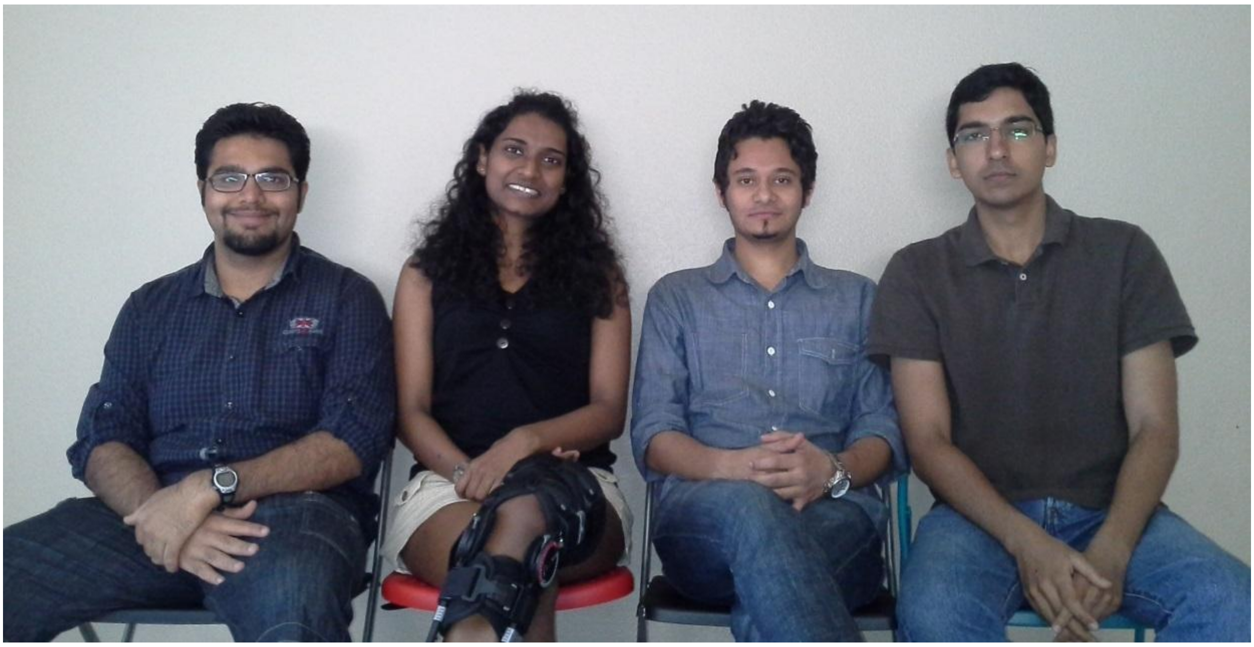
2013

MAE-598 Energy Systems Design

SOLAR TOWER POWER PLANT WITH THERMAL STORAGE

ASU
ARIZONA STATE
UNIVERSITY

Solar Tower Power Plant with Thermal Storage



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Sponsor: Dr. Steven Trimble

Date: 22nd, April, 2013

Declaration of Responsibility

I hereby declare that I have contributed to and reviewed the contents of this final report and take responsibility for the content herein.

Lalita Nayagam
22nd, April, 2013

I hereby declare that I have contributed to and reviewed the contents of this final report and take responsibility for the content herein.

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Executive Summary

The objective of this report is to fulfill the need for the preliminary design of a solar thermal power plant with thermal storage and optimize it for lowest cost of electricity. The plant has a rated output of 100MW and thermal storage of 4 hours. The plant is divided into three major blocks: solar input, thermal storage and power block.

The solar input block consists of heliostats and power tower. Heliostats concentrate the solar energy on a receiver on top of a power tower. The thermal storage is a two tank direct storage system with molten salt as the heat transfer and storage fluid. The power block is a thermodynamic Rankine cycle with a single stage of reheat.

Sun rays are reflected by the heliostats and directed towards a receiver. The receiver contains a eutectic mixture of sodium and potassium nitrate which is heated up by the solar concentration. Part of this molten salt goes to a storage tank while the rest passes through a steam generator where water is converted to steam. The steam drives a turbine to generate electricity. The turbine outlet goes to a condenser which utilizes water from a lake. The water is then pumped back to the steam generator, thus completing the cycle.

The pre-concept phase started with need identification, solar technology research and selection of a reference plant. This was followed by the conceptual design phase. A functional block diagram was made according to the requirements. Trade studies were performed for different functional blocks. This led to selection of components for the plant. The thermodynamic cycle was optimized for highest efficiency and lowest cost of electricity by varying the reheat pressure. Cost model was made using the same methodology as the reference plant. This was done by expressing the component cost in terms of percentages of the capital investment. Inflation and contingency were also considered. Project management tools like work breakdown structure, Gantt chart and labor schedule were used to plan and monitor the progress of the project.

The capital investment on this project is $ 830 million and the optimized cost of electricity is $0.169/kWh.

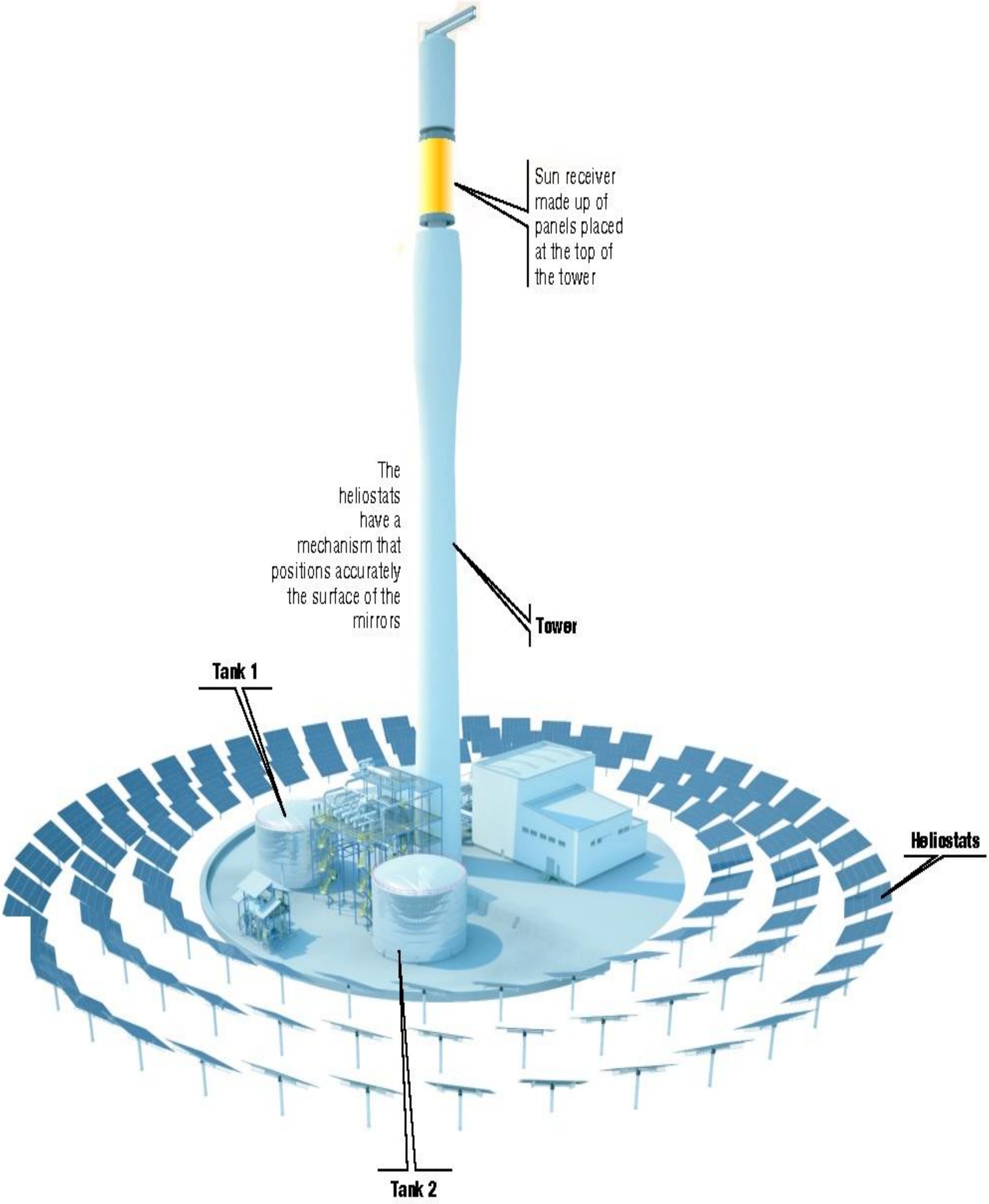


Fig 1: Fundamental diagram of solar tower power plant

Reference: Gema Thermo-solar power plant, Seville, Spain

1 Introduction:

This MAE 598 energy systems design project conducted at Arizona State University addresses the need for the preliminary design of a solar power plant with thermal storage. The project deliverables are 1) Final Report, 2) Final presentation, and 3) Project Notebook. The sponsor of this project is Dr. Steven Trimble, instructor for this course. The project team consists of the following members: Lalita Nayagam, Fraaz Tahir, Akshay Batra, and Shubham Sharma. The project period is January 07, 2013 to April 24, 2013.

1.1 Design need:

Customer requires a solar power plant with thermal storage for four hours; generating 100MW guaranteed output. The plant is to be optimized for lowest cost of electricity.

1.2 Problem Statement:

The goal of the project is to complete the preliminary design of a solar power plant based on idealized solar input and guaranteed electric power output profiles as given in figure 2. The effect of clouds, wind and other weather effects will not be considered. The ultimate heat sink is a large lake with a constant temperature of 80 degrees Fahrenheit. The ambient temperature and relative humidity will be assumed to be constant at 70 degrees Fahrenheit and 10% respectively.

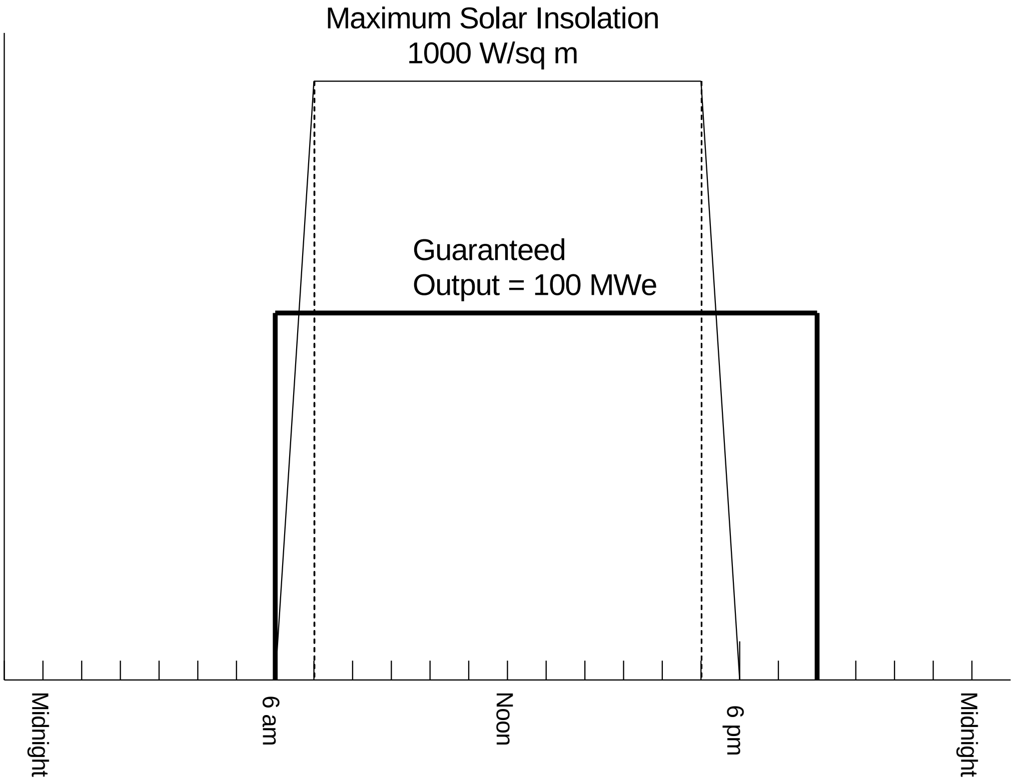


Figure 2 Problem Statement

In the preliminary design will select the thermal storage material and the operating state points (temperature, pressure, flow) for each major component. The power block will be defined to the major component level. A Cost of Electricity performance model will be prepared and used to optimize the plant for the lowest COE.

1.3 Societal Impact:

Societal impacts are very important part and hence are considered in this project report. Here are some impacts listed below which are significant.

1.3.1 No greenhouse gases

The foremost advantage of solar energy is that it does not emit any greenhouse gases. Solar energy is produced by using radiations from sun – a process void of any smoke, gas, or other chemical by-product. This is the main driving force behind green energy technologies, as nations attempt to meet climate change obligations in curbing emissions

1.3.2 Saving eco-systems and livelihoods

Because solar does not rely on constantly mining raw materials, it doesn't result in the destruction of forests and eco-systems that occurs with most fossil fuel operations. Destruction can come in many forms, from destruction through accepted extraction methods, to more irresponsible practices in vulnerable areas, to accidents

1.3.3: Depletion of Fossil Fuels

The fossil fuels cannot remain the dominant source of energy forever. Whatever the precise timetable is for the depletion, oil and gas supplies will not keep up with growing energy demands.

1.3.4 Infinite Free Energy

Another advantage of using solar energy is that beyond initial installation and maintenance, solar energy is one hundred percent free. Solar doesn't require expensive and on-going raw materials like oil or coal, and requires significantly lower operational labour than conventional power production.

1.3.5 Solar jobs

A particularly relevant and advantageous feature of solar energy production is that it creates jobs. Solar jobs come in many forms, from manufacturing, installing, monitoring and maintaining solar panels, to research and design, development, cultural integration, and policy jobs. With solar energy currently contributing only an estimated 4% of the world's electricity and an economic-model where raw materials don't have to be indefinitely purchased and transported, it's reasonable to assume solar jobs are sustainable.

1.4 Report Organisation:

The report is divided into eight sections. Section 1 discusses the societal need, the project problem statement and project scope. Section 2 presents the final preliminary design that meets the problem statement. Section 3 discusses how the team planned the project. Section 4 explains how the design requirements were developed. Section 4 and 5 present the conceptual and preliminary design efforts, respectively. Section 6 summarises how effective was the team in following the project plan in terms of schedule, labour budget, material budget, meeting requirements and mitigating risks. Section 7 discusses the project conclusions and section 8 provides go forward recommendations. Following section are Appendices.

1.5 Project Notebook:

The team organises all its work into a team ***Project Notebook*** *that is used throughout the project to document the work. The notebook contains detailed descriptions of all the trade studies, analyses, tests and team discussions. The final report is written as a comprehensive, stand-alone document. However, it refers to the notebook as needed to direct the reader to more detailed information regarding the design.*

2. Final Preliminary Design Description:

This section describes the final design that meets the customer’s need. The remaining sections of this report explain the design process that resulted in this final preliminary design.

2.1 The technology at a glance [2]:

The first stage in our project was to understand the basic principle of solar thermal power plants which use the concentrating reflector systems in large-scale versions also known as solar fields. The solar fields direct the solar radiation onto a receiver. The concentrated radiation is then transformed into thermal energy at temperatures ranging from around 200 to over 1,000 degrees (depending on the system). As in a conventional power plant, this thermal energy can then be converted into electricity via steam or gas-powered turbines, or it can also be used for other industrial processes such as water desalination, cooling or, in the near future, the production of hydrogen.

Due to this principle, solar thermal power plants excel in their ability to store the thermal energy generated in a relatively simple and cost-effective manner, allowing them to generate electricity even during hours of darkness. Consequently, they can make a key contribution to planned, demand-oriented electricity production.

There are four different configurations of concentrating reflector systems: linear concentrating systems, such as parabolic trough and Fresnel collectors, and point focus concentrating systems, such as solar towers and dishes.

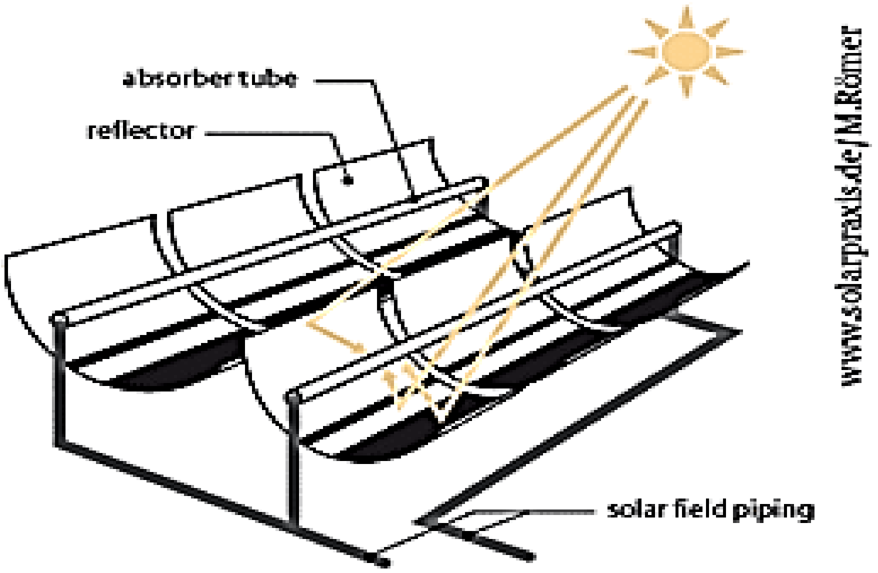


Fig 3: Functional principle of a parabolic trough collector

All systems must track the sun in order to be able to concentrate the direct radiation. The solar field of a parabolic trough power plant (Fig. 3) consists of numerous parallel rows of collectors which are made of parabolic reflectors. These concentrate the sunlight onto an absorber tube that runs along the focal line, generating temperatures of approximately 400°C. Circulating thermo-oil serves as a heat transfer medium to conduct the thermal energy to a heat exchanger, where water vapour is generated with a temperature of around 390 °C. This is then used to power a steam turbine and generator, the same as in conventional power plants.

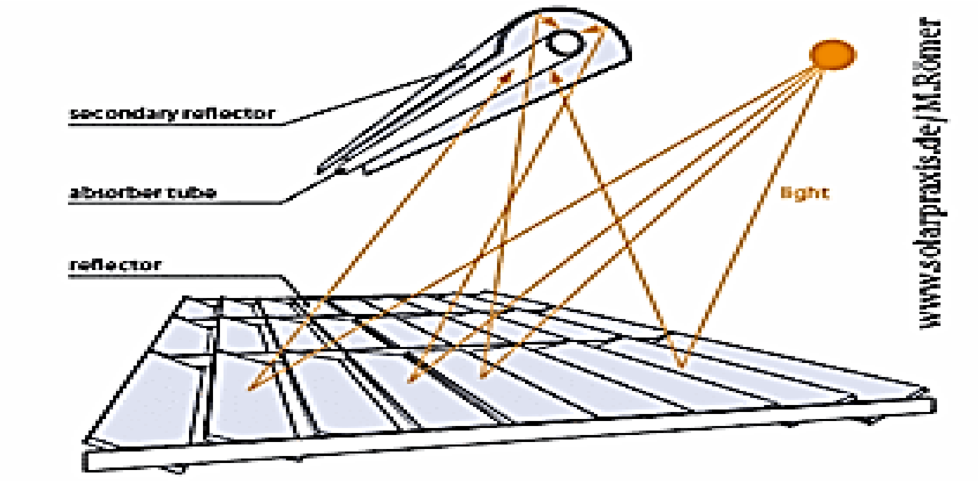


Fig 4: Functional principle of a Fresnel collector

In concentrated solar tower power plants (Fig. 5), solar radiation is concentrated onto a central absorber at the top of the tower by hundreds of automatically positioned reflectors. The significantly higher concentration in comparison to parabolic trough collectors, for example, allows higher temperatures in excess of 1,000 °C to be achieved. This enables greater efficiency, particularly when using gas-powered turbines, thereby resulting in lower electricity costs.

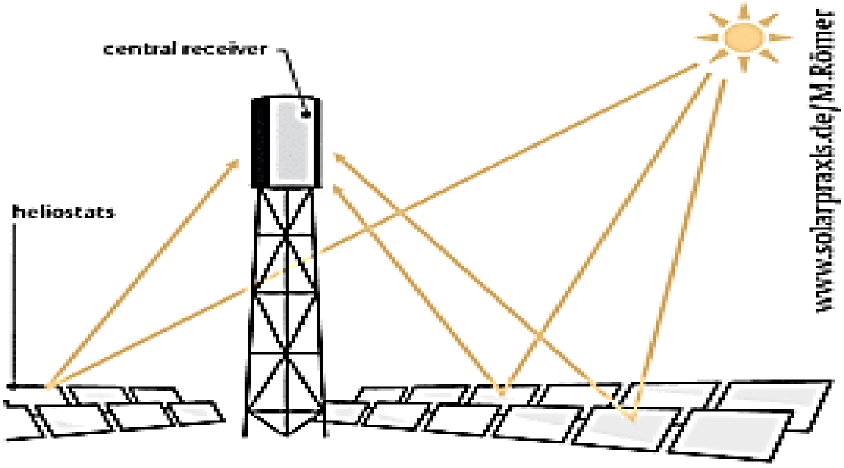


Fig 5: Functional principle of a solar tower.

Dish/Stirling systems (Fig. 6) comprise of parabolic reflector mirrors (dish) that concentrates the solar radiation onto the receiver of a connected Stirling engine. The engine then converts the thermal energy directly into mechanical work or electricity. These systems can achieve a degree of efficiency in excess of 30 per cent. Although these systems are suitable for stand-alone operation, they also offer the possibility of interconnecting several individual systems to create a solar farm, thus meeting an electricity demand from 10 kW to several MW.

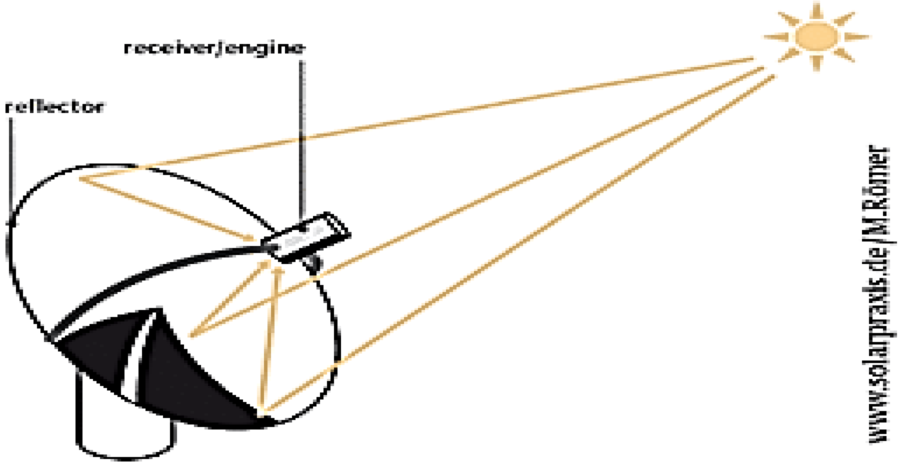


Fig 6: Functional principle of a dish/Stirling system.

Table 1 shows the weighted decision matrix study of the various solar collectors and explains the reason for selection of Heliostat field collectors.

Table 1: Weighted decision matrix for selecting the solar receptors [4]

		Alternatives			
Evaluation Criteria	**Weighing Factor**	**Parabolic Dish**	**Trough Collectors**	**Linear Fresnel Collectors**	**Heliostat Field Collectors**
Initial Cost	0.30	3	7	8	8
O&M Cost	0.20	3	7	9	9
Collector Efficiency	0.15	8	6	5	8
Thermal Efficiency	0.15	8	6	3	8
Area Covered	0.10	8	5	6	8
Effective Tracking	0.10	8	7	7	5
	Total Score	**5.50**	**6.5**	**6.7**	**7.90**

The weighing factors are based on the importance of the mentioned characteristics. Initial cost is given the maximum weightage as cost is the driving factor in any decision making process. Efficiency of collector and thermal efficiency were also considered. Based on the data in the table it can be concluded that heliostat collector field is the best alternative.

2.2 Thermal Storage system [3]:

Thermal energy storage comprises a number of technologies that store thermal energy in energy storage reservoirs for later use. They can be employed to balance energy demand between day time and night time. The thermal reservoir may be maintained at a temperature above (hotter) or below (colder) that of the ambient environment. Thermal energy is often accumulated from active solar collector and transferred to insulate repositories for use later. The applications today include the production of ice, chilled water, or eutectic solution at night, or hot water which is then used to cool / heat environments during the day.

2.2.1 Two tank direct system:

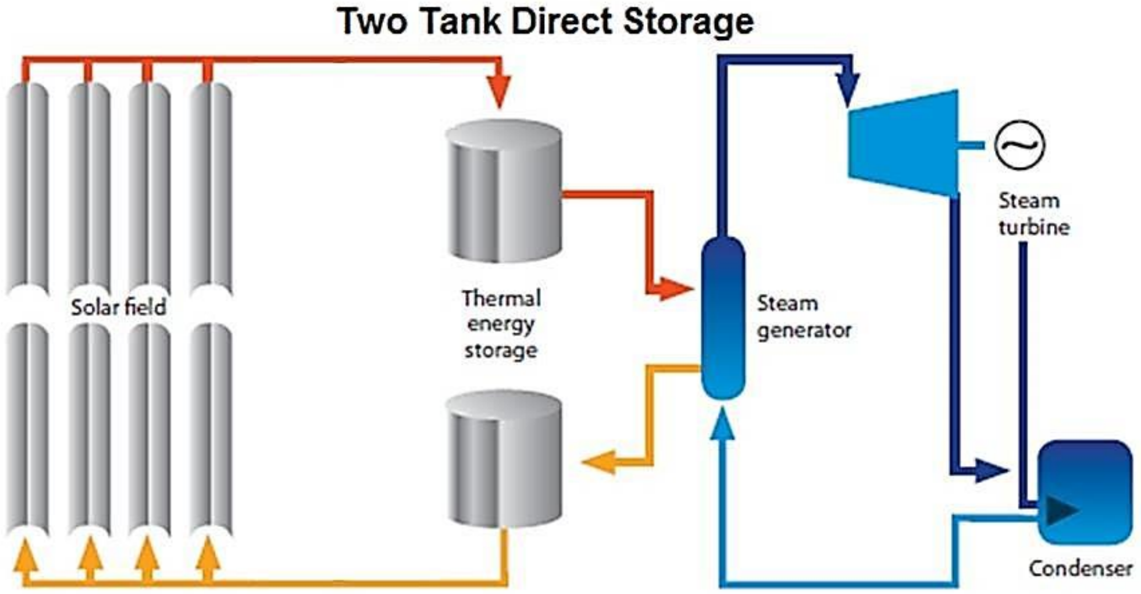


Fig 7: Two tank direct system

(Ref: www.eere.energy.gov/basics/renewable energy/thermal storage.html)

Solar thermal energy in this system is stored in the same fluid used to collect it. The fluid is stored in two tanks—one at high temperature and the other at low temperature. Fluid from the low-temperature tank flows through the solar collector or receiver, where solar energy heats it to a high temperature and it then flows to the high-temperature tank for storage. Fluid from the high-temperature tank flows through a heat exchanger, where it generates steam for electricity production. The fluid exits the heat exchanger at a low temperature and returns to the low-temperature tank.

Two-tank direct storage was used in early parabolic trough power plants (such as Solar Electric Generating Station I) and at the Solar Two power tower in California. The trough plants used mineral oil as the heat-transfer and storage fluid; Solar Two used molten salt.

2.2.2 Two tank indirect system:

Two-tank indirect systems function in the same way as two-tank direct systems, except different fluids are used as the heat-transfer and storage fluids. This system is used in plants in which the heat-transfer fluid is too expensive or not suited for use as the storage fluid. The storage fluid from the low-temperature tank flows through an extra heat exchanger, where it is heated by the high-temperature heat-transfer fluid. The high-temperature storage fluid then flows back to the high-temperature storage tank. The fluid exits this heat exchanger at a low temperature and returns to the solar collector or receiver, where it is heated back to a high temperature. Storage fluid from the high-temperature tank is used to generate steam in the same manner as the two-tank direct system. The indirect system requires an extra heat exchanger, which adds cost to the system.

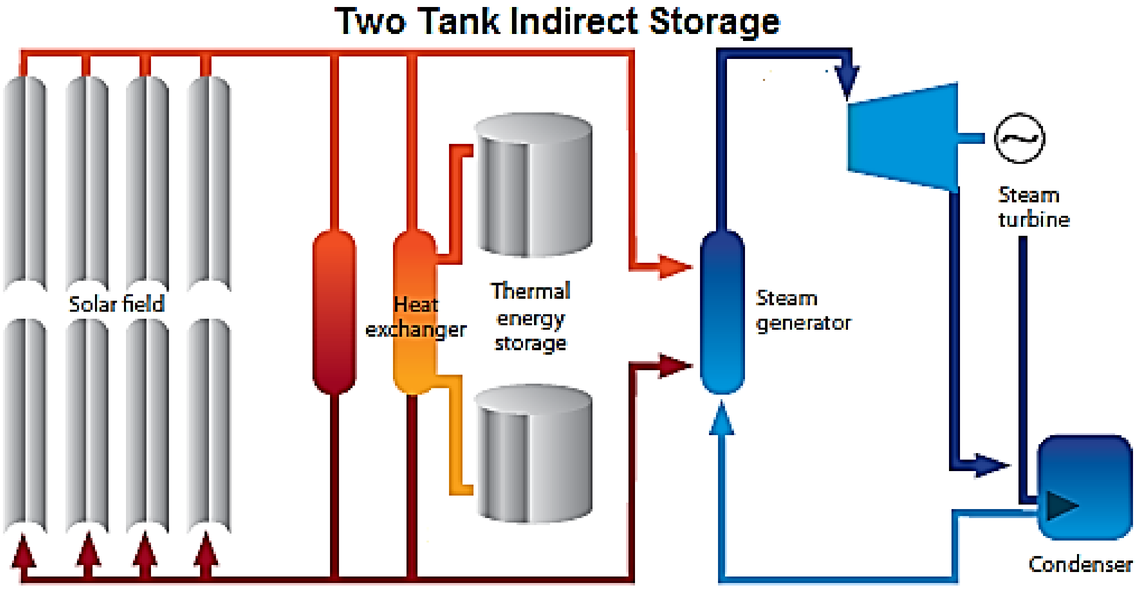


Fig 8: Two tank indirect system

(*Ref: North American Renewable Energy Directory)*

This system will be used in many of the parabolic power plants in Spain and has also been proposed for several U.S. parabolic plants. The plants will use organic oil as the heat-transfer fluid and molten salt as the storage fluid.

2.2.3 Single-Tank Thermocline System:

Single-tank thermocline systems store thermal energy in a solid medium—most commonly, silica sand—located in a single tank. At any time during operation, a portion of the medium is at high temperature, and a portion is at low temperature. The hot- and cold-temperature regions are separated by a temperature gradient or thermocline. High-temperature heat-transfer fluid flows into the top of the thermocline and exits the bottom at low temperature. This process moves the thermocline downward and adds thermal energy to the system for storage. Reversing the flow moves the thermocline upward and removes thermal energy from the system to generate steam and electricity. Buoyancy effects create thermal stratification of the fluid within the tank, which helps to stabilize and maintain the thermocline. Using a solid storage medium and only needing one tank reduces the cost of this system relative to two-tank systems. This system was demonstrated at the Solar One power tower, where steam was used as the heat-transfer fluid and mineral oil was used as the storage fluid. Fig. 9 explains the working setup of the thermocline storage system.

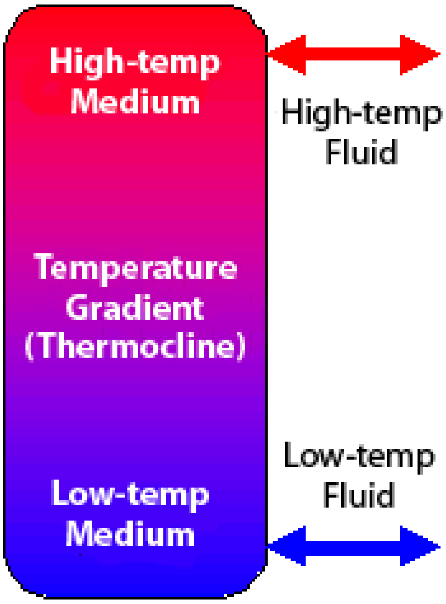


Fig 9: Thermocline System
(Ref: North American Renewable Energy Directory)

2.2.4 Trade Studies:

Table 2: Thermal storage system comparison [3]

Attributes /Options	**Indirect 2 Tank System**	**Thermocline**	**Direct 2 tank system**
Capital Cost	-	+	+
Operating temp.	-	+	+
Maintenance	-	+	+
Heat losses	-	-	+
Volume of the fluid	-	-	+
Operation cost	-	-	+
The Result	-6	0	+6

The driving factor in the selection of the storage system is the cost and the operating temperatures of salts. Based on the trade studies we have used the *Two Tank Direct Thermal storage* for our plant.

2.3 Storage Salts [3]:

Molten salt can be employed as a thermal energy storage method to retain thermal energy collected by a solar tower or solar trough so that it can be used to generate electricity in bad weather or at night. The molten salt mixtures vary. The most extended mixture contains sodium nitrate, potassium nitrate and calcium nitrate. It is non-flammable and nontoxic, and has already been used in the chemical and metals industries as a heat-transport fluid, so experience with such systems exists in non-solar applications. Molten salts are abundant and not very costly. They behave themselves that is they are neither decomposing nor volatizing at the high temperature needed in a CSP plant — about 565 degrees Celsius (°C). . At room temperature, the salts look like powdery white table salt. At the higher temperatures in a CSP plant, the salts look like water.

The molten salts used for storage are a mix of calcium, sodium nitrate and potassium nitrate. Sodium nitrate is mined from dry lake beds in Chile, in surroundings similar to the Utah salt flats. Potassium nitrate also occurs in nature and is mined in Chile, Ethiopia, and elsewhere. Most salt melts at 131 °C (268 °F). It is kept liquid at 288 °C (550 °F) in an insulated "cold" storage tank. The liquid salt is pumped through panels in a solar collector where the focused sun heats it to 566 °C (1,051 °F). It is then sent to a hot storage tank. When electricity is needed, the hot salt is pumped to a conventional steam-generator to produce superheated steam for a turbine/generator as used in any conventional coal, oil or nuclear power plant.

2.3.1 Trade Study:

A comparative trade study was performed to select the most suitable salt composition for our system. Table 3 Show the parameters used for trade studies were cost and coefficient of heat transfer. Based on the comparative analysis**,** solar salt has been selected as a thermal storage medium for our system.

Table 3: Thermal storage salts comparison [3]

Salts	Density (kg/m³)	Cp (J/Kg°K)	Cost, $/Kg	$/kWh
Hitec XL® (42:15:43 Ca:Na:K Nitrate)	1992	1447	1.43	18.2
Hitec (7: 53 Na:K nitrate)	2083	1561	0.93	10.7
Solar Salt (60:40: Na:K nitrate)	1870	1600	0.49	5.8
Calcium Nitrate (42:15:43 Ca:Na:K Nitrate)	1400	2500	1.19	20.1
Therminol VP-1™ (Diphenyl biphenyle oxide)	815	2319	100	57.5

2.4 Method of Operation:

In a solar power plant with thermal storage, salts are stored in two tanks and are pumped from the "cold" tank to the power tower, where it collects the solar energy that is focused on the receiver, raising its average temperature to 575 °C. The salts then descend into the "hot" tank, where they can maintain this very hot temperature for fourteen hours. The salt in the hot tank is then sent to a heat exchanger that generates the steam at 500 °C needed to turn the turbines at a power plant. The turbines generate electricity that goes to homes and businesses.

When the sun is shining, the CSP plant can take the salts out of the cold tank, heat them up at the tower's receiver, and then dump them into the hot tank for storage the system. Steam is generated by Rankine cycle with reheat. System is designed for a guaranteed Molten salts tend to freeze at about 200°C, so as long as the two tanks range between 293°C and 565°C, the salts are in no danger of reverting to a solid state. Fig.10 shows the setup and working of the CSP system.

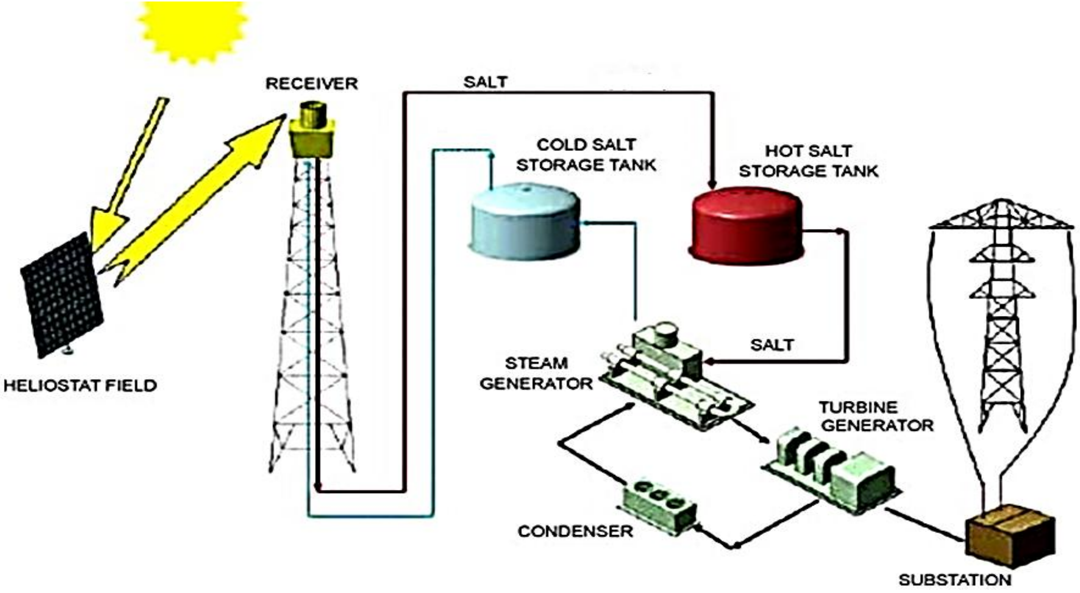


Fig 10: The two-tank direct molten-salt thermal energy storage system at the Solar Two power plant.

(Ref: National Renewable Energy Laboratory)

2.5 Key Features and benefits:

Here we have included the key features of our plant, as stated under the problem statement we have firstly considered the Ideal conditions and then after taking the actual conditions thus getting 2 sets of data that are listed below in Table 4.

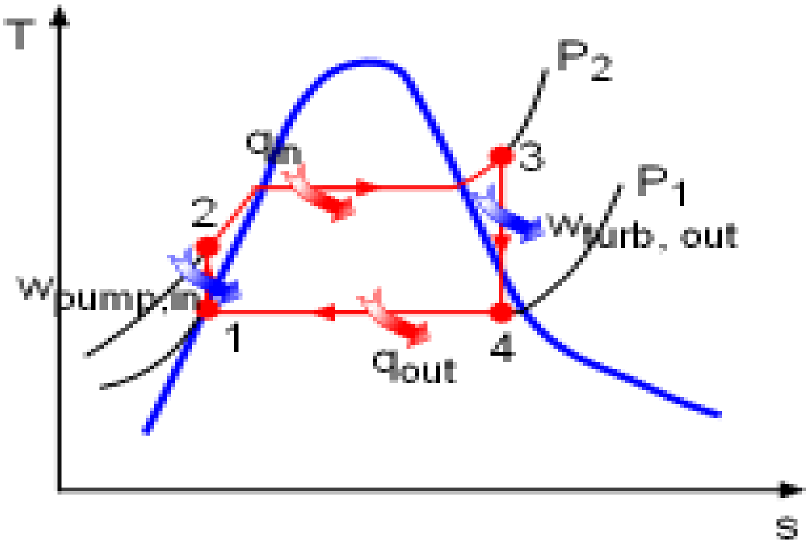
Table 4: Final key design Parameters

Component	**Parameter**	**Our Plant**	
		Ideal*	**Actual**[#]
Heliostat	Reflecting Surface Area	0.43 km^2	0.74 km^2
	Size	7.31m x 8.5m	7.31m x 8.5m
	Height of tower	167 m	167m
	Number	6935	12,000
Turbine	Inlet temp	500°C	500°C
	Inlet pressure	120 Bar	120 Bar
Heat Transfer Salt	$NaNO_3 + KNO_3$	$NaNO_3 + KNO_3$	$NaNO_3 + KNO_3$
Thermal Storage		Two Tank Direct	Two Tank Direct
Capacity Factor		0.60	0.60
Energy production		511 Million KWh/year	511 Million KWh/year
Capital Investment		\$441.8 million	\$830 million
Cost of Electricity		0.095 \$/kWh	0.169 \$/kWh

Note:
*Ideal – Solar irradiance = 1000 W/m² & Heliostat η = 99% (neglecting weather conditions, cosine, shading & blocking effects
[#]Actual – Solar Irradiance = 580 W/m² (for Arizona) & Heliostat η = 70% (considering weather conditions, cosine, shading & blocking effect)
Source: *NREL- Solar Radiation Data Manual for Building by William Marion & Stephen Wilcox*

2.6 Optimization Results:

The system was optimised for the lowest cost of electricity. This was done by varying the reheat pressure. Since the maximum required pressure is 120bar and the least pressure in the system is 0.6 bar, the reheat pressure played an important role in cost as the range is quiet high. Hence iterations were performed several times and the results were plotted on the graph representing reheat pressure versus efficiency and cost of electricity. The iterations done are as follows;

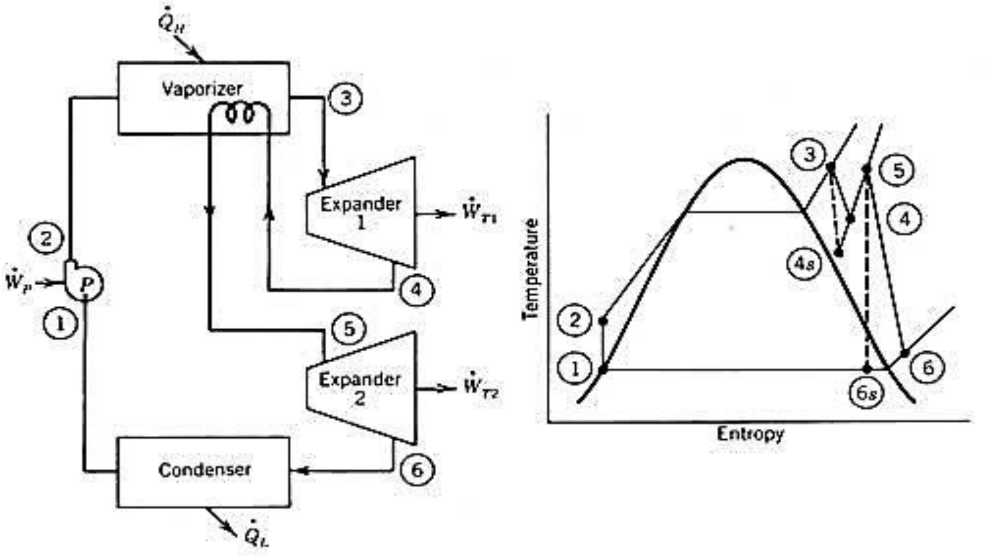


The Rankine cycle is an ideal cycle if water passes through the four components without irreversibility and pressure drops. The ideal Rankine cycle consists of the following four processes, as shown on the T-s diagram on the left:

- 1-2: Isentropic compression in a pump
- 2-3: Constant pressure heat addition in a boiler
- 3-4: Isentropic expansion in a turbine
- 4-1: Constant pressure heat rejection in a condenser

Table 5: State Points without reheat

State Points	**T (° C)**	**P (Bar)**	**H(KJ/Kg)**	**S (KJ/Kg°K)**
1	84.93	0.6	359.8	1.145
2	86.61	120	372.8	1.145
3	500	120	3350	6.49
4	85.93	0.6	2279	6.49



Reheat Cycle

An attempt is made to increase the efficiency of the Rankine cycle. The same is done by adding a reheating unit between the two turbines thus attaining staged pressure drop.

- 1-2 Isentropic Compression to 120 Bar
- 2-3 Constant Pressure heat addition to 500°C
- 3-4s Isentropic expansion in High Pressure (HP) turbine
- 3-4 Actual expansion in High Pressure (HP) turbine
- 4-5 Reheat to 500°C
- 5-6s Isentropic expansion in Low Pressure (LP) turbine
- 5-6 Actual expansion in Low Pressure (LP) turbine

Here reheat pressure is set at

1. **20.5 Bar and the state points are calculated:**

State Points	**T (° C)**	**P (Bar)**	**H(KJ/Kg)**	**S (KJ/Kg°K)**
1	85.93	0.6	359.8	1.145
2	86.61	120	372.1	1.145
3	500	120	3350	6.49
4	240	20.5	2874	6.49
5	500	20.5	3467.5	7.42
6	85.92	0.6	2613	7.42

Thermal Efficiency: 31.92%
Heat Input: 3570.9KJ/Kg
Mass Flow rate: 0.078kg/sec
Dryness: 98.25%

2. Reheat pressure: 40.4 Bar

Table: 6 State Points at reheat pressure 40.4 bar

State Points	T (° C)	P (Bar)	H(KJ/Kg)	S (KJ/Kg°K)
1	85.933	0.6	360	1.145
2	87.71	120	374.11	1.145
3	500	120	3350	6.49
4	347	40.4	3085	6.57
5	500	40.4	3445	7.09
6	85.93	0.6	2637	7.48

Thermal Efficiency: 33.97%
Heat Input: 3384.9KJ/Kg
Mass Flow rate: 0.079kg/sec
Dryness: 93.75%

3. Reheat pressure: 60.3 Bar

Table: 7 State Points at reheat pressure 60.3 bar

State Points	T (° C)	P (Bar)	H(KJ/Kg)	S (KJ/Kg°K)
1	85.93	0.6	359.9	1.145
2	86.61	120	372.1	1.145
3	500	120	3350	6.49
4	380	60.3	3124.2	6.49
5	500	60.3	3422.6	6.88
6	85.93	0.6	2419	6.88

Thermal Efficiency: 32.06%
Heat Input: 3384.9KJ/Kg
Mass Flow rate: 0.084kg/sec
Dryness: 84.93%

4. Reheat pressure: 80.2 Bar

Table: 8 State Points at reheat pressure 80.2 bar

State Points	T (° C)	P (Bar)	H(KJ/Kg)	S (KJ/Kg°K)
1	85.93	0.6	359.8	1.145
2	86.61	120	372.1	1.145
3	500	120	3350	6.49
4	431.9	80.2	3225.7	6.49
5	500	80.2	3399	6.725
6	85.93	0.6	2363.4	6.725

Thermal Efficiency: 32.8%
Heat Input: 3151.2KJ/Kg
Mass Flow rate: 0.0862kg/sec
Dryness: 87.85%

5. Reheat pressure: 100.1 Bar

Table: 9 State Points at reheat pressure 100.1 bar

State Points	T (° C)	P (Bar)	H(KJ/Kg)	S (KJ/Kg°K)
1	85.93	0.6	359.8	1.145
2	86.61	120	372.1	1.145
3	500	120	3350	6.49
4	468.6	100.1	3292.6	6.49
5	500	100.1	3374.9	6.599
6	85.93	0.6	2318.2	6.599

Thermal Efficiency: 32.71%
Heat Input: 3060.8KJ/Kg
Mass Flow rate: 0.0908kg/sec
Dryness: 85.40%

Based on the above results the following graphs were plotted:

1. **Thermal Efficiency v/s Reheat (Reheat Optimization)**

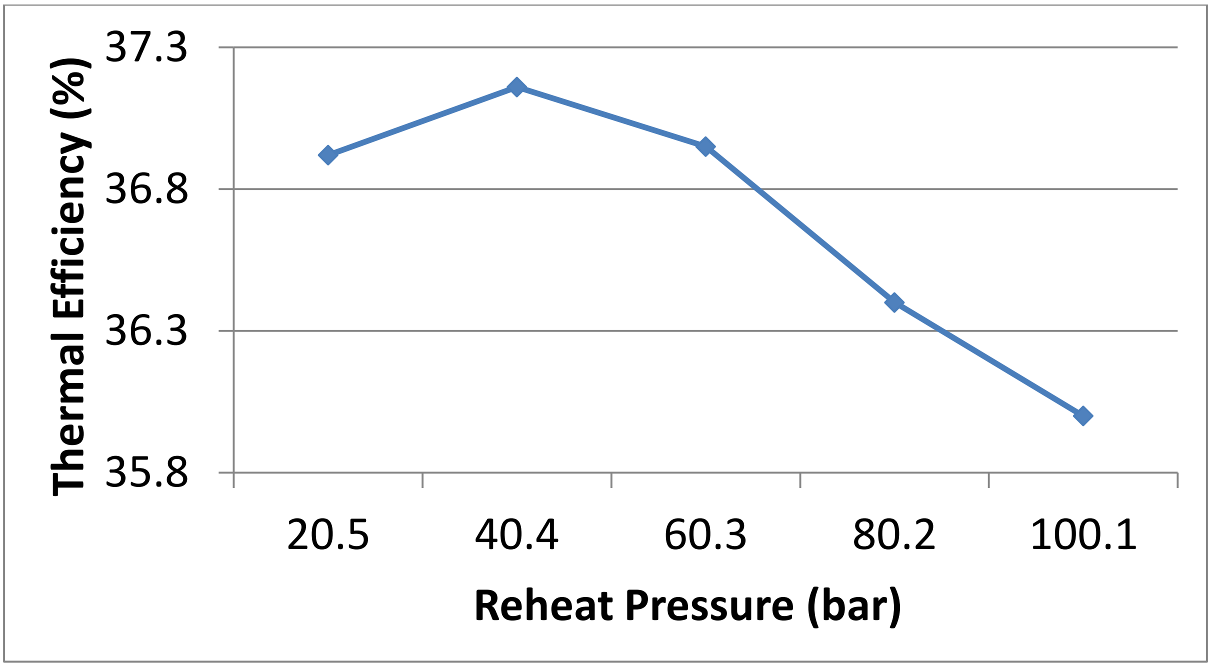


Figure 11: Thermal Efficiency v/s Reheat Pressure Optimization

2.6.1 Optimization and Cost Results:

1) **Number of Heliostats Required:**
   Total heat Input = heat per heliostat X number of Heliostats
   Number of Heliostats = 11,981

1) **Total Cost of Heliostats:**
   Total Costs of Heliostats = Number of Heliostats X Cost per heliostat
   Cost per Heliostat = $30/ m²
   Total Costs of Heliostats = $ 198,915,840

2) **Total reflective area:**
   Total number of heliostats X Area per heliostat = 744000 m²

3) **Volume of Salt required:**
   Volume of Salts required = 7374 m²

4) **Volume of Tank**:
   Volume of Tank required = 8896 m²

5) **Fixed Charges:**
   Fixed Charges = (FCR * CI) / (RC * CF * 8760 hrs/year)
   Fixed Charges = $ 830 Million

6) Cost of Electricity:

Cost of Electricity = Fixed Charges + O& M + Fuel Charges

Cost of Electricity = $ 0.169/ KWhr

Cost of Electricity was calculated for different reheat pressures. The system was optimized for the lowest cost of electricity. Table10 below shows the final results of optimization performed for different reheat pressures.

Table: 10 Reheat Optimization

Reheat Pressure (bar)	Mass Flow Rate (kg/s)	Heat Input (MW)	Thermal Efficiency (%)	No. of Heliostats	Cost of Heliostats ($)	Cost of Electricity ($/kWh)
20.5	75.86	303.2	32.94	12045	199,942,560	0.172
40.4	82.15	301.6	33.15	11981	198,915,840	0.169
60.3	79.95	302.9	32.96	12033	199,726,800	0.178
80.2	86.21	304	32.47	12077	200,519,160	0.175
100.1	90.76	310.8	32.11	12347	205,005,480	0.176
No Reheat	94.46	314.8	31.67	12507	207,603,900	0.185

Based on the results of the Table 10, the following graph was obtained

10

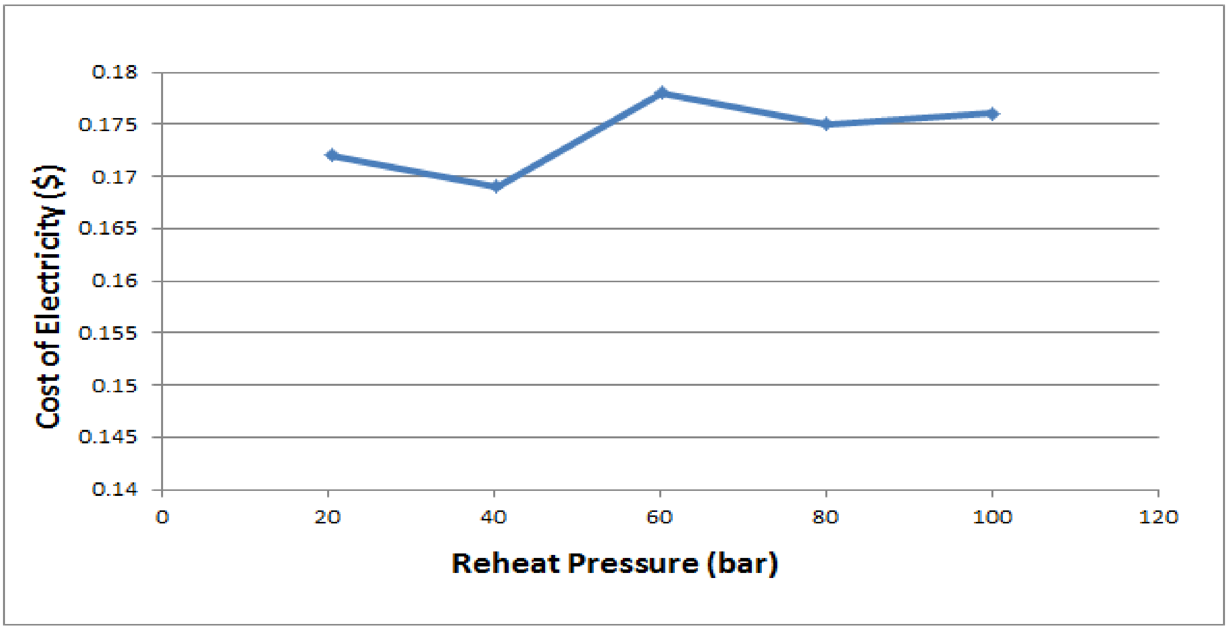


Fig. 12: Reheat v/s COE Optimization

The above graph also suggests that the cost of electricity is the lowest when reheat pressure is 40.4 Bar. Hence the optimization of the system was performed.

2.7 Commercial Plan Summary:

Since the plant is based on existing technology, the plant is ready to be commercialized once the stages after the conceptual design are completed.

3. Design Process and Project Planning

Design Process and Project Planning for a system is a foundation to efficient and effective functioning of the system. This design process is the formulation of the basic action plan that would lead to a system that would fulfil the intended function. For our case, the design of a 100MWe Solar-Tower Power Plant with Thermal Storage was a tedious and a detailed system as it was affected by number of variables.

3.1 IPDS Design Process

The integrated product development and support is a state-of-the-art development approach towards our performance goal that has specific outcomes. Fig. 13 shows a model that depicts all the stages of the IPDS Design process but due to development constraints we are detailing our report to Phase 3 – Preliminary Design and will come up with a conclusion which states the Final Preliminary Design.

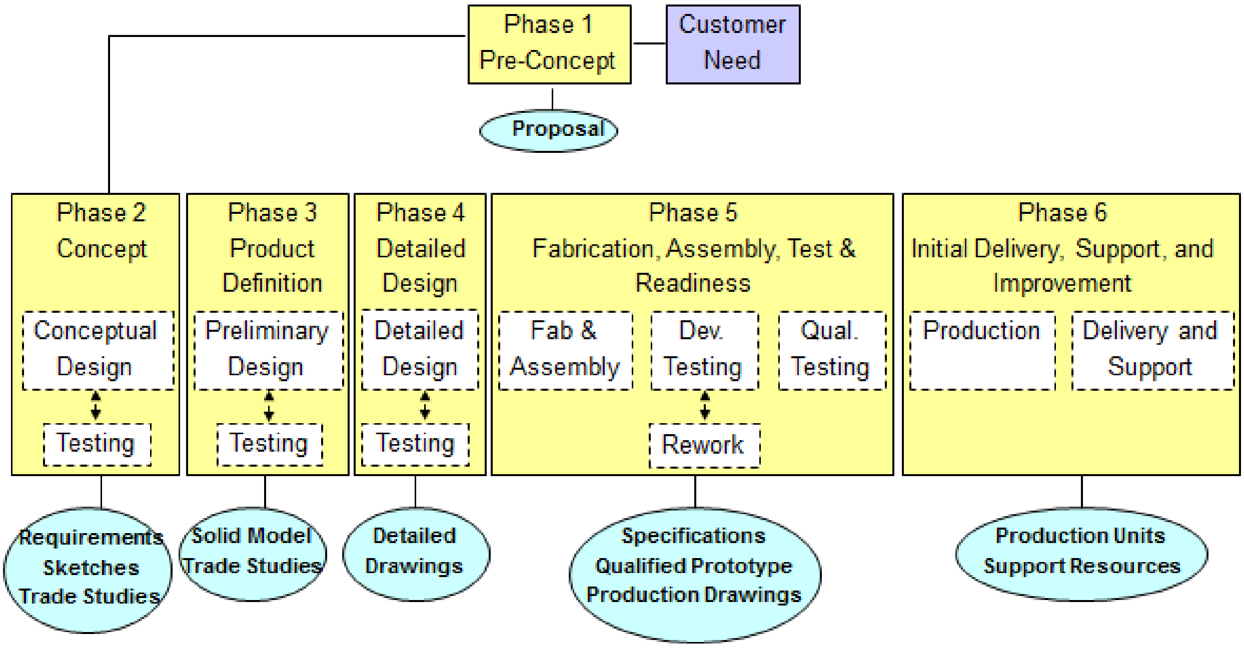


Fig 13: IPDS [5]

According to our problem statement we will be working to develop our preliminary design and finalize our design accordingly. Fig. 14 shows the Block diagram depicting the first three phases of the IPDS plan.

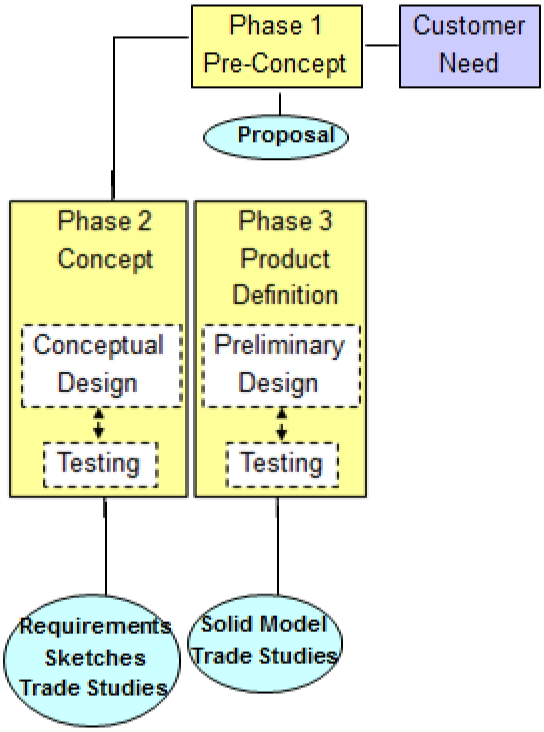


Fig 14: Three phase of IPDS process [5]

This 3 block diagram is subset of overall IPDS plan. This consists of only first three blocks namely Pre-Concept, Concept and Preliminary Design; the final preliminary design was achieved using this staged process.

3.2 Project Plan

Our project plan delineates the basic approach that we have followed throughout to ensure our design meets all the requirements and facilitates the design process and hence forth the final preliminary design of the power plant.

3.2.1 Overview

The initial plan laid down at the beginning of the project was diligently followed with improvements. This included the block diagram that acted as a guideline for the tasks to be performed. This block diagram is our work breakdown structure. Fig. 15 shows the Work Breakdown Structure that broadly classifies the scope of our study.

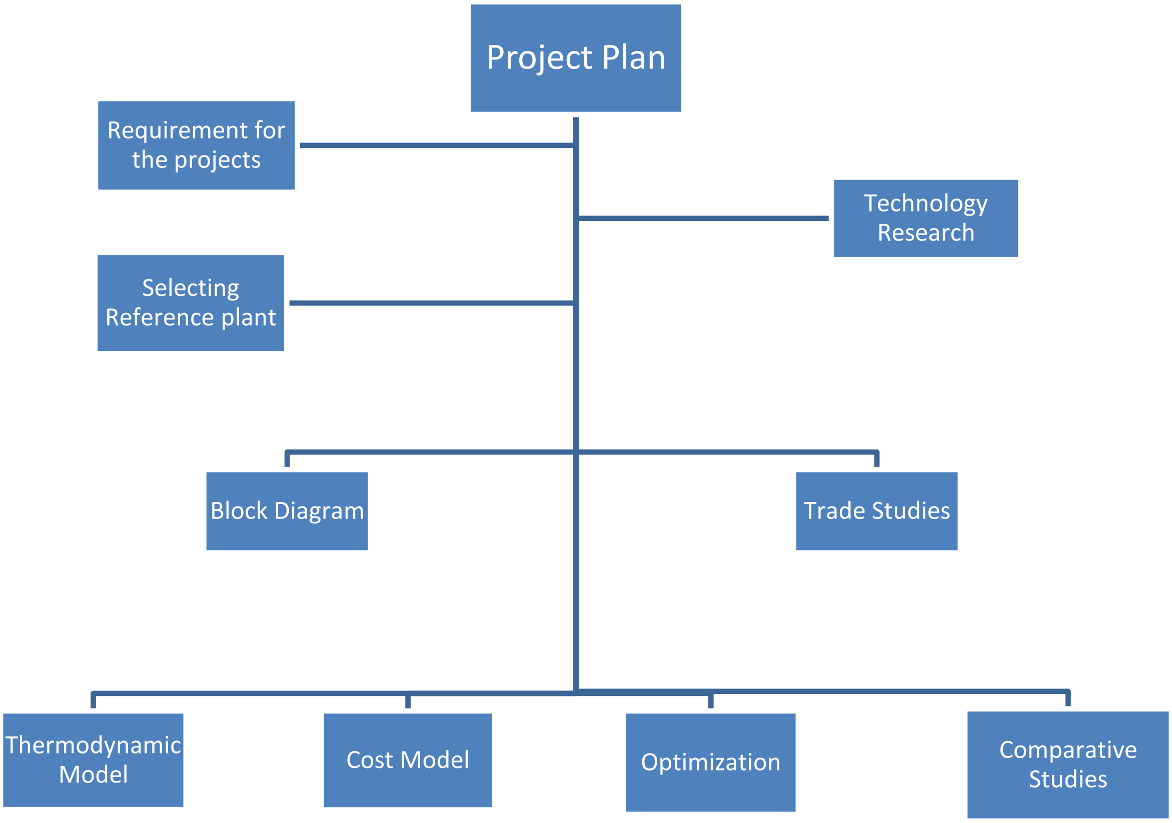


Fig 15: Work Breakdown Structure

A. Requirements for the project
   - Guaranteed output of 100MWe
   - 14 hours of continuous energy production
   - Thermal Storage of minimum 4 hours
   - Optimization for the lowest cost of electricity

B. Technology Research

   Technology research was a major part of our project. We not only looked into the existing technologies but also at the new technologies used in the solar thermal industry. That was done by conducting literature survey, reading technical papers and collecting information from the internet.

List of attributes those are incorporate directly from existing technology:

- Two tank direct system for heat storage
- Solar salt (60:40: Na:K nitrate) for heat transfer
- Steam turbine with reheat cycle
- Shell type heat exchanger
- Direct absorption volumetric Molten Salt Receiver

C. Selecting Reference Plant

The most important of all was the data accumulation from the reference power plant, since the prime motive of the study is based on optimizing the Cost of Electricity (COE) hence the data accumulation from the reference power plant was very important for us. We have chosen the Crescent Dunes Power Plant, NYE County, Nevada as our reference plant.

D. Block Diagram

The following block diagram is made during the project:

- Functional block diagram
- IPDS Design process diagram
- Conceptual Design Final block diagram
- Final Thermodynamic Cycle diagram

E. Trade Studies

The most important part of the project report is the trade studies. We have conducted trade studies for the following important components:

- Solar Receiver/collectors
- Thermal storage system
- Thermal Salt

F. Thermodynamic Model

This includes the analysis of our cycles and models. Analysis was done for No-reheat and reheat conditions. Several iterations were performed for different reheat pressures. The results gave the best reheat pressure value corresponding to the lowest Cost of Electricity and maximum efficiency Fig. 16 and Fig. 17 shows the thermodynamic model without and with reheat respectively.

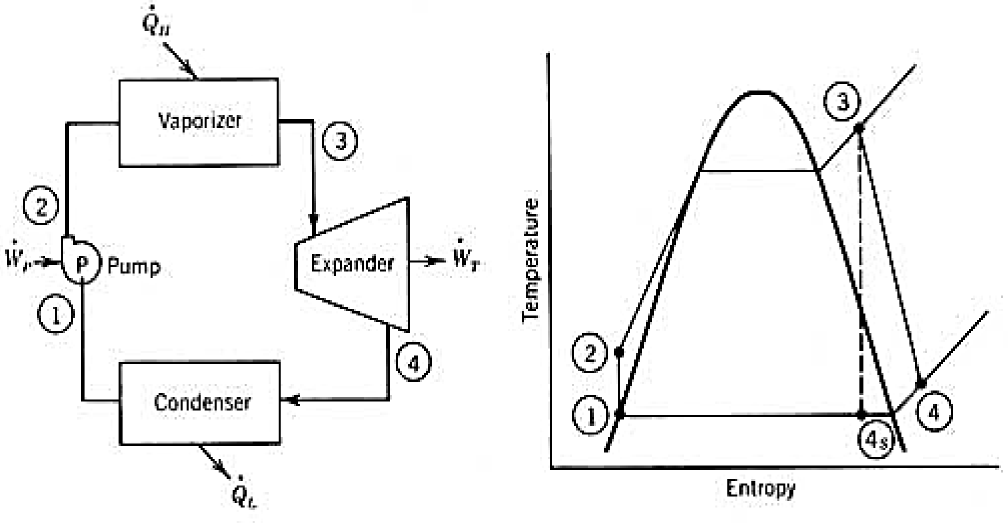


Fig 16: Thermodynamic Cycle without Reheat

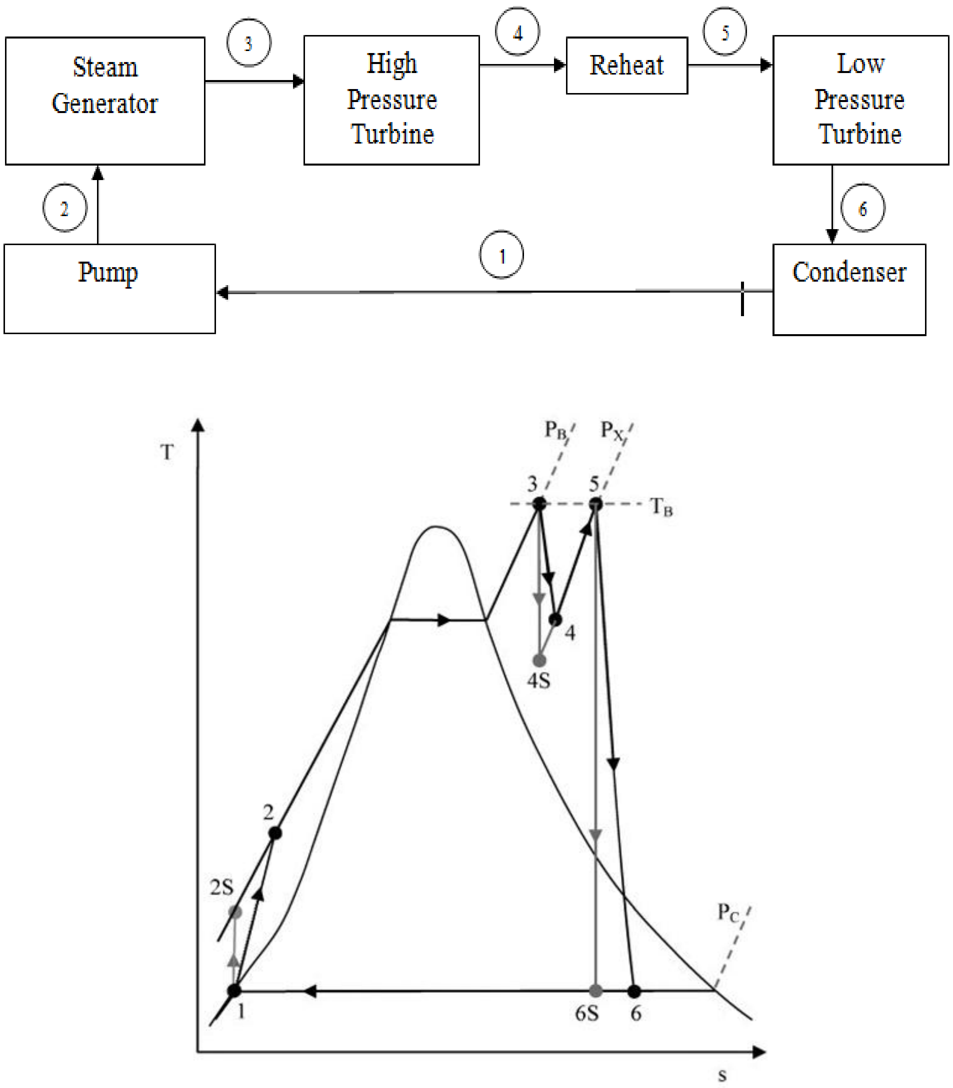


Fig 17: Thermodynamic Cycle with Reheat

G. Cost Model

The cost model was made analogous to the Crescent Dunes plant. We have also given the costs in terms of percentages of the total cost. Hence the equipment costs were also finalized.

H. Optimization

Optimization was done for the lowest cost of electricity and maximum efficiency, by conducting different iterations of the thermodynamic cycles and varying the reheat pressures

I. Comparative Studies
We performed comparative studies of all the elements that we included in our study and thus came up with the most optimized element. We have involved various methods to do this like Weighted decision matrix.

3.2.2 Key Issue

1. Selection of Solar Reflectors:
2. Solar reflectors play a key role in the process of trapping solar energy. The same is done by using solar reflectors. We have selected the solar reflectors using the weighted decision matrix method. That helped us to use heliostats as solar receivers
3. Selection of Heat transfer agent
   Heat transfer agent was also selected using the methods of trade-offs. The decision was to use the eutectic mixture of Sodium Nitrate and Potassium Nitrate also known as Solar Salt (Na: K: nitrate).
4. Selection of Turbine
   We have decided to use Siemens SST 700, 2 stage turbine with output of 500MW for our plant.

3.2.3 Project Strategy Approach

For the project to be actually entering the production stage, optimization of the solar field needs to be done. Also the selection of auxiliary equipment is to be done. Design and calculation of insulation and heat exchangers should also be done. Once the said tasks are performed, the plant can be put for production. Also, FMEA was performed so as to secure the system.

3.2.4 Risk Reduction Planning

We have made efforts to plan the risks that we have anticipated and hence came up with a FMEA model to resolve the contingencies coming our way.

3.2.5 Schedule:

The milestones in the chart below were taken from our work breakdown structure. A project timeline of about three months was assumed. This was divided into three stages taken from the Integrated Product Development and Support (IPDS) methodology namely; Pre-concept, Conceptual Design, Preliminary Design. An additional stage of documentation was included at the end. The Gantt chart served two purposes: setting time-based goals and monitoring progress.

Figure 18 shows the Gantt chart of the project. It can be seen that major time share was devoted to the conceptual design and preliminary design stage. Cost model was also an important phase that was allotted a good time share.

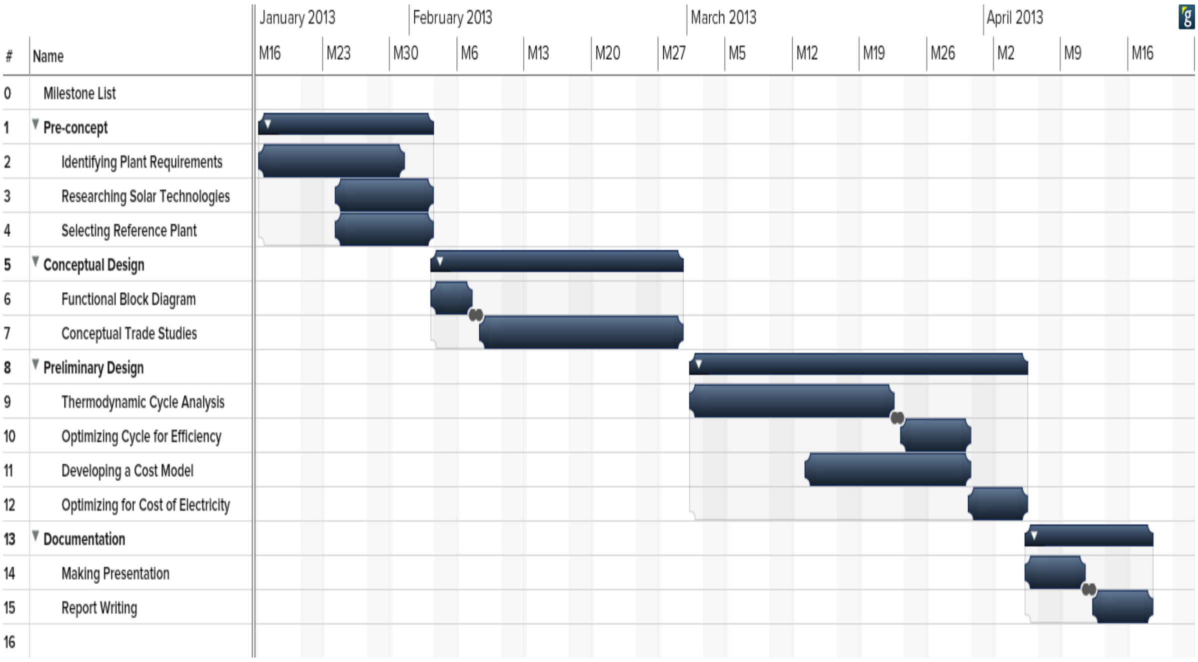


Fig 18: Gantt Chart

3.2.6 Labour budget:

The following is the cumulative labour schedule for our project:

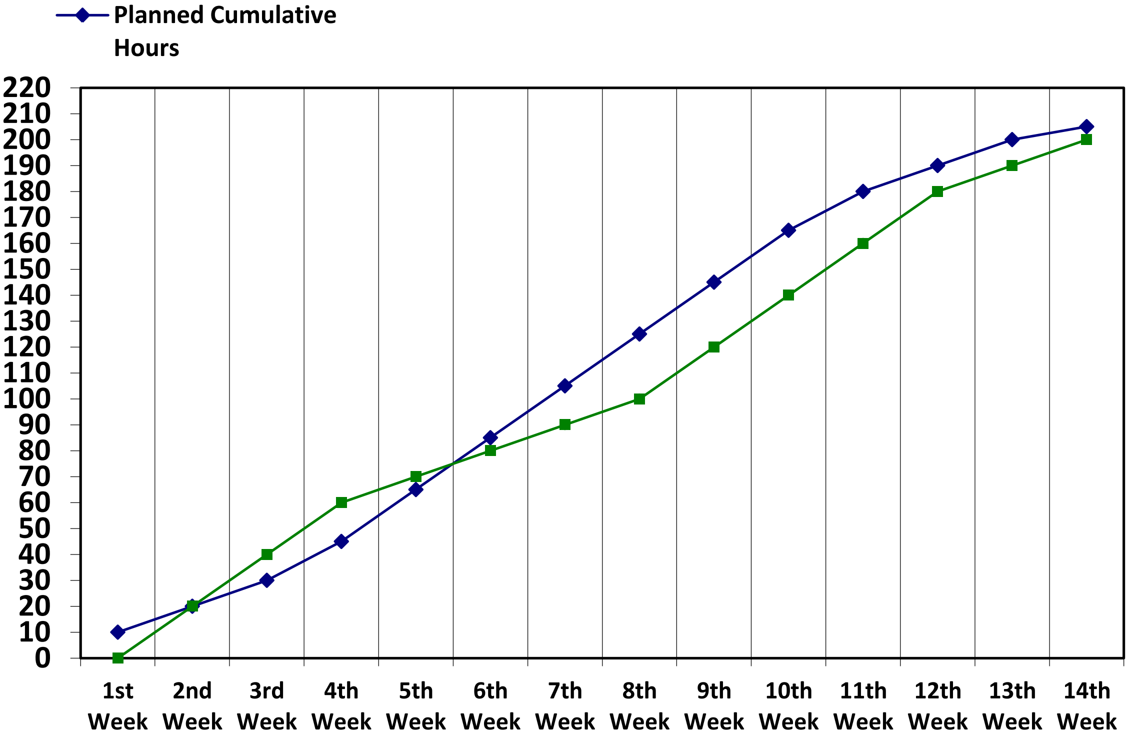


Fig 19: Labor schedule

3.2.7 Success Factors:

The most important factor for our team for success was the completion of set of activities within the constraints of time, cost, and performance. The primary task was to complete the preliminary design within allocated time period and with specification level at the acceptance level of the customer.

4. Requirements and Constraints

The customer need of a 100MW solar power plant with four hours of thermal storage was the objective of this project. The same was done up to the preliminary design stage by various methods of selecting components and thermodynamic cycles by trade studies and thermodynamic iterations respectively.

4.1 Voice of Customer:

The requirement of the customer to make a solar thermal power plant of 100MW with thermal storage of 4 hours was completed up to the preliminary design stage. This included the selection of components and the defining the state points for the system. The results obtained were validated using the thermodynamic models and calculations.

4.2 Requirements/Validation Matrix

Table 11: Requirements/Validation Matrix

	Validation			
Requirements	**Thermodynamic Analysis**	**Cost Optimization**	**Trade Studies**	**Volumetric Analysis**
100 MW Power Output	X			
Efficient Thermal Storage System			x	
Thermal Storage of 4hrs				X
Lowest Cost of Electricity		x		
Optimum Storage Salt	X		x	
Optimum Solar Collectors		x	x	
Turbine and Generator Selection	X	x	x	

5. Conceptual design

The last section of the report dealt with quantifying the customer's needs into some measureable engineering units, thus establishing the needs and the requirements of the system that would satiate the customer needs. Thus owing to the previous section, it was established that the power demand from the plant would be 100 MWe of power for 14 hours a day (problem statement). After the sizing of the plant, the components (and their functions) that would satisfy the requirements were investigated upon.

The conceptual design phase, dealt with two main aspects. One, establishing functional requirements that would fulfil the customer needs and formulating a detailed functional block diagram. And second was the review of the prior art i.e. the research of the technologies that are existing in the current market and choosing the one that quench the plant requirements. Trade studies were conducted between the major existing technologies and the combination of the technologies that fulfilled the requirements were chosen for the plant.

5.1 Functional Block Diagram

Functional block diagram was formulated based on the needs and the requirements of the plant. The plant that is to be designed to generate 100 MWe of power from the solar input and must have a storage unit that can store the heat of the Heat Transfer Fluid up to 4 hours after the sun set.

Figure 20 shown below describes the functional block diagram. The solar radiation strikes the reflecting surface and heats up the Heat Transfer Fluid (HTF). The hot HTF passes from storage system where it is stored depending on the plant load requirements. The HTF then pumped to heat exchange system where the HTC transfers heat to water and converts it into steam. Then the energy conversions take place, from thermal to mechanical in the steam turbine and from mechanical to electrical in the generator. The power produced is then transmitted to grid and additional heat is rejected.

Based on the functional block diagram the types of components required for setting up a 100MWe solar thermal power plant with storage were selected. Also, while selecting the components prior art was reviewed and compared after the components were selected.

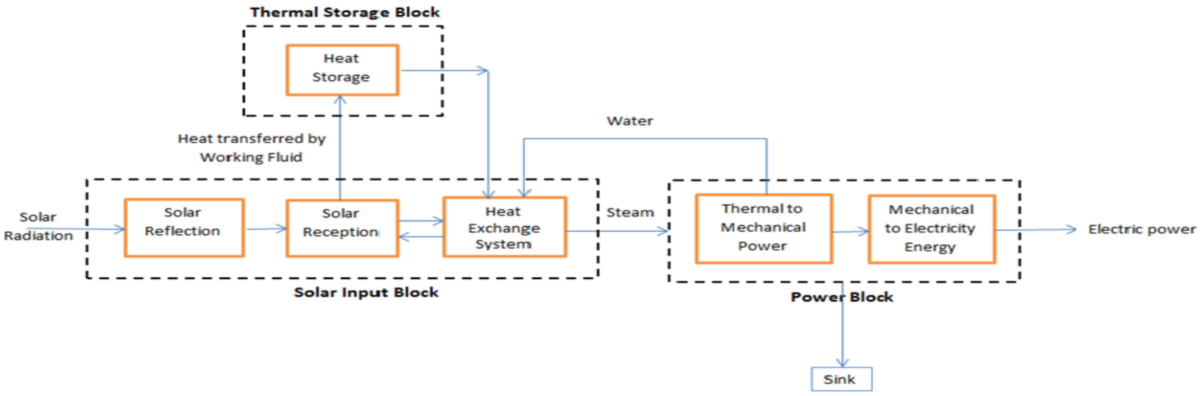


Fig 20: Functional Block Diagram

5.2 Review of the Prior Art

Keeping the customers need in mind, the functions satiating the needs were formulated. Now, components fulfilling the functions were required. . For that, functional block diagram was constructed. The functional block diagram divided the plant into 3 sub systems. Finalizing the each sub system required a detailed analysis of the existing technologies in the current market.

For the first subsystem, solar receiver, there were 4 technologies that were being used for current CSP power plants,namely solar tower, parabolic troughs, linear fresnel, parabolic dishes. There were advantages and disadvantages for each of the system. Doing the research it was seen that parabolic trough receiver system was the most extensively used receiver system in the current market.

For the second block, the thermal storage system, there were 3 options that we looked into namely, 2 tank direct strorage, 2 tank indirect storage and single tank thermocline system. The current market trend is to use parabolic trough technology with two tank indirect storage system.

The power block uses a simple rankine cycle that is quite same as the the conventional power block.

A reference plant was selected with the similar specifications and its parameters were later compared to the current plant.

5.3 Trade Studies

A very important aspect of the conceptual design stage was the trade study. Based on the functional block diagram, the power plant was divided into 3 main blocks and trade studies were conducted for each block individually. As per the division, the blocks were mainly solar input block, thermal storage block and power tower. Also the Heat Transfer Fluid (HTF) was also decided on the basis of detailed trade study.

6. Preliminary design

Preliminary design phase was the next step in design process of the power plant. The conceptual design stage explored the options available in the market for the functions to be fulfilled which were formulated by the customer needs. In the conceptual design stage trade studies were conducted between the available technologies and most at technology satiating the needs were selected.

Now in the preliminary design phase, detailed anaysis was conducted for the 3 blocks of the plant namely, Solar Input Block, Thermal Storage Block, 100 MW Power Block. The solar input block was analysed for total reflective area required(for 100 Mw power generation), number of heliostats, height of the towers. However, positioning of the heliostats was beyond the scope of the report (This required extensive matematical modelling and coding). The heat transfer fluid was also selected in the conceptual design study.

The next block , thermal storage block, was pursed in detail for the volume of tanks and insulation (design of the insulation was beyond the scope of the report). Maximum temperature of the salt reached was also calculated in this phase of the design process (575°C).

The last block of the system was the power block, where the actual conversion of power takes place from heated fluid to steam. The power is produced in the generator that is rotated by the prime mover i.e. multistage turbine. The power plant follows conventional Rankine cylce with reheat. The complete thermodynamic model was formulated and the thermodynamic efficiency of the plant was calculated to be 33.16%.

6.1 Configuration Block Diagram

After the decision of the components was taken, the system and system parameters was defined. The flow direction of the Heat Transfer Fluid and the system parameters were defined. Below in the figure 21, is shown the complete schematic of the power plant. The diagram shows three blocks that are integrated together to produce the required power. The temperature of the heat transfer fluid is 575°C and the steam reaches the temperature of 500°C. The turbine inlet pressure is 120 bar and temperature is 500°C. There is a reheat at 40 bars. The incorporation of the reheat increases the plant efficiency by 3%.

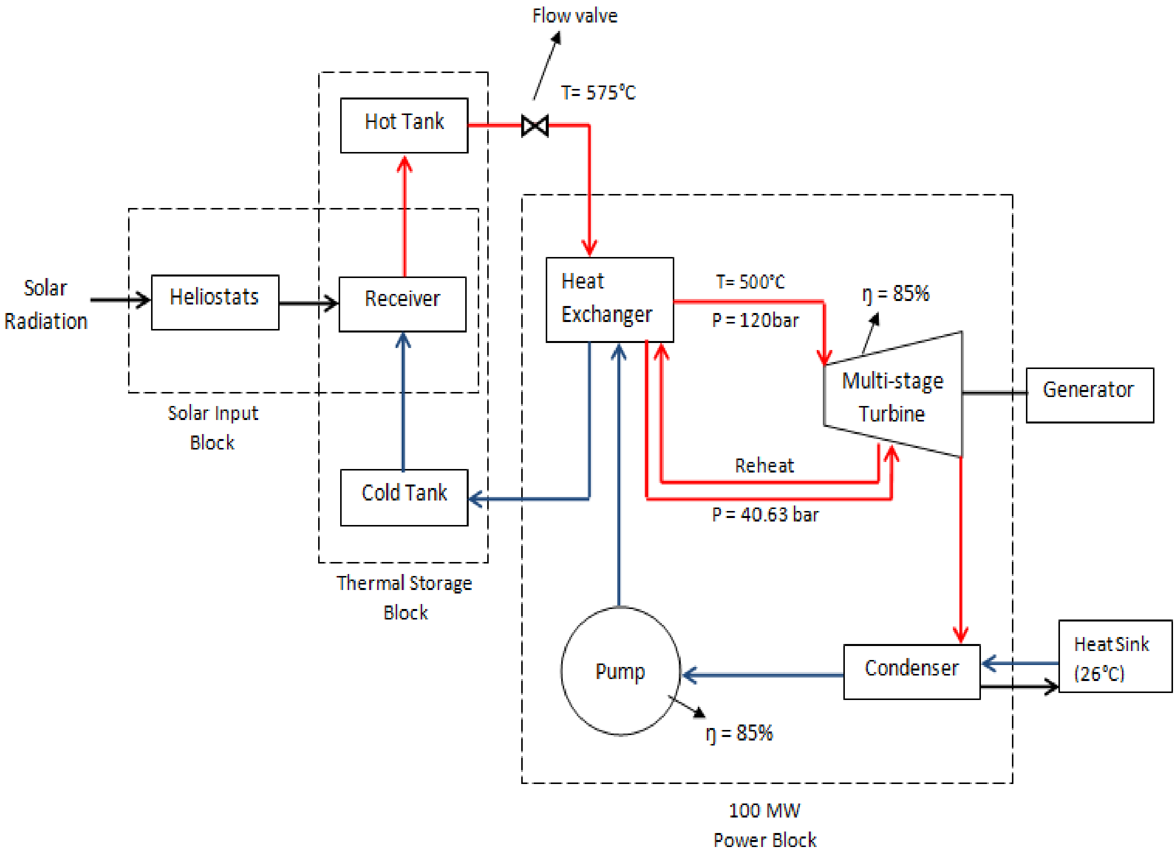


Fig 21: Schematic of the Solar Thermal Power Plant

From fig. 21, Heat Transfer Fluid (HTF) initially resides in the cold tank. The power production takes place when HTF travels from the cold tank to the central receiver . There it traps the heat coming from the heliostats and becomes hot. The temperature in the central tower may reach close to 575 °C. Then the HTF passes through the hot tank where the flow is regulated by the regulatory valve. Then the heat is transferred to water where it is converted into steam. The HTF returns to cold tank and the steam go into the conventional power block where power is produced in the generator and additional heat is rejected to the condenser(a lake). The pump transfers water back to the heat exchanger where the processs continues and thus the power generation.

The regulatory valve regulate the flow. From fig. 22 it is seen that in the peak sunlight times (0800 hrs to 1400 hrs) there is storage. The heat transfer fluid carries more heat than what is required and thus there is a chance of the storage. The regulatory valve regulates te flow of the heat transfer fluid and thus maintaining the required amount of storage.

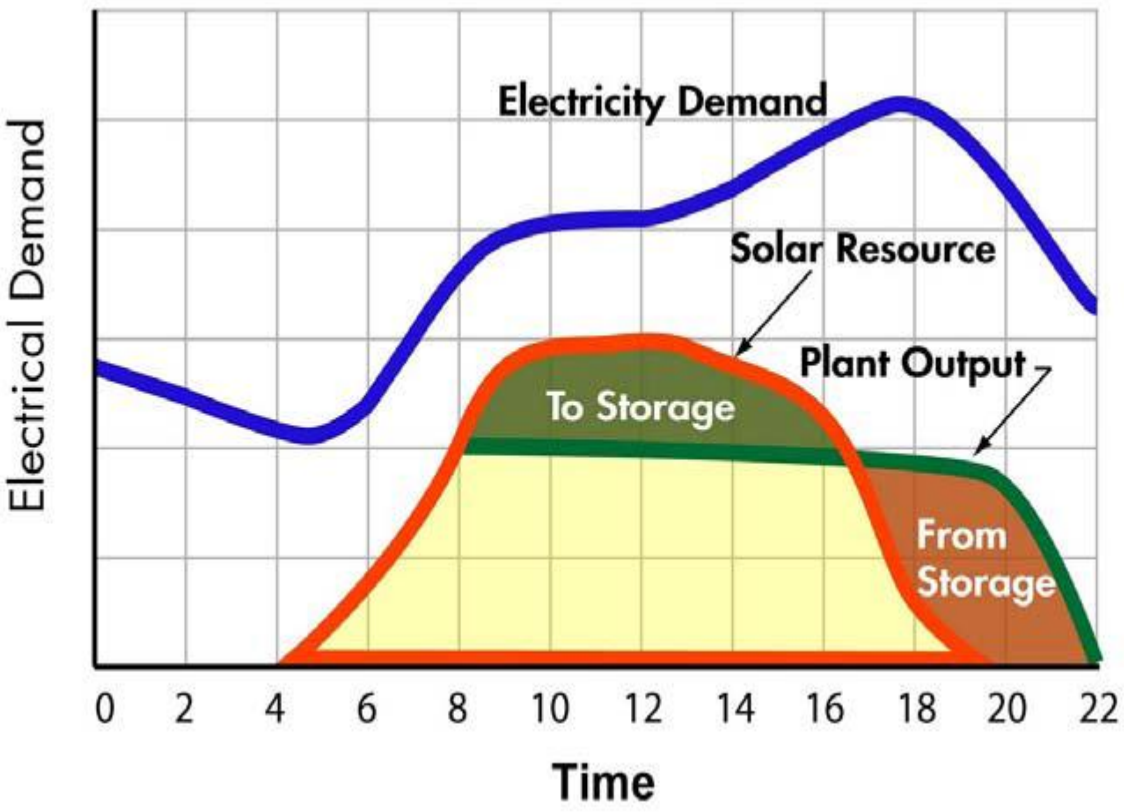


Fig 22: Storage System Management

6.2 Analysis Plan and Results

6.2.1 Reference Plant Description

The reference plant that is being considered is the Crescent Dunes located in NYE County, Nevada. The plant uses the same technology for power generation as our plant. The plant has a central tower that heats up the Heat Transfer Fluid (HTF) inside it. Total reflective area for the reference plant was 1.1km^2. The plant has 17,500 heliostats and height of the central tower is 167m. Table 12 shows complete description of the reference plant that we considered.

Table 12: Prior Art [1]

Component	**Parameter**	**Specification**
Heliostat	Area of reflecting surface	1.1 km^2
	Size of heliostat mirror	7.31m * 8.5m
	Height of tower	167 m
	Number of heliostats	17,500
	Land area occupied	5.7 km^2
Turbine	Inlet temp	554°C
Molten Salt	Hot tank temperature	566°C
	Cold Tank temperature	288°C
Heat transfer salt	NaNO3 + KNO3	Eutectic salt mixture
	Melting point	238°C
Thermal Storage	Time	14 hours per day
Capacity Factor		0.52
Energy production		500 Million KWh/ year

6.2.2 Thermodynamic Model

Thermodynamic model was one of the most important aspect of the plant and demanded a detailed investigation. The total power produced by the plant was reliant on the effective functioning of the thermodynamic model. Looking at the reference plant it was noticed that it was working on a Rankine cycle with reheat. For our plant we did the complete thermodynamic analysis and a trade-offs between system with or without reheat.

Figure 16 shows the cycle diagram and the T-S chart of the thermodynamic model without reheat. The system uses Rankine cycle. The working of the system is quite standard and is self-explanatory. The state points are shown in the table 6. Doing the thermodynamic analysis of the system, the efficiency of the system came out to be 31.67%.

Now, to increase the efficiency of the system we considered adding an extra turbine stage (i.e. the reheat). But selecting the reheat pressure was also a task that we had to accomplish. Iterations were done for various pressures ranging from the 120 bar (turbine inlet pressure) to 20 bar. Table 6 to 9 consists of the table for the reheat iterations. Optimization gave us the reheat pressure of 40.4 bar (figure 11) where the highest thermodynamic efficiency of 33.16% was reached. Figure 17 shows the complete thermodynamic model with reheat with T-S chart and the complete cycle. The state points are shown in table 6. It can be seen that turbine inlet pressure is 120 bars and reheat pressure was 40.4 bar.

6.2.3 Cost Model

The cost of power generation system is huge. Also, when the power generation system is non-conventional source, the upfront cost (capital cost) is immense. Thus, efforts should be made to keep the capital cost to the minimum. This can be done by the tradeoffs between cheaper and efficient technologies. Pertaining to our plant we have done efforts to optimize the plant for lowest capital investment and highest efficiency. The cost breakdown for individual components is shown in table 13.

The plant is estimated for 2 years of the construction and thus inflation is added accordingly. Building a power plant is a huge task and everything cannot go as planned as it has many variables to look into. Thus a contingency of 12.5% was used to overcome any unaccounted cost. **Thus, total capital investment with inflation (@ 7.5%) and contingency (@12.5%) comes out to be $830 million.**

Table 13 Cost Break Down

Cost Parameters	**Expected cost ($ millions)**	
	Our Plant	**Reference Plant [1]**
Receiver, Tower, Salt Tanks & Heliostats	191	225
Turbine and Steam Generator	126	135
Cooling System and Water	42	45
Miscellaneous Process Equipment	49	52.5
Electrical Instrumentation	63	67.5
Civil and Site Work	14	15
Structural	70	75

Buildings	14	15
Piping & Instrumentation	77	82.5
Mechanical Utilities	35	37.5
Total capital investment	**687**	**750**
Inflation	51	56
Contingency	92	100
Total cost of the plant	830	906

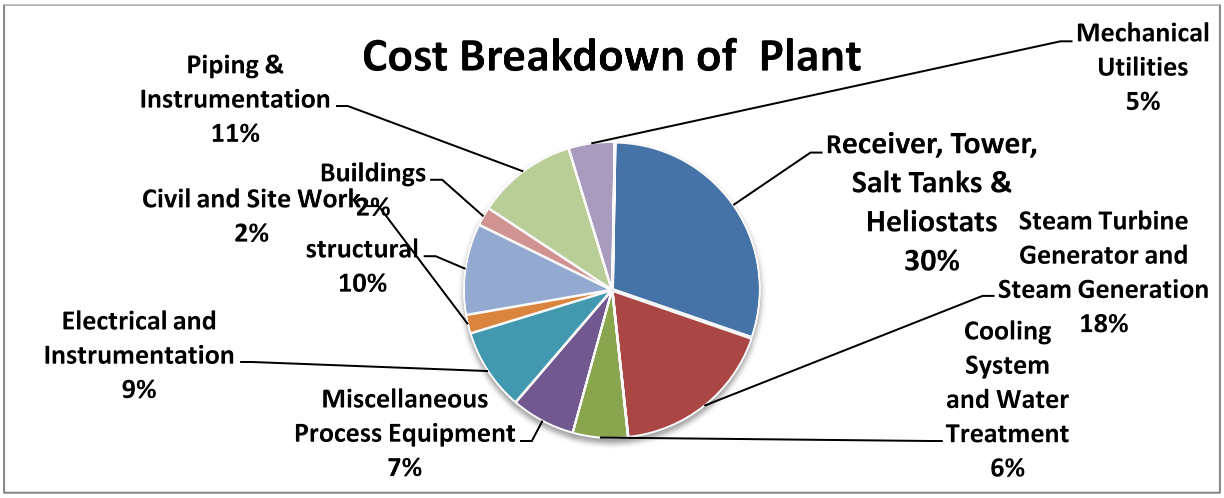


Fig 23: Cost Distribution of the plant Component wise

Fig. 23 explains the cost division between the plants components. It can be seen that major share of the cost goes into the Receiver, tower and storage. This explains the reason that highest weighing factor in trade off for the receiver was given to cost. The second most expensive component of the system is the steam generation system. And thus the others follow.

6.2.4 Cost of Electricity (COE)

Thriving of the non-conventional sources of energy is primarily dependent on its cost of electricity. Cost is the major driving factor for the installation of any power plant. But when it comes to non-conventional power plants the cost of electricity is slightly higher than the conventional sources. But with the tax benefits, carbon tax input and decreasing capital cost of the non-conventional sources of energy production, cost of electricity is decreasing continuously. The cost of electricity for the concentrated solar power (CSP) is quite competitive when compared with the cost of electricity by the conventional power generation system.

Non-conventional sources of energy production have a huge upfront cost and very low operation and maintenance cost. Because of such huge cost involved in such short tenure (the time of construction of plant) detailed analysis of the cost model is required so as to keep the capital cost to the lowest.

The total capital cost of our power plant comes out to be $830million Based on that value the cost of electricity was predicted.

$$Fixed\ charges = \frac{FCR * CI}{RC * CF * 8760\ (hrs\ per\ year)}$$

Fixed Cost rate (FCR) = 10%
Capital investment (CI) = $ 830million
Rated capacity (RC) = 100MW
Capacity Factor = 60%

$$\boxed{\text{COE for fixed charges = \$ .159/kWh}}$$

Cost of Electricity = Fixed Charges + O& M + Fuel Charges
For our plant there is no fuel thus fuel charges are zero.
O&M cost is $.01/kWh (problem statement)

$$\boxed{\text{Cost of Electricity = \$ 0.169/ kWhr}}$$

6.2.5 Cost of electricity (COE) Optimization

COE is the cost of electricity per kWh of power consumed. One of the biggest challenge in this plant design was to keep the COE the lowest. The cost of electricity drives the market and for the power plant to earn and thrive, CoE should be low. The plant was initially modelled as simple thermodynamic model without reheat. But with that model efficiency was low and thus the COE was large. Thus the optimization was done by adding the reheat in the system. After selection of the reheat was done, reheat pressure was optimized for the lowest cost of electricity. Table 3 shows the exact COE at a reference reheat pressure. From the table it is clear that lowest COE occurs at a reheat pressure of 40.4 bar. Figure 8 describes the best combination for reheat pressure and COE.

Table 14 Cost optimization for reheat pressure

Reheat Pressure (bar)	**Heat Input (MW)**	**Thermal Efficiency (%)**	**No. of Heliostats**	**Cost of Electricity ($/kWh)**
20.5	303.2	32.94	12045	0.172
40.4	301.6	33.15	11981	0.169
60.3	302.9	32.96	12033	0.178

80.2	304	32.47	12077	0.175
100.1	310.8	32.11	12347	0.176
No Reheat	314.8	31.67	12507	0.185

7. Project Performance

7.1 Budgeting of Team Labour

The Figure 19 shows the team labour hours as they accumulate through the life of the project. Our baseline for this project is the typical S-curve. As can be seen from the chart, there are at least four notable deviations from the planned S-curve.

The main tasks during the 1st and 2nd weeks understood the problem statement, identifying plant requirements and researching solar technologies. It was decided early on that only those technologies would be considered which are already being used. Hence, this phase of the project took less time than expected. 3rd, 4th and 5th week were designated for developing a functional block diagram and conceptual design trade studies. This phase took more time than expected because the trade-offs required a deeper understanding of the various sub-systems of the plant. 6th week to 9th week were dedicated to developing and optimizing the thermodynamic model. Thermodynamic analysis took considerably more time than expected, mainly due to the complexity added by using a reheat stage. Hence, the team put in extra hours during the Spring break to complete the analysis. 11th and 12th week were utilized for making a cost model and obtaining cost data from various resources. This stage was completed on time. Finally, the last two weeks were kept for review and documentation. Because most of our calculations were hand-written, summarizing them and converting them to a meaningful form took a lot of time and effort. Hence, the planned budget hours were exceeded mainly in the documentation phase.

7.2 Gantt chart

Figure 18 shows the Gantt chart of the project. The milestones in the chart below were taken from our work breakdown structure. A project timeline of about three months was assumed. This was divided into three stages taken from the Integrated Product Development and Support (IPDS) methodology namely; Pre-concept, Conceptual Design, Preliminary Design. An additional stage of documentation was included at the end. The Gantt chart served two purposes: setting time-based goals and monitoring progress.

7.3 Key Lessons Learned

- Trade studies are a valuable tool for decision-making in conceptual design phase
- Project monitoring methods like labour schedule and Gantt chart helped the team complete the project on time
- Detailed documentation should be done at every phase of the project

- It makes sense from an economic point of view to work with technologies that have already been tested elsewhere. This ensures that your selected technology is cheaper, easily available and more reliable than a technology that is still in research phase.
- The actual cost of electricity from the plant is noticeably larger than the ideal value which neglects weather effects, shadowing, cosine losses and variance in solar isolation throughout the day.
- The thermal efficiency of Rankine cycle is not a linear function of reheat pressure.

8. Project Conclusions

The objective of the project was to obtain the preliminary design of a 100 MW concentrated solar power plant with 4hrs of thermal storage. This objective was achieved according to plan and within the scheduled timeline. The design specifications were then compared with the reference plant and the result was a lower cost of electricity for the proposed plant

Table 15: Final Design Specification [4] [1]

Design Specifications and Comparison with Reference				
Component	**Parameter**	**Our Plant**		**Reference Plant[1]**
		Ideal*	**Actual**$^{\#}$	
Heliostat	Reflecting Surface Area	0.43 km^2	0.74 km^2	1.1 km^2
	Size	7.31m x 8.5m	7.31m x 8.5m	7.31m x 8.5m
	Height of tower	167m	167m	167 m
	Number	6935	12,000	17,170
Turbine	Inlet temp	500°C	500°C	554°C
Heat Transfer Salt	$NaNO_3 + KNO_3$	$NaNO_3 + KNO_3$	$NaNO_3 + KNO_3$	$NaNO_3 + KNO_3$
Capacity Factor		0.60	0.60	0.52
Energy production		511 Million KWh/year	511 Million KWh/year	500 Million KWh/year
Capital Investment		$583 million	$830 million	$906.3 Million
Cost of Electricity		0.111 $/kWh	0.169 $/kWh	0.198 $/kWh

Note:

*Ideal – Solar irradiance = 1000 W/m^2 & Heliostat η = 99% (neglecting weather conditions, cosine, shading & blocking effects

$^{\#}$Actual – Solar Irradiance = 580 W/m^2 (for Arizona) & Heliostat η = 70% (considering weather conditions, cosine, shading & blocking effect)

Source: *NREL- Solar Radiation Data Manual for Building by William Marion & Stephen Wilcox*

It should be noted that the amount of heliostats for the proposed system is much less than the reference. Consequently, the Capital Investment and Cost of Electricity are also lower.

9. Project Recommendations

Following are some suggestions for future work in this project:

- Detailed design including piping and instrumentation of receiver, steam generator and condenser.
- Expanding the thermodynamic analysis for more than one reheat stage.
- Optimal design of solar collector field.
- Detailed analysis of shadowing, cosine losses and varying intensity of solar isolation on the solar collector field.
- Comprehensive trade-off studies between additional cost of reheat equipment versus the increased thermal efficiency due to reheat.
- Establishing a budget and using capital budgeting techniques e.g. payback period.
- Selection and costing of auxiliary components.
- Failure modes and effects analysis (FMEA).
- Creating site plans for building and construction.

10. References

[1] Crescent Dunes Solar Energy Project Plan of Development

[2] Assessment of Parabolic, Trough and Power Tower Solar, Technology Cost and Performance Forecasts

[3] EPRI -Program on Technology Innovation: Evaluation of Concentrating Solar Thermal Energy Storage Systems

[4] Low Cost Heliostat Development DOE – CSP Program Review.

[5] Dr. Steven Trimble Slides.