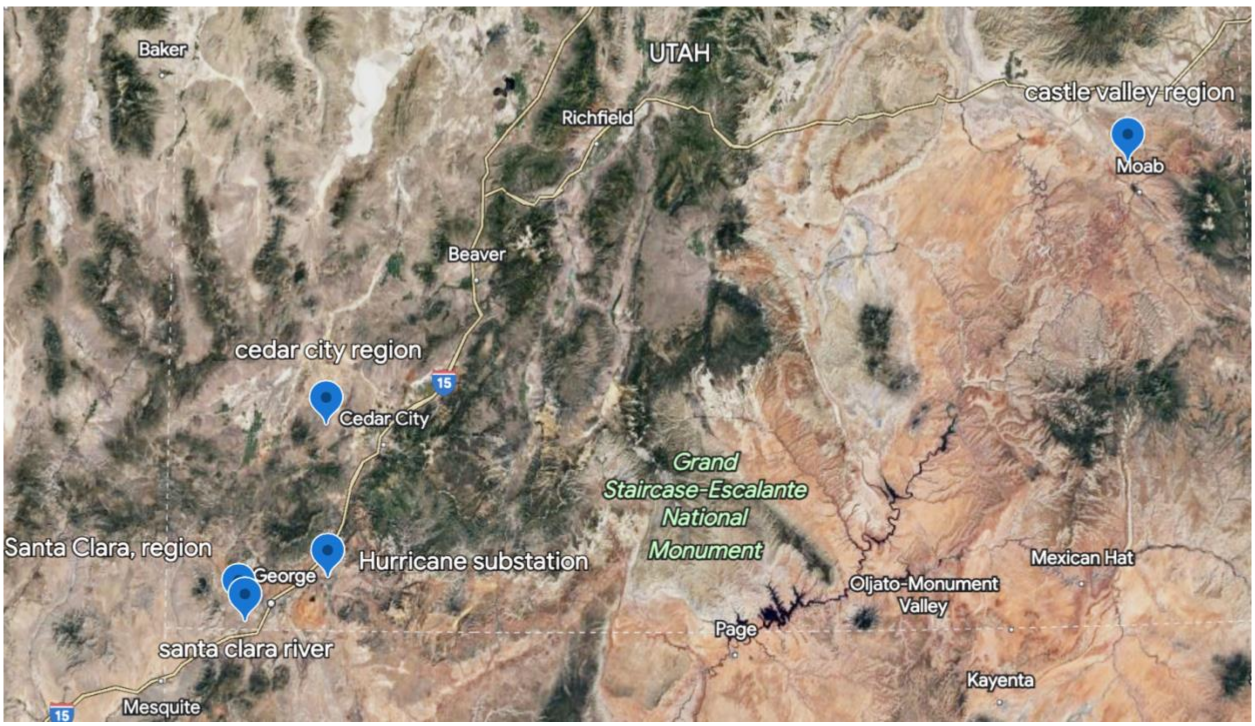


Figure 3: Plot for land investigation

6.3 Utility Connection

Connecting the 20MW CSP plant to the nearest electric substation utility is a tedious task. The nearest utility is the Hurricane Substation unit, 23.3 miles away from the solar facility. The electrical energy is supplied using overhead transmission gridlines operated at 345kV to carry 20MW of electric power to the utility. We reviewed different specifications of gridlines like single circuit, double circuit, and power ratings to carry 20MW power, however we've selected 345kV since that is suitable for our CSP Plant specifications.

Figure 4: Hurricane Electric Substation or utility.

6.4 Electrical System

For readiness of the CSP plant for construction in terms of electric system, it is necessary to list out the considerations for all the equipment components, specifications and schematic layout for power generation and distribution.

6.4.1 One Line Diagram

One line diagram is a schematic representation of interconnection of all the components in a CSP plant. This gives an overview or visual representation of floor plan for CSP plant electrical system design including solar fields, power blocks, heat exchangers, turbine generators, transmission gridlines and protection devices. The 21.6 MWA ABB steam turbine generator produces 13.8KV that is connected to a single circuit highly efficient transmission line of 345KV voltage ratings using step up and step-down transformers to distribute the power to utilities. The transmission lines are integrated with breakers and disconnectors to prevent wear and tear of electrical device for heavy voltage operations. One line diagram for our plant is shown in figure 5.

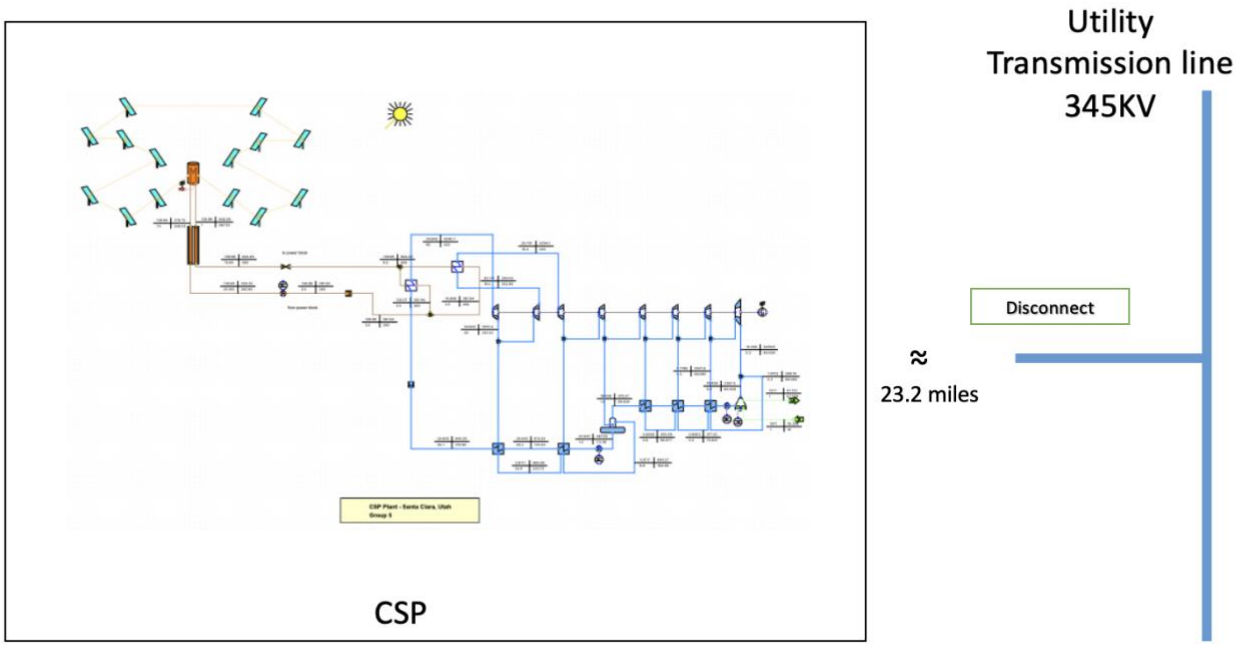


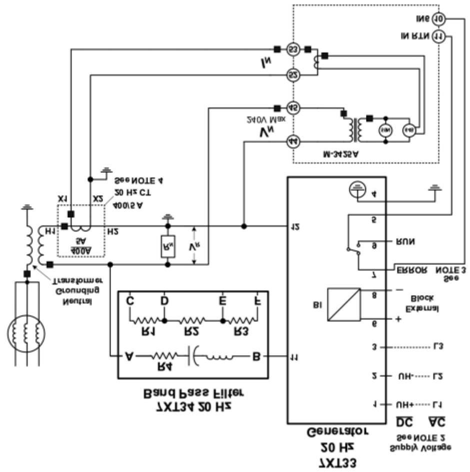
Figure 5: One Line Diagram.

6.4.2 Protection & Metering

Protection and metering in the CSP plant is important for maintaining safety and security of electric systems according to NEC and NFPA electrical code standards that include providing necessary insulation to electric components, earthing and grounding of power devices, placing surge protection for high energy production devices due to environmental disasters, placing metering or output measuring devices to record performance of each component to analyze and monitor the behavior of electrical components in near future. It includes,

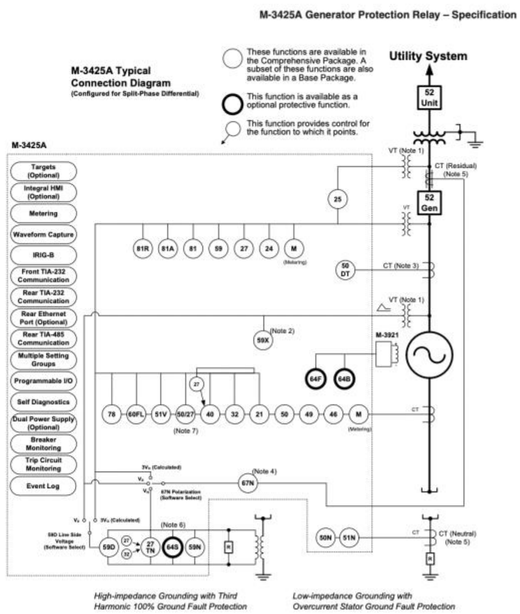
- Antistatic floors and grounding cords for electrostatic discharge of electrical devices.
- Surge protection devices like surge arrestors and voltage regulators to minimize the outburst of power generation due to sudden rise in solar radiation due to environmental constraints like lightening, heat waves, etc.
- Relays and generator protectors for safeguarding the transformers and generators.

The circuit diagram for relay and generator protectors are visualized in figure 6 and figure 7 respectively.



The schematic of relay circuit to protect transformers and generators.

Figure 6: Relay Circuit.



The schematic of generator protection device used in CSP plant.

Figure 7: Generator protector circuit.

6.5 Network

Switches, routers that are used and other kinds of network devices are frequently used in a CSP plant's network infrastructure to ensure dependable and secure connections among the various systems and parts of the plant. To safeguard the plant's data and systems from illegal access or assault, the network may also incorporate devices such as firewalls, intrusion-detection systems, along with additional security measures.
In every power plant there are some sub networks which have their own network connections to protect and monitor the plants. They are:

- Monitoring and Data Acquisition Network
- Control Network
- Communication Network
- IT Network

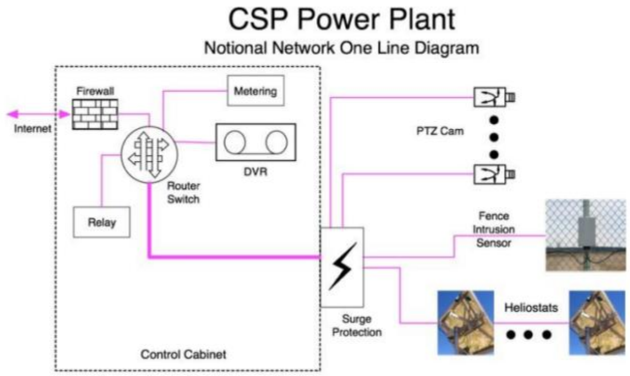


Figure 8: Network Diagram.

6.6 Land Ready

When a location is deemed to have been declared "land ready," additional development can be accomplished with the development and building of the CSP plant. There are some factors to be evaluated during the assessment of land readiness as listed below.

6.6.1 Infrastructure

It could be essential to carry out feasibility examinations, assessments of environmental impact, and other studies to analyze the viability of developing an CSP plant in the region in order to make sure that the infrastructural needs are satisfied. There are some of the requirements to plan for a power plant, they are mainly power transmission, water supply, communication network and the accessibility for the roads.

6.6.2 Soil Characteristics

For a CSP plant, it would be ideal if the type of soil had adequate load-bearing ability and drain. The Santa Clara area's typical sandy loam substrates offer strong absorption characteristics and may be appropriate for various sorts of building projects. To establish whether a particular soil is suitable for a CSP plant, its unique properties, such as its compactness, strength against shear, and bearing capacity, must first be assessed.
The land is located near to the river of Santa Clara River, and which has a good characteristic is suitable for the high capacity of the projects.

Figure 9: Land for CSP plant in Santa Clara, Utah

Total land required for the CSP plant is 420 acres. The rest of the land will be used for the Power tower and molten salt tank for storage purposes.

6.6.3 Environmental Hazard

There are some environmental factors which are to be considered during the selection for the Land criteria, they are wind, water, temperature, dust and Health and safety factors. Studies of environmental impact and other research may also be required to examine the possible effects of installing a CSP plant on the neighborhood ecology and to choose the most effective mitigation strategies.

6.6.4 Weather

The average temperatures shown below were calculated using information from the closest official meteorological station. The closest weather station, which is also used to measure temperature and precipitation, is situated 2,770 feet above sea level and is about 11 miles distant.

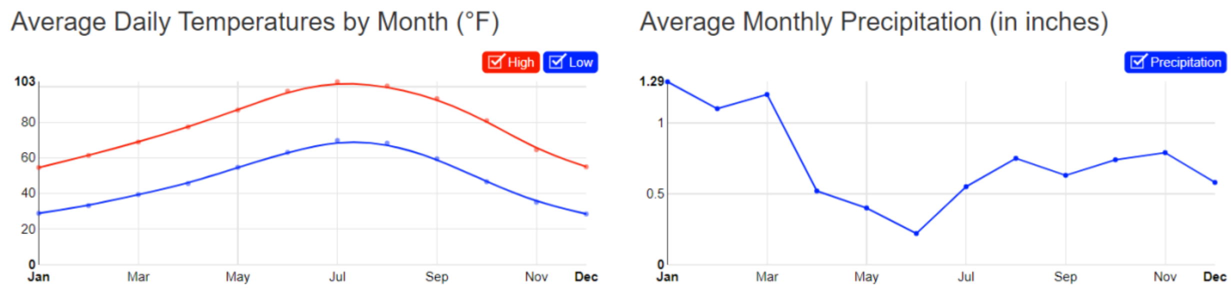


Figure 10: weather data representation in Santa Clara, Utah.

Santa Clara is a city in the southwest of the United States. It has a desert environment with scorching summers and moderate winters. Santa Clara experiences frequent highs of 100°F (38°C) throughout the summer, in addition to low humidity levels and lots of sunlight. However, Santa Clara's wintertime low temperatures, along with sporadic snowfall and other weather-related events, can influence a CSP plant's ability to run.
A CSP facility in Santa Clara may combine several design elements, including as automatic maintenance systems, climate-resistant materials, and cutting-edge conditioning technologies, to ensure maximum effectiveness and productivity in a range of weather situations.

6.6.5 Topography

Santa Clara's landscape is distinguished by a combination of flat and undulating terrain, with some parts having steep slopes and canyons. For the installation of the plant's bases of support and to guarantee the security of the solar energy field, the CSP installation site typically must be largely level.

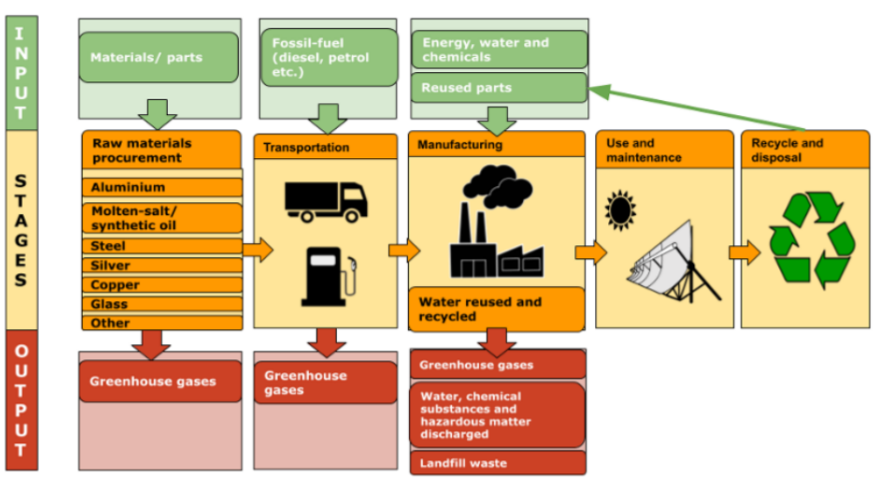


Figure 11:Topography for the CSP Plant.

6.6.6 Solar Resources

An area with an abundance of solar resources surrounds Santa Clara, Utah, making it an ideal spot building Concentrated Solar Power (CSP) facility. Heliostats are employed in solar power tower architecture to focus the sun's rays into a tiny region, creating heat that may be converted into steam and energy.

Direct normal irradiance, which gauges how much solar energy strikes an object that is orthogonal to the sun's beams, is received by Santa Clara averagely at about 7.61 Kilowatt-hour (kWh) per square meter per day (kWh/m2/day).

The low frequency of foggy or gloomy days, which might lower the quantity of solar energy that is accessible for gathering, is another advantage of Santa Clara. Due to its excellent solar conditions, Santa Clara has attracted numerous large-scale CSP projects that can be established.

6.7 Engineering & Permits

It is an essential factor when coordinating the designs for approvals and connections. There are some engineering aspects for the site preparation, solar power tower, heliostat field, storage tanks for the molten salt as heat transfer fluid and the power block. Some of the engineering aspects are site, structural, electrical, and mechanical for the drawings and submitting the application with environmental, construction and land use permitting.

6.8 Build Ready

A site's ability to be "build ready" is crucial because it enables the building process to go quickly and effectively, reducing delays and guaranteeing that the work can be finished on time and under budget. The site is prepared to support both the construction and the operation of this CSP plant, and developers may be certain that its construction will be considered a success by taking all the required procedures to attain "build ready" status.

7. ITERATIE DESIGN

The CSP plant's iterative design procedure generally entails several phases. A theoretical design is first produced, outlining the fundamental specifications of the facility, including its overall dimensions, capacity, and area. Then several types of tests are performed on this design, which might include measurements in the field, simulations on computers, or model construction.

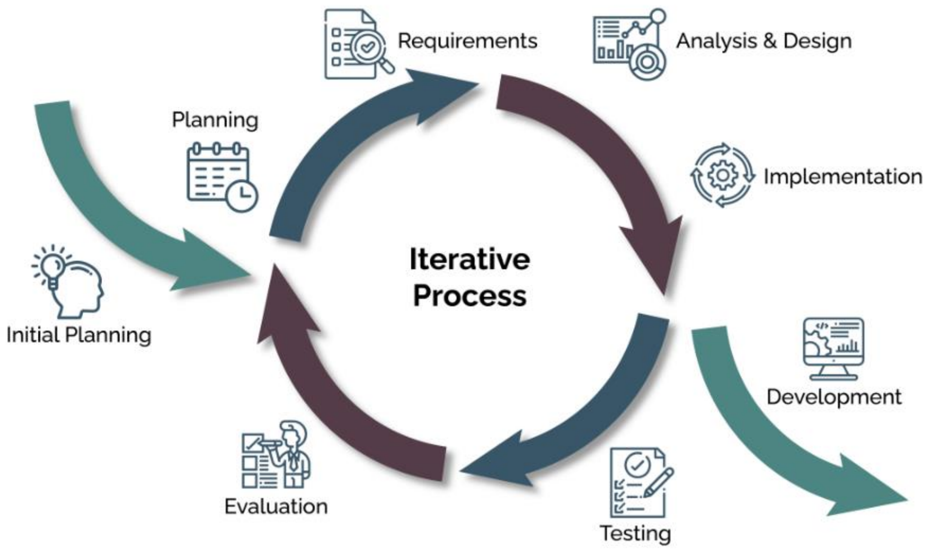


Figure 12: Iterative Design diagram.

Designers often start this process by thinking through a variety of possible design possibilities for implementing the plant, taking into consideration the unique site characteristics, available technology, and other pertinent aspects. They should be mainly focus on the primary selection of

- Power tower
- Solar Receiver
- Heliostats
- Type of heat transfer fluid
- Storage hours

8. SYSTEM DESIGN

8.1 Design Parameters

8.1.1 DNI selection

There are some criteria to select the DNI measurements they are Elevation, Climate, Land cover, Time of year, Data availability.
Santa Clara experiences scorching summers and mild winters due to its wilderness environment. DNI is the unit of solar energy received by a surface that is constantly at a right angle with the sun's beams. The sun's location in the sky at any particular time determines the direction of the rays. For this project, the Design point DNI is 950 W/m^2.
According to solar radiation historical data of 84765 they are always tilted against the latitude of Santa Clara would receive 7.62 kWh/m^2/Day which is the highest place of recording highest DNI in Utah. The amount of Solar radiation is normally at its maximum during the summer months of June to August, while it is at its lowest radiation levels during the winter months of December to February.

8.1.2 Solar Multiple and Hours of Storage

The Solar Multiple is the ratio of a Concentrated Solar Power (CSP) plant's installed capacity to the capacity it could generate if it were running continuously at its maximum output. For this project, the solar multiple is 2.4, Adequate power generation for storage purposes would be achieved with this Solar Multiple. The full load hours of Thermal storage are 6 hours and the solar field hours of storage is 2.50 hours. One may determine whether the Solar Multiple is sufficient for producing the required power for storage by performing a parametric evaluation of it for the particular site.

8.1.3 Fluid Properties

For the aim of collecting primarily focused solar radiation and then transmitting the resultant heat towards the power generating process, a fluid that transfers heat is frequently used as the principal fluid in a CSP system.
Molten Salt is used for transferring heat and storing thermal energy. It is the most commonly used fluid for the CSP power plants because of its properties like High boiling point and heat capacity, Low vapor pressure, Non-Corrosive and Non-toxic.

- The HTF type used in this Salt (60% $NaNO_3$ 40%KNO_3).
- The maximum flow rate to receiver is 432.15kg/s.
- The Design HTF velocity in receiver tube is 3.102 m/s.
- The hot and cold temperature of HTF cycle was set to be 560°C and 290°C.

8.1.4 Power Cycle parameters

Depending on the kind of cycle employed in the power plants, the power cycle's parameters will change. We utilized the Rankine power cycle in this CSP facility. The blowdown fraction of a steam cycle is 0.02, and the turbine input pressure is controlled by a fixed pressure type. We employ surface condenser technology for cooling, and the Santa Clara River, which is located two miles from the power plant, provides the cooling water. The mass flow rate of Heat Transfer Fluid is 150.1 kg/s and pump power are 0.083 Mwe.

8.1.5 Thermal cycle parameters

The thermal cycle power is 61 MWt with 6 hours of storage. In this thermal storage consists of two tanks for heating and cooling the fluid. The following table gives the details and capacity of the tanks.

Thermal Energy Storage	366 M Wt-hr
Total HTF volume	1950 m^3
HTF volume in this plant	1788 m^3
Total tank height	12 m
Cold tank heating capacity	15 MWe
Hot tank heating capacity	30 MWe
HTF density	1813 kg/m^3

Table 2: Thermal Cycle Parameters.

8.2 Tower Cycle

8.2.1 Heliostat Field Layout

The figure displays the final configuration of the heliostat field seen in Fig. 1762 which includes heliostats with an area of 144.37 sq. meters and dimensions of 12.2 m in height and 12.2 m in width. An 8-degree angle is used for each heliostat since the wind speed is 15 m/s. The entire amount of land needed for the 1762 heliostats, with a total reflecting area of 2,54,388.4 sq. meters, is 45 acres. The maximum and minimum distance from the heliostats to tower is 68 meters and 863 meters.

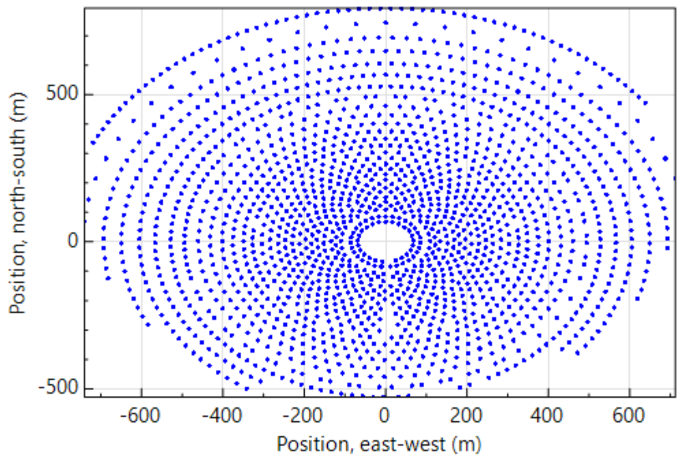


Figure 13: Heliostat Layout from SAM.

8.2.2 Tower and Receiver Dimensions

The tower and receiver's measurements, as determined by SAM, are listed in the following table.

Components	Dimension
Tower height	90.8 m
Receiver height	9 m
Receiver area	212.28 m^2

Table 3: Receiver and Tower dimensions.

8.2.3 Pumps and Auxiliary power

According to SAM, the pumping power for HTF through power block is 0.55kW/kg/s. In this project an 83 KW power pump is required to pump the HTF to the receiver. A temperature above 290^0C is required to heat the fluid.

8.3 Power Cycle

Solar energy is utilized in a power tower CSP plant's power cycle to warm a working fluid, usually molten salt, this is subsequently utilized to produce steam and drive a turbine. Solar field, Heat transfer system, Steam turbine, Condenser, and cooling system are the components of power cycle.
The primary elements that set it apart from other CSP systems are the solar field and heat transmission mechanism. The sun's beams are precisely focused on the main receiver thanks to the computer system that manages the heliostats. Molten salt is frequently used as the working fluid in a power tower CSP plant because it has a high specific heat capacity and can retain heat for a long time. This makes it possible for the plant to produce power even when the sun is not out.

8.3.1 Condenser

In this CSP plant, hybrid type condenser is used as the type of cooling system it combines both wet and dry cooling. Water is sprayed over a heat exchanger by the wet cooling tower to cool them. The heat that the water takes from the process fluid as it evaporates cools and condenses the vapor, converting it back into liquid. In order to remove heat, the dry cooling system circulates air across the heat exchanger. Wet cooling is more effective, but this method is more ecologically friendly and uses little to no water.
When temperatures are high, such as during the summer when the air is hot and there is plenty of water available, a hybrid condenser uses a wet cooling tower. The dry cooling system is employed in the cooler months because of how much more effective it is with the lower ambient temperature and increased humidity. With this strategy, water usage is decreased without sacrificing performance or effectiveness.
The hot temperature of HTF is 560^0C and the cold temperature is 290^0C.

8.3.2 Pumps

A CSP plant's power cycle depends heavily on pumps since they move the heat transfer fluid across the entire system. The function of the pumps is to transfer the fluid from the thermal energy storage to the solar field for heating, and then to the power block where the heat energy is utilized to produce electrical energy. The condensed water was pushed by the feed water pumps between 0.08 bar and 1 bar. This enabled the de-aerator, which combined output steam and condensed water at 1 bar, to operate at equal pressure. Condensed and recycled water were pumped at pressures between 1 bar and 100 bar using high pressure pumps.
The feed water pump used in the plant has a capacity of 83KW.

8.4 Final System Specifications

The below table shows the final specifications of 20MW CSP plant, which are main parameters and required for plant.

Estimated net output	19.68MW
Cycle thermal efficiency	35%
Cycle thermal power	61 MWt
Solar multiple	2.4
Hours of storage	6
Heat transfer fluid type and flow rate	Molten salt & 150.1kg/s
Operating temperature range	290^0C to 560^0C
Total land area	419 acres
Number of heliostats	1762
Land required for Heliostats	45
Tower height	90.8 m
Receiver height	9 m

Table 4: Final System Specification.

9. NOTIONAL WORK BREAKDOWN STRUCTURE

At the beginning of project established, an organization will list out all the business actions and or requirements to be carryout out throughout the project starting from research and development, design, procurement, permissions, implementation, and maintenance. A Notional work breakdown structure, also known as WBS gives the structural blueprint of all the action items in scope for the establishment of CSP solar facility. It happens during the planning stage to estimate the unforeseen situations, risks in the location, plan budget and divide the workload equally between capable team members to proceed with a flawless business operation. Once the NWBS is laid out, it is sent to the superior management for review and approval.

In specific to our concentrating solar facility in Utah, we have listed out few elements as the work breakdown structure of highest priority.

9.1 Project Management

9.1.1 Administration

The administration process takes care of initial plan and monitor action of a CSP project. It is initially carried out by research and development team to gather and estimate all the project requirements along with action plan which includes, project plan, recruiting knowledge workers, sourcing funds, operational risk management, documentations supporting government regulations, Plant and Insurance, Quality assurance and inspection.

9.1.2 Systems Engineering

All the electrical systems involved in the solar project are designed, estimated, and tested to meet plant requirements. System engineers are hired to design and develop an efficient design by laying out all the equipment(s) and showing necessary connection between them. They are also responsible for validating the functions and working operations of an equipment and perform end to end testing in compliance with the design requirements and maintain a report for future use. It is crucial because it acts as a key factor for the successful operation of the plant.

9.1.3 Project Control

Control engineers are hired to design, develop, and maintain strong plans to carry out the operations in our solar facility. They are responsible for monitoring and controlling the progress of project, conducting regular inspection plans on the systems for efficient operations on periodic basis and maintain supporting reports for further use and analysis of the project expectancy.

9.1.4 Configuration Management

The configuration team keeps records of day-to-day operations of the solar facility by making notes of all the hardware's physical condition, identifying, and reporting all the physical damage they see in the solar facility to respective operating team. This includes wear and tear of devices, breakdown in electrical connections, inefficient performance from any device that might need some engineering to be done.

9.1.5 Quality assurance and control

QAE and QC engineers are responsible for laying out plans to inspect the high-quality standards, working conditions, issues related to quality of a device being purchased, maintain government standards and regulations such as ISO, IS009 standard protocol of quality for safety. They conduct regular vendor audits, inspect their supplies, negotiate, and align it with our company's budget. All the quality related issues of a device that we use in our plant, be it flat mirror reflectors, transmission lines, clamps to hold equipment are all tested and analyzed for issues by the QAC team along with proper documentation.

9.1.6 Finance

The Finance team is responsible for proposing the project plan to major funding organizations like banks and investors to find financial sources for funding the operation. They are responsible for researching the local taxes and incentives in our region and propose a bidding loan or debt estimate to investors. On the other hand, they conduct various financial strategies and perform data analysis on the performance and revenue of the plant to forecast and maximize the returns of the project to both investors and developers.

9.2 System Design

9.2.1 System Parameters

Analysts and configuration engineers are hired to use the information from the research team and configure the system parameters of each device at which they must be operated. This includes the configurations like the temperature at which the hot and cold tanks are operated, the angle at which reflectors are installed, chemical composition of salts used, optimization and improvements for design of balance of plant, power block and solar field.

9.2.2 Requirement capture

This process includes researching, identifying, and documenting all the needs and expectations of the solar field which is used by other engineers to bring them into action. According to the weather data of Santa Clara, Utah, research engineers estimate the type of energy to be used, range of sustainability of equipment under the region environmental constraints and considering meeting global safety and regulatory needs. For our design, the analysis is performed on the following units and requirements are gathered which acts as a sturdy foundation of the overall design.

9.2.2.1 Heliostats

Flat mirror reflectors to collect the solar radiation and reflect to receiver.

9.2.2.2 Tower and collector

Manage to determine the appropriate height and size of tower to hold the receiver. A receiver's requirements include aperture and focal length for not missing out any reflected solar radiation from the heliostats.

9.2.2.3 Heat Transfer System

Specifies the type of fluid used for transferring heat waves from the receiver. Molten salt is used as a heat transfer fluid.

9.2.2.4 Thermal Transfer System

Water Cooling system is used adjacent to a heat exchanger, here the hot fluid from the receiver system is passed on to a heat exchanger that converts heat to steam in downstream that drives the steam turbine and generates electricity.

9.2.2.5 Electrical System

The steam that runs the steam turbine generates electricity though generator. As mentioned, we use a 19.5 MW three phase condensing steam turbine generator from ABB to drive electric energy from the solar energy input.

9.2.3 High level architecture

A prominent level of system architecture was constructed through IPSE-GO software where we could list out all the electrical and mechanical components, make necessary connections and simulate to see the performance of the analytical model. Below is the pictorial representation of CSP farm in Santa Clara, Utah.

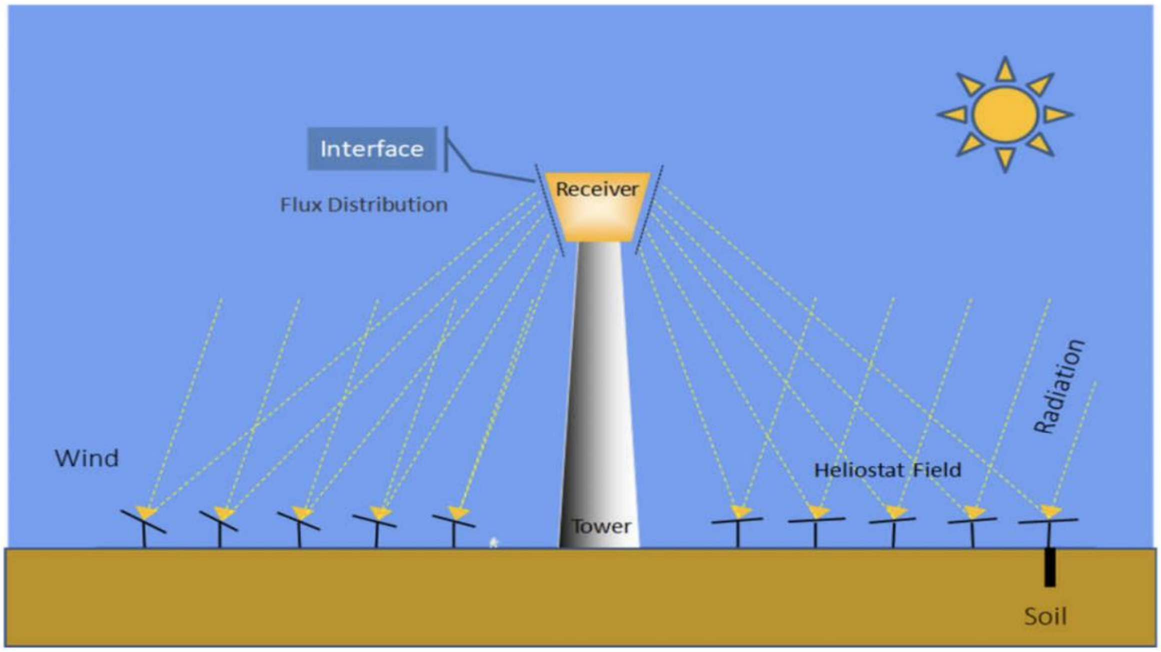


Figure 14: Solar Unit Architecture.

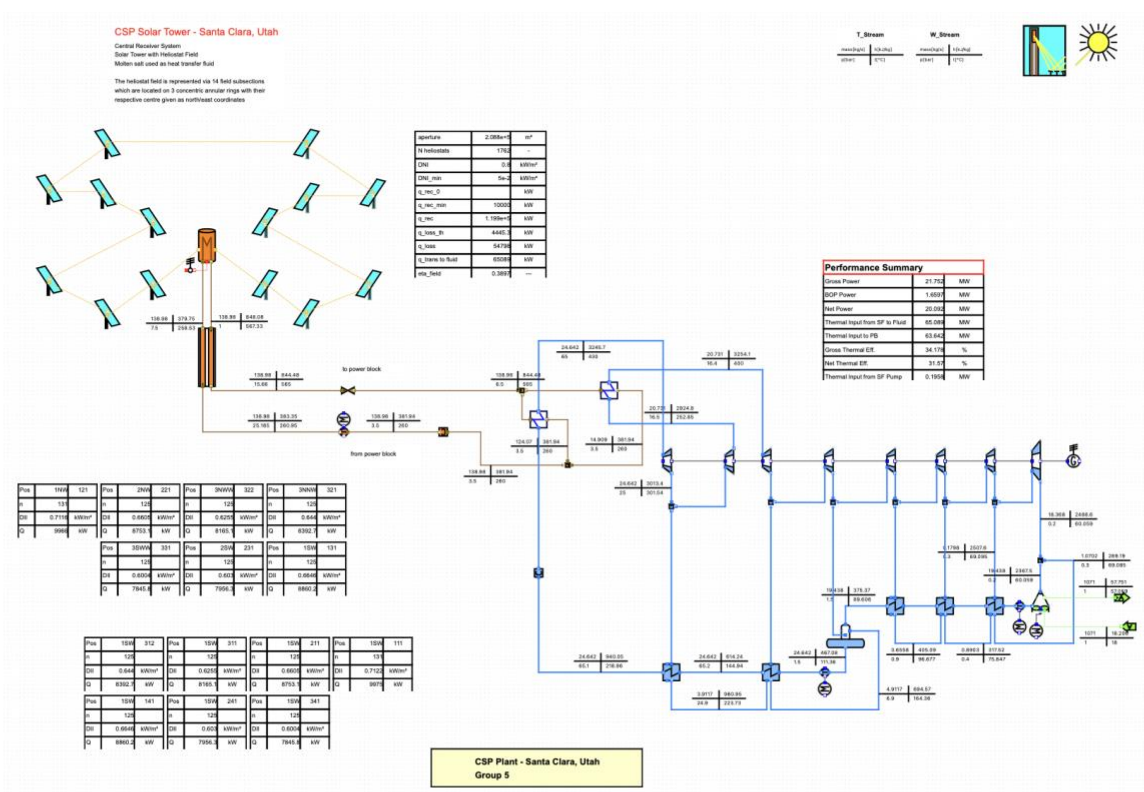


Figure 15: IPSE-GO Model design for CSP plant.

9.3 Subsystem design

As mentioned in the system design block of notional work breakdown structure, along with electrical and mechanical design, civil engineers, technicians, analysts contribute to layout the design by installing equipment and making necessary electrical connections between them. These include consistently testing the capability of the land, estimating resources, and laying out the ground plan & design for infrastructure for office, amenities, tool storage rooms, etc. with detailed specifications and component selection.

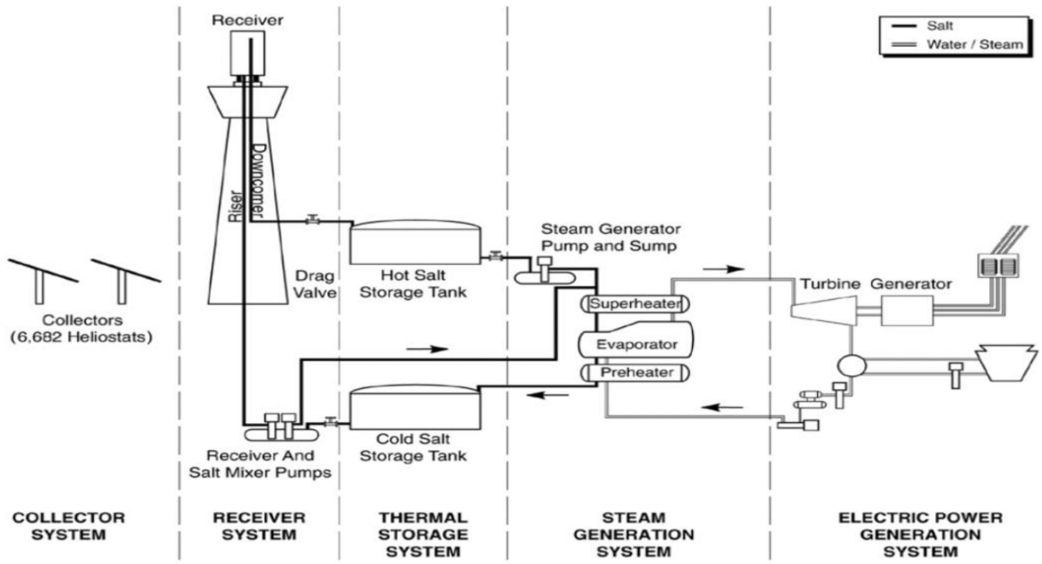


Figure 16: Process overview of CP Plant.

Below are areas in which subsystem engineering is deployed.

9.3.1 Civil Engineering

- Location, Site survey & inspection.
- Ground plan and component selection for supporting electrical and mechanical devices.

9.3.2 Electrical and Mechanical Engineering

- Heliostats, Tower, Receiver, Steam turbine Generator.
- Heat transfer system, Heat Exchanger, Type of Fluid.
- Thermal system.
- Gridlines, Utility interconnect, Type of connection to electric substation.
- Installation specification and plans.

9.3.3 Data Engineering/ Analysts

- Security.
- Bill of Material estimate.
- Data ingestion and analysis.

9.4 Bill of Materials

Bill of Materials (BOM) gives a list of each component used in a CSP plant. This document serves as a base information for vendor or procurement engineers to buy all the electrical, mechanical, and civil components needed for a CSP plant. It is documented and used by vendors, finance analysts, control engineers and stakeholders.
We have listed a breakdown of all components under each domain.

9.4.1 Electrical

- Grounding and Interconnecting materials.
- Power protection devices.
- Switch gears.
- Power transformers, transmission cables.
- Heliostats.
- Receiver.

9.4.2 Mechanical

- Pumps.
- Condensers.
- Motors.
- Equalizers.
- Heat Exchangers.
- ABB Steam Turbine Generator.
- Valves and Insulators.
- Receiver Tubes.

9.4.3 Civil

- Raw materials for infrastructure such as concrete, steel, glass, etc.
- Boundary fencing for security systems.
- Sewage system accessories.
- Clamps and supporting components to hold major devices.
- Labors
- Transportation facilities for sourcing raw materials.

9.5 Permits & P.E Stamps

Before installing and operating a CSP Plant, the developer must get a license and approval from regulatory governing agencies in that region which can be referred to as Permits. This ensures the safety standards of the surrounding environment and species by establishing a CSP solar plant. This includes rights from regional water quality control boards, building and environment permits from Santa Clara County. All the project design and plans must be reviewed and approved by a licensed white collar professional engineer prior implementation focusing on connections, system design, parameters, and structure to run a safe, efficient, and reliable facility. The major components are as follows,

9.5.1 Stamped Engineering Drawings and Design

A Professional Engineer will review and stamp the system design, electrical design, mechanical design, civil construction plan of a CSP plant before implementation to meet renewable energy standards and code of ethics.

9.5.2 County

The regional county will provide approvals for building, environment, water, and land permit to ensure safe operation of the CSP plant.

9.5.3 Utility (Hurricane Sub-Station)

Collaborate with a utility and sign a power purchase agreement to sell the net energy generation in our CSP plant to an electric substation for commercial and industrial purposes. As mentioned earlier in the report, the nearest utility we have is the Hurricane Sub-Station located 23 miles from the facility.

9.6 Construction

Construction deals with all the physical activities taking place in a solar facility considering both building and maintaining the plant from scratch. This part of work breakdown structure gives information about plant location, infrastructure and equipment setup, construction of mounting support such as tanks, tower pillars, field fencing and office setup, etc. Following are the breakdown of major tasks associated with construction unit.

9.6.1 Equipment Procurement

Once the quality control engineer gets their vendor agreement reviewed and makes an order from the vendor and completes their quality inspection, it is the construction team who is responsible to store the raw materials and use it wisely for construction purposes.

9.6.2 Contractor selection

Engineers will get help from the technicians and builders to bring their project plans into action. Once the system design and infrastructure bule print is reviewed and stamped by professional engineers, the staffing teams look out for interviewing contractors for labors and technicians to support the construction activities in CSP Plant. It takes nearly 10% of the total budget for these operations.

9.6.3 Access Roads, Infrastructure Preparation & Safety

Construction of sewage systems, balance of plant, access roads, short term offices, health center, rest areas, foundation setup, infrastructure design implementation, clamp, and bolts to hold the equipment(s) are carried out in this stage as per safety and company standards.

9.6.4 Heliostats, Tower & Collector

Under the supervision of design and implementation engineer, technicians would place heliostats at desired angle and position with necessary cable collections as per the system parameters. The receiver tubes are embedded inside the tower and a receiver or collector is placed at the top of tower at 91 meters as per the system design.

9.6.5 Heat Transfer System

The construction of heat exchanger unit, heliostats, collector, tower, receiver tubes integration, molten salt composition, pumps and valves are constructed in this unit.

9.6.6 Thermal Storage System

Insulated large hot tank, cold tank and molten salt storage units, steam generation unit, condenser unit, and generator unit are placed by construction team as of Thermal storage system.

9.6.7 Utility Interconnect

Overhead transmission grid lines, supporting electric transformer, switchgears, control systems, insulation and grounding for HVAC power is constructed as part of utility interconnect.

9.6.8 Perimeter & Security

The construction unit is responsible for safeguarding the plant location with fencing and electrical supply to avoid trespassers along with security alarms and systems.

9.7 Verification & Acceptance

9.7.1 Test Plan

Verification engineers are hired to develop a step-by-step constructive test plan to check the reliability and working efficiency of all the components in terms of performance, technical specification, tolerances in compliance to design and safety standards.

9.7.2 Install Test

Once the installation set up is completed, the verification & test engineer will inspect all the equipment one after the other and document the proper placements of components as per the stamped design document.

9.7.3 Functional Verification

After the first plant cycle, engineers note down the output readings of every single component and then document, analyze, and compute the readings to check if the values align as per the functional testing results or performance results carried out in IPSE-GO software synthesis.

9.7.4 System acceptance

The performance of the plant is evaluated before accepting or rejecting the plant operation. It includes validating the reliability of the components, gross and net thermal energy output, gross and net electrical output from the generator, conversion factor, thermal efficiency, safety standards, monitoring the behavior of components.

9.7.5 Commissioning

The facility manager will review all the operating records and evaluate the results before declaring the plant to have commissioned and projected as per the approved system design by comparing the as built drawings to initial proposal.

9.8 Operator & Maintenance

9.8.1 Develop Training

Document all day-to-day operations, test cases, results, and working behavior of all the components to used it as training material or manuals for some other employee in the company to use for their reference and practices. In some cases, job training or knowledge training may be required to the maintenance people to effectively understand and show progress in work.

9.8.2 Operations

The components need to be tested every day for their physical condition and operations. The O&M team will develop tasks and plans to test and monitor the components periodically and generate reports to optimize issues due to physical damage.

9.8.3 Troubleshooting

Troubleshooting is crucial to prevent the operations in a CSP plant from stopping abruptly due to physical or technical issues. The main objective of this maintenance involves identifying the issue, isolating the region temporarily, developing an action plan, implementing the repair, test, and verify the correction before resuming general operations.

9.8.4 System administration

Since many people work in a megawatt solar facility, not everyone can perform every other operation. System administration specifies the job roles and responsibilities of a personnel regarding their position in terms of access, permission, configuration, installation, support, and maintenance as per administration procedures and policies.
System maintenance

9.9 System Turnover

Once the plant is built and installed with all the components, the project is ready for transition or in other words, it is ready from installation phase to operation phase and maintenance phase. At this stage, it is important to maintain proper documentation of all the working prospects, instructions to use, confluence to back up systems and verification of operations.

9.9.1 Manuals

It is the detailed step by step guide used to manually operate all the components when a new employee is joined for references. It has documents supporting test cases, scenarios, setup plan, quality standards and compliance to governing standards.

9.9.2 Certification & Warranty Support

Maintains all the document supporting permissions, permits, certification of operations, insurance agreements, sale deeds and assurance document for all components for prosed lifetime by the manufacturer.

10. SYSTEM COSTS

As mentioned earlier in the report, the system costs include all the direct costs like equipment procurement for thermal block, power block and distribution unit, and indirect costs like site ready, labor, financing, and construction. Main objective considered was to optimize the cost and improve the performance efficiency of CSP plant to produce 20MW power output. All the information or data gathered from research process were used to perform economic analysis for the following components of the field.

- Site ready.
- Solar field: Heliostats, tower, and receiver.
- Thermal Plant, Heat Transfer Fluid System & Storage tanks.
- Electrical systems
- Maintenance and operations.

The energy consumption of solar facility in Santa Clara, Utah over a year is mentioned in below heat map or figure 17.

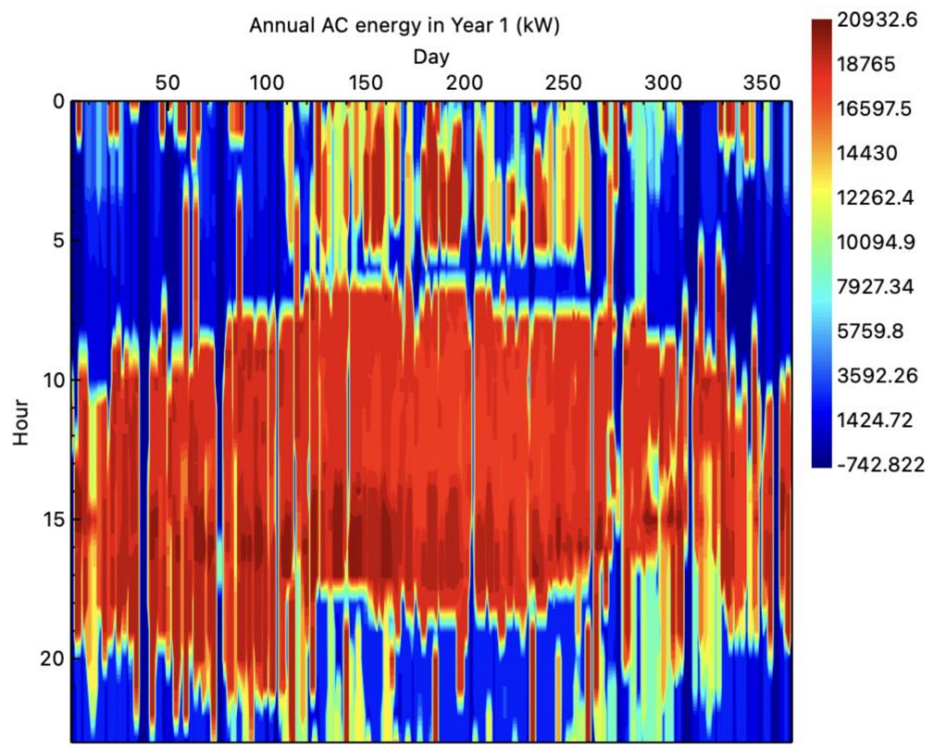


Figure 17: Energy Data in the plant.

10.1 Site Ready

Is comprised of indirect costs focusing on purchasing and preparing the land, producing engineering design for approval, and stamping from P.E, and outlining network & security system schematics, permits and associated fees to produce a Bill of Material of the CSP plant as detailed below.

Bill of Material	CSP in Santa Clara, Utah					
Item	Description		units	USD per unit	Net Cost	cost based on
Land Area						
1	Land		420 acres	2000	840000	Real estate records
2	Survey		1	2500	2500	government survey
					842500	Total
Border and security						
3	Site Fencing		5500 ft	21 per sqft	115500	Technician dealers
4	Gate		3	700	2100	Technician dealers
5	Sign Boards		85	15	1275	Technician dealers
					118875	Total
Permit and Stamps						
6	PE Stamp		1	200000	200000	government survey
7	Design Permit		1	27000	27000	government survey
					227000	Total
Surveillance and Safetly						
8	Camera pole		2	1500	3000	internet
9	camera		8	1210	9680	internet
10	DVR, ethernet switch & cables		4	1300	5200	internet
11	sensors		12	250	3000	internet
12	misc parts		34	10%	2100	internet
					22980	Total
				Total cost:	1211355	

Table 5: Site Ready Cost Estimates.

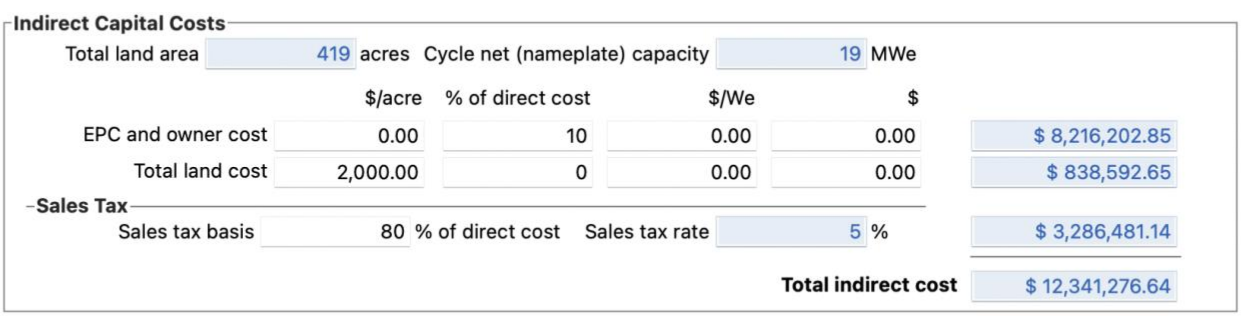


Figure 18: Indirect Capital Cost from SAM.

10.2 Solar field: Heliostats, Tower, and Receiver.

The energy source for a power plant is the solar energy that is collected using the flat mirror reflectors or heliostats and directed towards collector or a central receiver place at a certain height using towers. There are the direct costs for the plant and the figure below shows the detailed cost analysis for these components including labor, material, and taxes.

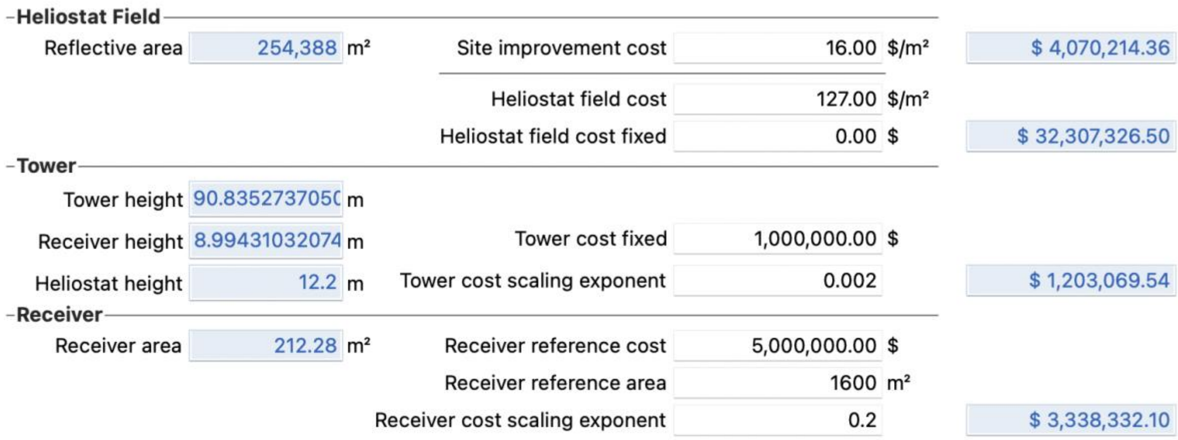


Figure 19: Direct Capital Cost from SAM.

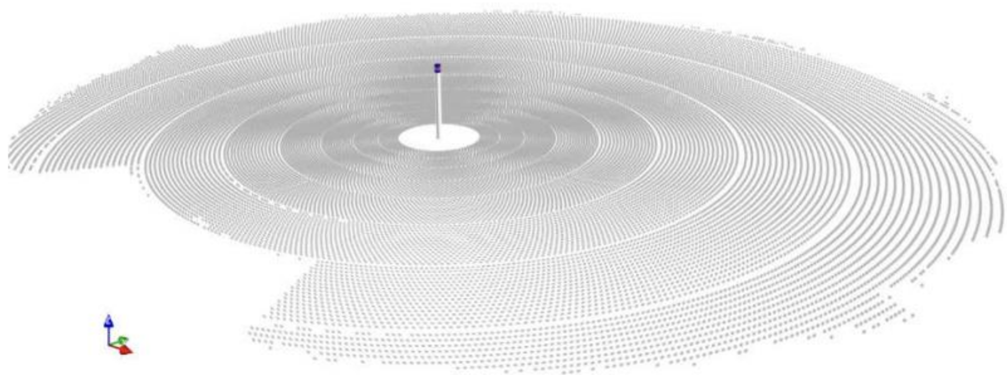


Figure 20: Heliostat Layout for placing 1762 units.

10.3 Thermal Plant, Heat Transfer Fluid System & Storage Tanks.

The thermal plant is operated at 6 hours of storage and the storage capacity of the tanks are 427 MWht. The cost associated with storing the thermal energy is estimated to be 22 USD per KWht as per the solar practice in Utah. Below figure 21 shows illustrated cost analysis of storage system.

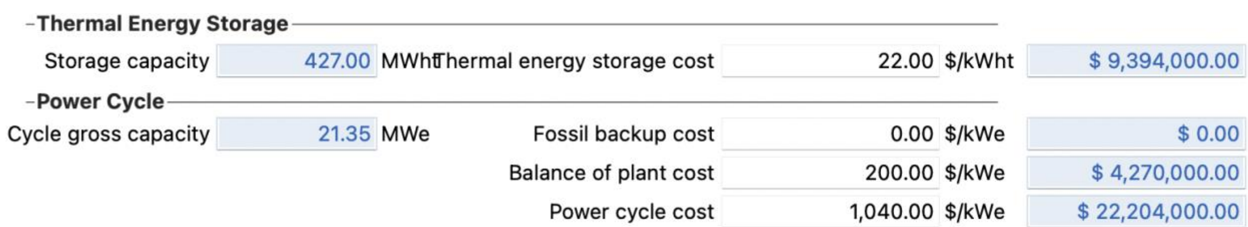


Figure 21: Thermal Storage Cost from SAM.

10.4 Electrical Systems

All the costs associated with electrical components of the CSP plant, and the distribution unit is mentioned in this section of the report. These include power block and utility components like steam turbine generator, switch gears, relays, breakers, protectors, transmission line and metering devices.

Transmission line Analysis.

Upon iterative research on capital costs for transmission line and generation estimates from trustworthy resources, we found WECC tool as the best practice for capital cost calculation for transmission lines as per the NREL ATB predictions for Utah.
We considered to use 345KV single circuit model our design at USD 1,434,290 per mile length. For our CSP plant, the nearest utility is 23.2 miles away and the capital cost for the transmission line procurement would come up to 33.275 million USD approximately.

Table 31: Per-mile Transmission Line Costs

Transmission Line Type	Per Mile Cost (2018$)
230 kV Single Circuit	$1,024,335
230 kV Double Circuit	$1,639,820
345 kV Single Circuit	$1,434,290
345 kV Double Circuit	$2,295,085
500 kV Single Circuit	$2,048,670
500 kV Double Circuit	$3,278,535

Figure 22: Transmission line calculations.

Electric Power Generator.

We decided to go with a used ABB three phase steam condensing turbine generator for our project. The capacity of the generator is 19.5MW AC output operated at 13.8KV and 60 Hz of frequency. The cost of this equipment is approximately $1.3 million USD excluding taxes.

Figure 23: ABB Steam Condensing generator

Disconnects, Breakers and protection of transmission lines for 23.3 miles of 345KV transmission line.

Foundation Cost	**2100 $ per mile**
Installation Cost	**59650 $ per mile**
Grounding Cost	**2720 $ per acre**
Breakers (345KV) – 3 phase from ABB	**33000 $**
Disconnects (345 KV) from ABB	**7000 $**

Table 6: Breakdown of Utility Cost

10.5 Maintenance and Operating Cost

The selected land in Santa Clara, Utah is a land of terrains, landslide and located near to water, it is known for drastic heatwaves and environmental changes. To stand by the unforeseen scenarios, the project has estimated 7% of the total cost as contingency. The maintenance and operation include trainings, labors, insurances, and nominal fixed maintenances in the Plant. The below picture from SAM shows the maintenance cost breakup.

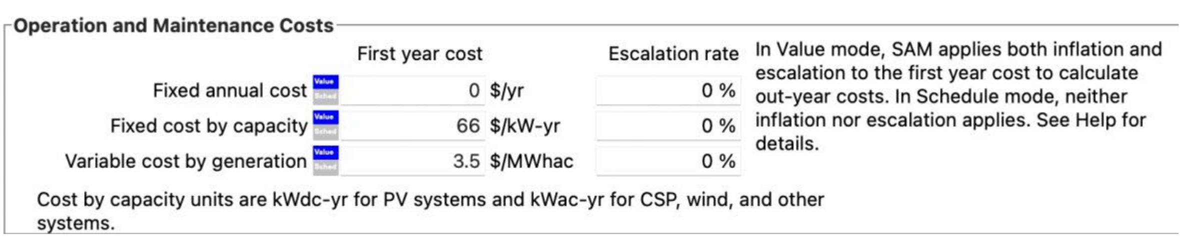


Figure 24: Operation and Maintenance Cost from SAM.

11. COST ANALYSIS

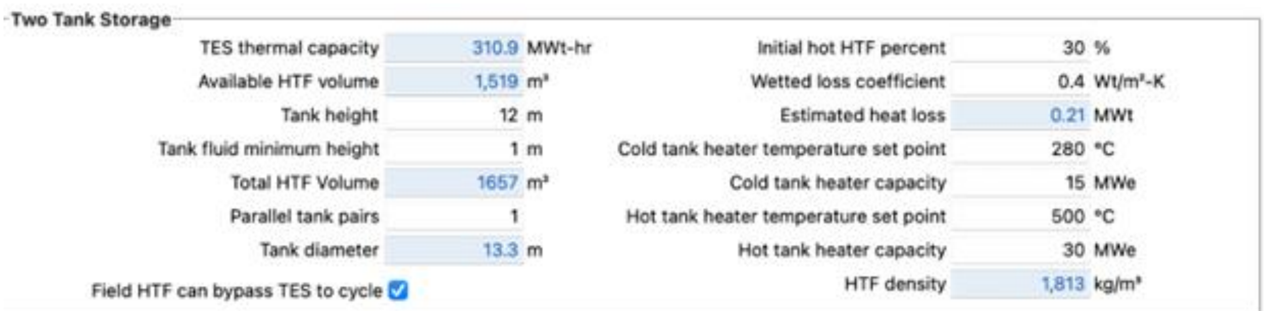
This part has the complete CSP cost analysis and LCOE economic analysis.

11.1 Utility Tariff for our system

Since we want to connect to the transmission line, our location has relatively low peak and off-peak electricity costs. The tariff goes down when energy production distance from user increases. We discussed using a more reasonable price with the instructor and ultimately decided on 0.13 dollars per kWh. We have incorporated a capacity for storage of six hours of storage into our design in order to meet the most active hours, which are from 11 AM to 9 PM.

11.2 Molten Salt Tanks

We use two tanks for the heat transfer process namely, the hot tank and Cold Tank operated at 560 degrees and 290 degrees respectively. The thermal capacity of these tanks is 310.9 MWt/hr. The detailed specification and parameters of these two storage tanks are mentioned in the below picture.


Two Tank Storage

TES thermal capacity	310.9	MWt-hr	Initial hot HTF percent	30	%
Available HTF volume	1,519	m³	Wetted loss coefficient	0.4	Wt/m²-K
Tank height	12	m	Estimated heat loss	0.21	MWt
Tank fluid minimum height	1	m	Cold tank heater temperature set point	280	°C
Total HTF Volume	1657	m³	Cold tank heater capacity	15	MWe
Parallel tank pairs	1		Hot tank heater temperature set point	500	°C
Tank diameter	13.3	m	Hot tank heater capacity	30	MWe
Field HTF can bypass TES to cycle	☑		HTF density	1,813	kg/m³

Figure 25: The specifications and parameters of two tank storage

The cost associated with thermal energy storage in this tank unit is approximately 22USD/KWh and for the total storage of 311MWh, the installation cost of storage tanks comes to $7 million USD approximately.


Thermal Energy Storage

Storage capacity	310.92	MWht	Thermal energy storage cost	22.00 $/kWht	$ 6,840,291.26

Figure 26: Thermal Energy Storage

11.3 Heliostat field

The detailed information on Heliostat field cost is mentioned in the Tabular column below. We are using 1762 units of heliostats of dimensions 12.2m by 12.2m in length and width, giving an area of 144.4 sq. meters. We finalized a provider who bit for 135 USD per sq. meter, namely Solar Dynamics, LLC and signed the contract for 127 USD per sq. meter after negotiation. The Site improvement cost is the cost included with positioning and setting the platform to install the heliostats in location. Heliostat field cost is mentioned in the Tabular column below.

Figure 27: Heliostat Field cost.

11.4 Cooling System, Tower, Piping, and Insolation

The data on the Tower, Piping and Insolation cost is mentioned below.

	Hot tank	Cold tank
Bricks	250 mm	0 mm
Foamglas	400 mm	500 mm
Concrete	50 mm	50 mm
Compacted gravel	150 mm	150 mm
Sand	300 mm	300 mm

Figure 28: Material Specification for Hot and Cold Tank.

	Cold Storage Tank	Hot Storage Tank
Number	1	2
Outer diameter	44.3m	44.3m
Shell height	12m	12m
Max. filling height	11m	11m
Min filling height	1m	1m
Cost	3.5M USD	3.5M USD

Table 7: Cooling system cost specification.

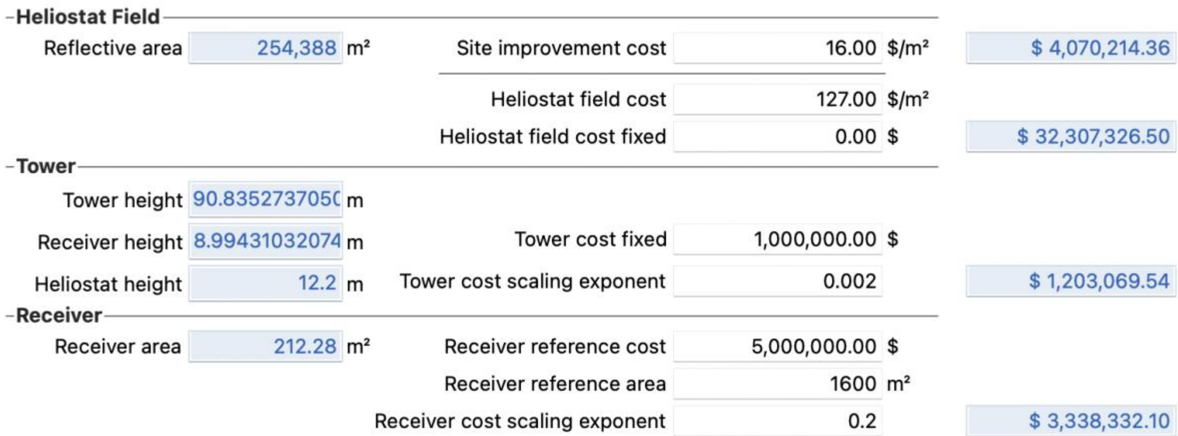


Figure 29: Tower cost including piping.

11.6 Financial Tax Rate and Incentives.

The federal government offers 2 major tax credits for entities that purchase solar energy systems. They are the Investment Tax Credit (ITC) and the Production Tax Credit (PTC). Despite qualifying for both incentives, it is more fiscally viable to take advantage of the Investment Tax Credit (ITC) due to its high up-front installation cost. Under this credit, the total tax liability for the company is reduced by 30% of the installation cost, which amounts to $24,350,000 USD. The state tax comprises of municipal and county taxes with 4% each counting to 8% of total capital cost. However, the state sales taxes are exempted in Utah for purchases that produce renewable energy, which means there will be a savings of $3,280,000 USD when purchasing the materials.

The state of Utah provides tax credits via the Production Tax Credit (PTC-State) through the Utah Office of Energy Development. The PTC provides $0.0035 USD per KWh for systems producing over 2MW of solar electricity for the first 4 years. This leads to returns in taxes around $292,000 USD annually.

The installation of our solar project can also be depreciated via the MACRS depreciation schedule. This provides the highest overall Tax deductions up-front to maximize returns. In addition, since our project will be utilizing US-made steel manufactured parts, we also qualify for Bonus depreciation. Therefore, the 2025 Tax liability will be reduced by a factor of $7,540,000. Summing up these incentives, we arrive at $32,180,000 USD in tax incentives for the first year our plant is in operation. Now, since that amount will result in unused tax credits for the first fiscal year, those unused credits can then be carried forward to for up-to 22 years.

11.7 Cost Summary

The total cost summary of our project from SAM analysis is mentioned below,

Metric	Value
Annual AC energy (year 1)	67,141,040 kWh
Capacity factor (year 1)	39.7%
Annual Water Usage	18,578 m^3
PPA price in Year 1	13.00 ¢/kWh
PPA price escalation	1.00 %/year
LPPA Levelized PPA price nominal	14.08 ¢/kWh
LPPA Levelized PPA price real	11.18 ¢/kWh
LCOE Levelized cost of energy nominal	13.42 ¢/kWh
LCOE Levelized cost of energy real	10.65 ¢/kWh
Investor IRR Internal rate of return	11.26 %
Flip year	18
Investor IRR at end of project	11.55 %
Investor NPV over project life	$4,132,444
Developer IRR at end of project	11.93 %
Developer NPV over project life	$2,553,086
Net capital cost	$112,475,352
Equity	$30,246,850
Debt	$82,228,504
Minimum DSCR	0.49

Figure 30: SAM Performance Summary

Electricity Generation.

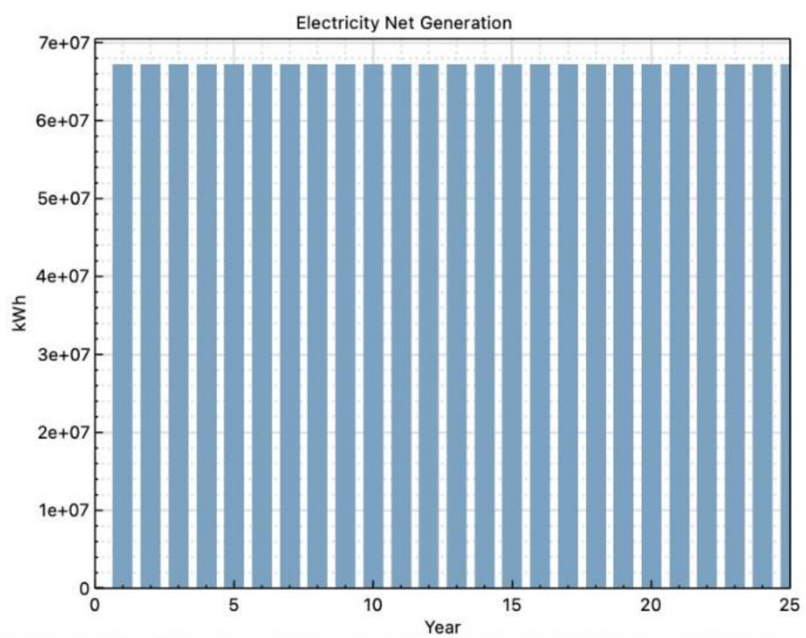


Figure 31: Net Electric generation annually.

Cashflow

The cash flow forecasts for this project are shown in the table. Due to the early investments, there is initially a drop in cash. However, profits are anticipated to be made after the first year. Additionally, a sizable income stream is anticipated from the significant salvage value at the conclusion of the 25-year life cycle of plants. The project's 20-year payback period is also shown in the table.

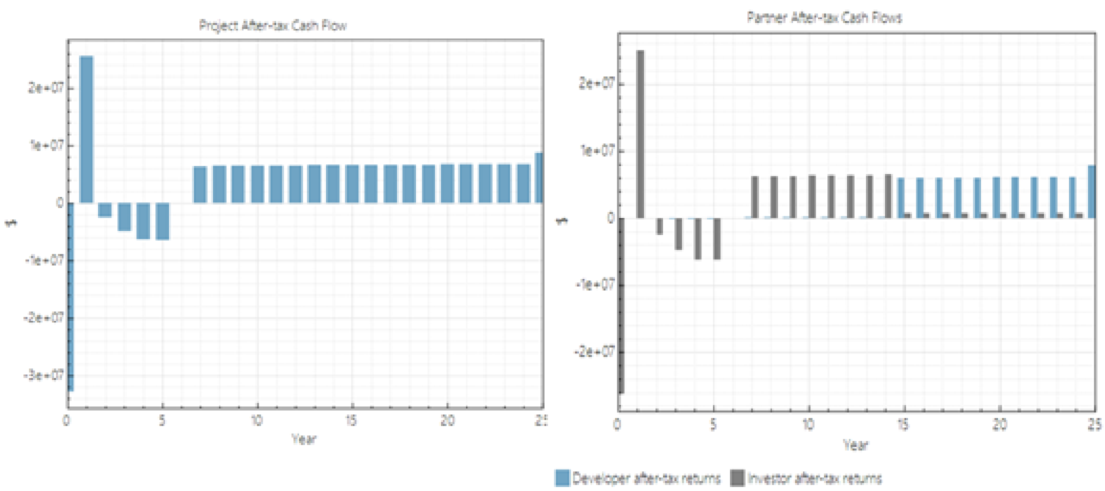


Figure 32: Project Cashflow.

IPSE-GO Performance Summary.

Performance Summary: IPSE-GO

Gross Power	**21.752 MW**
BOP Power	1.6597 MW
Net Power	20.092 MW
Thermal Input from SF to Fluid	65.089 MW
Thermal Input to PB	63.642 MW
Gross Thermal Efficiency	34.178 %
Net Thermal Efficiency	31.57 %
Thermal Input from SF Pump	0.1958 MW

Figure 33: IPSE-GO Performance Summary.

CONCLUSION

On a 419-acre plot of land, a 20 MW central receiver Concentrated Solar Power (CSP) facility is built, and the power is sold to utilities at 13 cents per KWh. To warm the working fluid (molten salt) to an ideal temperature of 560C, the plant uses a field of 1762 heliostats that focuses sunlight onto a central receiver. The system features a two-tank thermal storage structure that allows for 6 hours of storage while employing a combined steam Rankine cycle that has a solar factor of 2.4. Using local sources in the environment at the location, water is employed to cool the system. Using a generator that produces 20 MW and a net electrical output of 20.2 MW (adjusting to account for parasitic loads), the total efficiency of the system was calculated to be 23.1%.

Due to the Hurricane Electric substation's low tariff rates, a financial analysis was conducted using an expected peak tariff rate of 14 cents per kWh. The net capital expense for the system was calculated to be roughly $112 MM. According to the estimate, the Levelized Cost of Electricity (LCOE) will be 9.25/kWh and the Internal Rate of Return (IRR) would be 13.25% after 25 years. Along with the technical specification and financial aspects involved in establishing a CSP plant, we had a chance to learn about the Notional work breakdown structure of the plant from identifying granular details of intermediate activities starting from project plan proposal, procurement, quality inspection, installation, permits & permission from authorities, operation, maintenance, documentation, testing, and verification.

13. WORK BREAKDOWN BY TEAM MEMBER

Work Area	Team Member Area Lead
Weekly Progress Report Slide Deck	Ajith Muthu
Caveat, Purpose, Design Constraints, Purpose	Weskendel Augustin
Solar Radiation	Weskendel Augustin
Site Ready	Ajith Muthu
Iterative Design	Shekar Reddy Peesari
SAM Heliostats & Layout	Shekar Reddy Peesari
Final System Design	Shekar Reddy Peesari
Notional Work Breakdown Structure	Ajith Muthu
System Cost	Ajith Muthu
Cost Analysis	Vignesh Parimalam & Esteban Leal
Conclusion	Vignesh Parimalam
Appendix A	Ajith Muthu
Appendix B	Entire Team

Table 8: Work Breakdown within the team.

APPENDIX A: ACRONYMS

Acronym	Abbreviation
ASME	American Society of Mechanical Engineers - PTC (Performance Test Codes) for Thermal Plants, Mechanical, CSP, and Thermal Standards
IEEE	Institute of Electrical and Electronic Engineers - Electrical Standards and Interconnect
NFPA	National Fire Protection Association
NEC	National Electric Code for safety
UL	Underwriters Laboratory for safety and certification of electrical equipment
PTC	Production Tax Credit
NREL	National Renewable Energy Lab
USDA	United states Department of Agriculture
V	Volts in Kilovolts(KV), Megavolts(MV), hour thermal and electric as ht, he
W	Watts in Kilowatts(KV), Megawatts(MV), hour thermal and electric as ht, he
CSP	Concentrating Solar Power
LCOE	Levelized cost of electricity
SAM	System Advisor Model
IPSE-GO	Software for solar plant design and simulation
BOM	Bill of Materials.

APPENDIX B: REFERENCES

- https://www.energy.gov/sites/prod/files/DOE%20WBS%20Handbook%20%202012-08-16.pdf
- https://www.stakeholdermap.com/plan-project/engineering-solar-cell-work-breakdown-structure.html
- https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/RE_Technologies_Cost_Analysis-CSP.pdf
- https://www.nrel.gov/docs/fy13osti/57625.pdf
- https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/RE_Technologies_Cost_Analysis-CSP.pdf
- https://www.cag.org.in/newsletters/public-newsense/environmental-burden-concentrated-solar-power-plant
- https://radiant.digital/what-is-iterative-design/

- https://beckwithelectric.com/wp-content/uploads/docs/product-specs/M-3425A-SP.pdf
- https://elib.dlr.de/141315/1/Blueprint%20for%20Molten%20Salt%20CSP%20Power%20Plant.pdf
- https://cdn.misoenergy.org/20200211%20PSC%20Item%2005c%20Cost%20Estimation%20Guide%20for%20MTEP20%20DRAFT%20Redline425617.pdf